Pairing the concepts of ecosystem services and resilience to navigate in the current crises toward sustainability

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Abstract

In the last decades, humanity has considerably altered the functioning of Earth, resulting in global and inter-related social, economic, and environmental crises. To address these crises, the concepts of ecosystem services (ES) and resilience look promising to understand the complexity of the social-ecological system (SES) and its dynamics. However, operational frameworks that bring together these two concepts are still lacking. We therefore propose the Navigate framework to guide the researchers and the managers in finding sustainable solutions, in other words safe and just strategies.

This framework was built from a literature review, interviews with leading experts, and feedback from its implementation in a case study.

The conceptual part of the Navigate framework illustrates the multiple interactions between nature and society, depicted by the ES, occurring at various scales. Following disturbances, the SES responds by either persisting, adapting or even transforming (i.e. three forms of resilience). The operational part of Navigate suggests six steps to follow in an iterative process: (1) define the system, (2) define the problem, the stakes and goals, (3) define the pathways, (4) assess the ES, (5) assess resilience, and (6) design the action plan.

The implementation of this framework to a case study demonstrated that together ES and resilience with a participatory process gave a comprehensive picture of the SES, essential to making sound sustainable decisions. Indeed, the integrated assessment of ES combining various complementary methods highlights the stakeholders ’needs and perspectives, the various forms of knowledge, the scales, and the interactions. Resilience broadened the analysis by understanding how the important drivers impacted the SES and its ES.

In conclusion, the Navigate framework shows the way (i.e. which ES the stakeholders have requested) while considering the dynamic properties of the SES, amidst increasing social and ecological uncertainties, to navigate together toward sustainability. We recommend applying this framework for research or projects that have a strong focus on the social aspects with enough resources, notably a transdisciplinary team that will be able to implement the different and complementary methods needed to assess the different values of ES and resilience.

Résumé

Ces dernières décennies, l'humanité a considérablement altéré le fonctionnement de la Terre, menant à des crises sociales, économiques et environnementales globales et interreliées. Pour faire face à ces crises, les concepts de services écosystémiques (SE) et résilience semblent prometteurs pour comprendre la complexité des systèmes socio-écologiques (SES) et leurs dynamiques. Toutefois, il nous manque encore des cadres opérationnels qui allient ces deux concepts. Nous proposons donc le cadre Navigate qui guide les chercheurs et gestionnaires dans la recherche de solutions durables, en d'autres mots, de stratégies socialement justes et respectueuses de l'environnement.

Ce cadre a été construit à partir d'une revue de la littérature, d'interviews avec des experts et des retours d'expériences tirés de son application à un cas d'étude, la forêt communale de Sivry-Rance.

La partie conceptuelle du cadre Navigate illustre les multiples interactions entre la nature et la société, représentées par le concept de SE, survenant à de multiples échelles. À la suite de perturbations, le SES répond soit en persistant, soit en s'adaptant ou encore en se transformant (i.e. les trois formes de résilience). La partie opérationnelle du cadre Navigate suggère 6 étapes à suivre selon un processus itératif : (1) définir le système, (2) définir le problème, les enjeux et objectifs, (3) définir les alternatives, (4) évaluer les SE, (5) évaluer la résilience, et (6) mettre au point le plan d'action.

L'application de ce cadre à la forêt communale de Sivry-Rance a démontré qu'ensemble les concepts de SE et de résilience donnaient un tableau plus complet du SES, essentiel pour prendre des décisions durables éclairées. En effet, l'évaluation intégrée des SE, combinant de nombreuses méthodes complémentaires, met en lumière les besoins et perspectives des parties prenantes, les différentes formes de connaissances, les échelles, et les interactions. Le concept de résilience élargit l'analyse du système aux forces motrices principales et à leurs impacts sur le SES et ses SE.

En conclusion, le cadre Navigate montre la voie (i.e. quels SE les parties prenantes souhaitent avoir) tout en considérant les propriétés dynamiques du SES, face aux incertitudes sociales et environnementales croissantes, pour naviguer ensemble vers la durabilité. Nous recommandons d'appliquer ce cadre à des recherches ou projets qui mettent l'accent sur les aspects sociaux avec suffisamment de ressources, notamment une équipe transdisciplinaire qui est capable de mettre en œuvre les différentes méthodes complémentaires nécessaires à l'évaluation des diverses valeurs des SE et de la résilience.

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List of publications

Scientific papers

Maebe, L., H. Claessens, and M. Dufrêne. 2019. The critical role of abiotic factors and human activities in the supply of ecosystem services in the ES matrix. *One Ecosystem* 4:e34769.

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Table of content

List of figures

List of tables

List of acronyms

3R	Relevance, Robustness and Resource efficiency
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ARIES	Artificial Intelligence for Environment & Sustainability
BDFGM	Banque de Données Fauniques de Gembloux & Mons
Biodiv2.6	Biodiversity SSP1-2.6
Biodiv8.5	Biodiversity SSP5-8.5
BNIP	Belgian Nature Integrated Project
BOC	Biomass Organic Carbon
CAS	Complex Adaptive System
CBD	Convention on Biological Diversity
CICES	Common International Classification of Ecosystem Services
CPAS	Centre Public d'Action Sociale
DCE	Discrete Choice Experiment
DNF	Département de la Nature et des Forêts
DPSIR	Driver-Pressure-State-Impact-Response
EFESE	Evaluation Française des Ecosystèmes et des Services Ecosystémiques
ELECTRE	ELimination and Choice Expressing the Reality
EPPS	Ecosystem Properties Potentials and Services
ERRUISSOL	Erosion-RUISsellement-SOL
ES	Ecosystem Services
FEGS-CS	Final Ecosystem Goods and Services - Classification System
FN	False Negative
FP	False positive
GES	Greenhouse Gases
GIS	Geographical Information System
GLM	General Linear Modelling
GTSE	Groupe de Travail sur les Services Ecosystémiques
GxABT	Gembloux Agro-Bio Tech
INBO	Instituut Natuur- En Bosonderzoek
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs

IPBES	The Intergovernmental Platform on Biodiversity and Ecosystem Services
IPRFW	Inventaire Permanent des Ressources Forestières Wallonnes
IRM	Institut Royal Météorologique
IUCN	International Union for Conservation of Nature
KerDST	KerBabel™ Deliberation Support Tool
LUCI	Land Utilisation Capability Indicator
MAES	Mapping and Assessment of Ecosystems and their services
mAP	mean Average Precision
MCA	Multi-Criteria Analysis
MA	Millenium ecosystem Assessment
MIMES	Multiscale Integrated Model of Ecosystem Services
Multifct2.6	Multifunctional Forest SSP1-2.6
Multifct8.5	Multifunctional Forest SSP5-8.5
NAIADE	Novel Approach to Imprecise Assessment and Decision Environments
NCC	Natural Capital Coalition
NCP	Nature Contribution to People
NESCS	National Ecosystem Services Classification System
NGO	Non-Governmental Organization
NVE	Nature Value Explorer
OpenNESS	Operationalisation of Natural Capital and Ecosystem Services
PECS	Program on Ecosystem Change & Society
PNDO	Parc Naturel des Deux Ourthes
PNHF	Parc Naturel Hautes Fagnes Eifel
PPD	Press–Pulse Dynamics
Profit2.6	Profitability SSP1-2.6
Profit8.5	Profitability SSP5-8.5
RAVeL	Réseau Autonome des Voies Lentes
Recrea2.6	Recreation SSP1-2.6
Recrea8.5	Recreation SSP5-8.5
SENCE	Spatial Evidence for Natural Capital Evaluation
SES	Social-Ecological System
SFSTM	Structural-Functional State and Transition Model
SOC	Soil Organic Carbon
SolVES	Social Values for Ecosystem Services

SPW	Service Public de Wallonie
SSP	Shared Socioeconomic Pathway
STM	State-Transition Model
SWDE	Société Wallonne Des Eaux
TARA	Transformative Adaptation Research Alliance
TCM	Travel Cost Method
TEEB	The Economics of Ecosystem and Biodiversity
TESSA	Toolkit for Ecosystem Service Site-based Assessment
TN	True Negative
TP	True Positive
ULiège	Université de Liège
UN	United Nations
UNEP	United Nations Environment Program
User2.6	Users' Forest SSP1-2.6
User8.5	Users' Forest SSP5-8.5
VAST	Vegetation Assets, States and Transitions
Wal-ES	Walloon platform on Ecosystem Services
WAVES	Wealth Accounting and the Valuation of Ecosystem Services
Wood2.6	Wood Production SSP1-2.6
Wood8.5	Wood Production SSP5-8.5
WTP	Willingness-To-Pay
WWF	World Wildlife Fund
ZHIB	Zone Humide d'Intérêt Biologique

Chapter 1

Introduction

1. Context

Over the last decades, the ever-growing human and economic development in pursuit of material wealth has led to unprecedented population growth, increased global connections, urbanization and rising consumption around the world (Biggs et al., 2012). Humanity has substantially shaped the natural world to meet this growing demand (Kareiva et al., 2007), potentially creating a new geological epoch, the Anthropocene (Crutzen, 2002; Zalasiewicz et al., 2020). These human activities have had numerous impacts on the Earth system heavily altering land cover, climate, global biogeochemical cycles, and the mobility of species (Scheffer et al., 2001). Furthermore, they have led to completely novel and unpredictable effects characterized by their growing potential to cross critical thresholds (Biggs et al., 2015). The consequences of these human activities have taken the form of global and inter-related social, economic and environmental crises (i.e. polycrisis) such as biodiversity loss, the crossing of several planetary boundaries (i.e. climate change, biosphere integrity, biogeochemical flows, and land-system change) (Steffen et al., 2015), economic shocks, and human security risks (e.g. in the face of extreme weather events or novel pandemics), all threatening current and future human well-being (IPBES, 2019).

To address these mounting crises, the two concepts of resilience and ES look promising to lead the way toward sustainability (i.e. to ensure that current and future generations are all able to meet their needs without compromising the Earth system (Raworth, 2012)) (Sarkki et al., 2017). Since 1980, the ES and resilience concepts have established substantial credibility and are increasingly used around the world in the scientific, political, and practical arenas (Nikinmaa et al., 2020; Schoon et al., 2015). These two concepts have been examined together in the literature (e.g. Ruhl and Chapin 2014, Biggs et al. 2015, Field and Parrott 2017). However, to the best of our knowledge, an operational framework that brings together these two concepts is still lacking. Pairing them seems necessary when sustainably managing the SES (i.e. intertwined system of humans and nature where people and the biosphere are interconnected and mutually interdependent (Brown, 2021)). If we manage the SES to be resilient without knowing what we really want to maintain or conserve, we may well be getting off track. Conversely, when the focus is put on the ES a SES provides, we often forget to assess if the SES will still be able to provide them in the future considering the significant changes it undergoes or answer the evolving societal demands.

The aim of this thesis is thus to propose the Navigate framework which pairs closely the concepts of ES and resilience to bring together their unique added values. After presenting the concepts of ES and resilience, their pairing is discussed in Chapter 1. In Chapter 2, the Navigate framework is first presented. Then, the case study (i.e. the municipal forest of Sivry-Rance) to which the framework was applied is described. Finally, the different methods used to implement the framework are discussed. In

Chapter 3, the results of the implementation of the Navigate framework to the municipal forest of Sivry-Rance are presented following the six steps of the framework. In Chapter 4, the conceptual and operational parts of the Navigate framework are critically discussed to highlight their advantages, limits, and areas of improvement. Measures to improve the ES and the resilience of the municipal forest of Sivry-Rance are then described. Finally, in Chapter 5, the scientific advances and the perspectives of the doctoral research are synthetized. The potential policy uptake and practical implementation of the framework are also discussed.

2. Ecosystem services

The ES concept is discussed in this section to illustrate its emergence and evolution, its multiple conceptualizations and implementations, its assets and limitations.

2.1 History of the ecosystem services concept

Humans have been valuing the goods and services provided by ecosystems since the beginning of humanity (Caramelli et al., 2008). A few decades ago, this idea was formalized into the ES concept to answer environmental degradations caused largely by an economic system of unsustainable exploitation (MA, 2005). From this point of view, the ES concept is used as an incentive for nature conservation and as a unifying framework for transdisciplinary approaches in research, policy and sustainability (Lyytimäki and Petersen, 2014; Munns et al., 2015). On the other hand, this concept emerged also in the (neo)liberal context where the market is viewed as the most efficient management and regulatory tool (Brenner et al., 2010) and where 'ecological modernization' (i.e. promoting more and better modernization without getting to the heart of the problem: industry and consumption) is seen as a solution to environmental degradation (Kull et al., 2015).

This double origin of the ES concept has manifested from the beginning in the scientific arena. The first use of the term 'ecosystem services' can be traced back in the book of Ehrlich et Ehrlich (1981) on the extinction of species and its effects on Earth. However, Westman (1977) used the ES concept named as the 'nature's services', four years earlier when arguing in terms of economic valuation of the 'free services' delivered by nature. During around fifteen years, they were only one or two papers including the term of 'ecosystem service(s)' published each year (Dick et al., 2011). Then, in 1997, the ES concept took wings with the emblematic publications by high-profile ecologists and economists: Costanza et al. (1997) on the economic values of ES, Vitousek et al. (1997) on the impacts of human activities on ES, and Daily (1997) on the damage that has been done to ES and the consequent implications for human society (Kull et al., 2015). Since then, the number of papers on ES has grown exponentially (Abson et al., 2014; Dick et al., 2011).

ES research has progressed from conceptualization to practical applications (Potschin and Haines-Young, 2016) with growing research on its operationalization by developing tools, applying it in case studies, and using it in decision making (Kull et al., 2015; La Notte et al., 2017; Munns et al., 2015). The use of ES in policy was first undertaken by MA in the 2000s. This assessment, under the auspices of UNEP and funded by the UN Foundation, the Packard Foundation and the World Bank, gathered international institutions, governments, business world, NGO, indigenous people and scientists to assess the consequences of ecosystems changes on human well-being and to establish the scientific bases needed to take actions for the conservation and sustainable use of ecosystems (MA, 2005). This work is an important milestone of the ES research because it made prominent the idea that human well-being depends on ecosystems (La Notte et al., 2017). TEEB followed, launched by the environment ministers of G8+5 in 2007, to assess the economic impacts of the loss of biodiversity and the degradation of ecosystems at the global level in order to help decision-makers recognizing, demonstrating and capturing the values of ES and biodiversity (TEEB, 2010a).

Since then, the ES concept has been expanding in policy and practice at various levels. At the international level, major international environmental NGOs (e.g. WWF, IUCN) and conventions (e.g. CBD) incorporated ES in their programs (Kull et al., 2015). IPBES, launched in 2012, gathers governments, academia and civil society to assess and promote knowledge on biodiversity, ecosystems and ES in order to inform policy formulation (Díaz et al., 2018). At the regional level, the European Union incorporated the ES concept into its Biodiversity Strategy 2020 (Maes et al., 2012). At the national level, ES is more and more integrated into policies to justify the need for nature conservation, biodiversity protection and sustainable resource use (Bouma and Van Beukering, 2015; Kull et al., 2015). In Wallonia, the Wal-ES platform was launched in 2014 to create and disseminate decision support tools based on the concept of ES. Between 2014 and 2016, this platform developed a common framework for the implementation of the ES concept in Wallonia with a conceptual framework, an assessment framework, and a shared database to gather the existing typologies, indicators, methods to assess the ES. Relaunched in 2019, Wal-ES adapted NVE (i.e. pragmatic methods that value ES and helps planners, land managers and policy makers to map nature's socio-economic importance (Pairon et al., 2022)) for the northern part of Wallonia to have an operational tool to assess the ES in Wallonia. The private sector has also adopted the concept through initiatives such as the NCC or the World Bank's WAVES, the accounting system developed by the London Group (La Notte et al., 2017).

Now, the ES concept is widely used among scientists and policy makers as a crucial bridge between the environment and society and as a keystone concept in conservation, resource management, and ecological and environmental economics (Wu, 2013). The current popularity of the ES concept comes from the need to find more effective ways to convey the messages from ecological research to the decision-makers and to facilitate interdisciplinary debate between natural and social scientists and transdisciplinarity between research and practice (Lyytimäki and Petersen, 2014). Therefore, ES can be used as a tool to reach sustainability. Indeed, IPBES (2022) demonstrated that understanding how values are formed, changed and eroded helps policymakers identifying options to achieve decision outcomes that better align with sustainability objectives. The assessment of ES also provides the potential for developing an operational framework for sustainability (Lyytimäki and Petersen, 2014; Mulligan and Clifford, 2015). Moreover, thanks to its increasing popularity in decision making and civil society, this concept can act as a boundary object for sustainability by reinforcing the collaboration between policy makers and scientists (Abson et al., 2014). However, the implementation of this concept in sustainability should not overshadow important aspects of sustainability (e.g. intra- and inter-generational distribution), override other perspectives (e.g. intrinsic or relational values) or even be detrimental to sustainability (Lyytimäki and Petersen, 2014; Schröter et al., 2017). For instance, the increase of some provisioning services may be at the cost of sustainability, biodiversity and other natural capital that do not provide direct services (Mulligan and Clifford, 2015; Schröter et al., 2017).

2.2 Its multiple conceptualizations

2.2.1 Definitions

The ES concept has numerous definitions (see for example the table 1 in Nahlik et al. (2012) presenting the most commonly cited definitions of ES) primarily because of its use in various disciplines with their own particular interests and approaches (Abson et al., 2014; Nahlik et al., 2012). These multiple definitions can be broadly categorized as either favoring ecological or economic viewpoints (Dick et al., 2011) or as providing a more general perspective that can encompass a number of viewpoints (Munns et al., 2015). In ecology, ES are associated with ecosystem attributes (i.e. a biological, physical or chemical feature of the ecosystem) that lead to benefits (Nahlik et al., 2012). In that sense, Daily (1997) defined ES as “the conditions and processes through which natural ecosystems, and the species that make them up sustain and fulfill human life”. In the economic discipline, ES are the outputs of the ecosystem functions that provide utility to society (Freeman, 2014; Nahlik et al., 2012). For example, the NESCS framework defines ES as the flows from the producers/providers to consumers/users (United States Environmental Protection Agency, 2015). In a broader perspective, for instance, MA (2005) defined the ES as “the benefits humans derive from ecosystems”. This definition encompasses various viewpoints, types of values and meanings open to multiple interpretations. The different conceptualizations of ES lead to contrasting uses of this concept. The ecological conceptualization emphasizes ecosystem functioning and attributes while the economic one focuses more specifically on the benefits, regarded as calculable values, for humans (Boyd and Banzhaf, 2007; Fisher et al., 2009; Nahlik et al., 2012).

A distinction is often made between intermediate and final services, especially for the sake of economic valuation where only benefits from final services can be aggregated to avoid double counting (La Notte et al., 2017). Intermediate services indirectly contribute to human well-being (e.g. aquatic insect community) while final services directly contribute to it (e.g. fishing) (Munns et al., 2015). This differentiation is not always clear-cut and can change with the context (e.g. the aquatic insect community is a final service for the people who enjoy viewing aquatic insects) (Munns et al., 2015). Thus, the knowledge of people's preferences and values is required to distinguish between intermediate and final services (Munns et al., 2015).

Another term 'NCP' was introduced within the frame of IPBES to recognize the central role of culture in defining NCP and to emphasize the role of indigenous and local knowledge in understanding NCP (Díaz et al., 2018). NCP are defined by Díaz et al. (2018) as "all the contributions both positive and negative of living nature (diversity of organisms, ecosystems and their associated ecological and evolutionary processes) to people's quality of life". The NCP approach seeks to increase the equitability, effectiveness and social legitimacy of policies by integrating different knowledge systems and facilitating the connection with rights-based approaches to conservation and sustainable use of nature (Díaz et al., 2018). The introduction of this new term causes a lot of ink to flow in the scientific world. Some scientists argue that all the bottlenecks of ES addressed by NCP are already being tackled in a pluralistic and multi-worldview way or that it does not solve the semantic problems associated with ES (e.g. Braat, 2018; Groot et al., 2018; Kenter, 2018). Others agree upon the assets of the NCP concept over the ES (e.g. Baveye et al., 2018; Ellis et al., 2019).

Even if multiple definitions or even different terms (e.g. NCP) are used to characterize the contribution of nature to human well-being, the idea behind it is quite consistent and is centered on four elements: (1) something out there (e.g. ecosystems, nature), (2) providing things (e.g. resources, goods, services), (3) useful to people (e.g. livelihoods, health), and (4) should be valued (Kull et al., 2015). The term or the definition used to describe it is important but what really matters is the use makes of it and its consequences on policies and management. Depending on its use, the ES concept is either descriptive or normative. In its descriptive use, ES are used to characterize and explain the interdependencies of human and natural systems without addressing the value-laden assumptions that may shape such analyses (Abson et al., 2014). In its normative use, the values are explicitly ascribed to different system states, usually to identify aspects of human-nature interactions that ought to be improved (Abson et al., 2014).

2.2.2 Conceptual frameworks

Multiple conceptual frameworks have been developed to schematize the relationships between nature and human society and to provide common terminology and structure of the key components and their relationships (e.g. Fisher et al., 2009; Heink and Jax, 2019; Potschin-Young et al., 2018). A typical example is the ES cascade proposed by Haines-Young et Potschin (2010) linking natural systems to elements of human well-being (**Figure 1-1**), following a pattern similar to a production chain from ecological structures and processes generated by ecosystems to the services and benefits eventually derived by humans (La Notte et al., 2017). This framework entails a double vision: (1) a bio-centered vision emphasizing the role of structures and processes and their subsequent functions, and (2) a human-centered vision where ES are projected towards the human end use side (La Notte et al., 2017). This framework has been extensively applied (e.g. Mononen et al., 2016; Rozas-Vásquez et al., 2019; Wang et al., 2019) and improved notably to better integrate the holistic nature of the ES concept that could be narrowed down to individual measures because of the human-centered vision of the ES cascade (e.g. Evans et al., 2019; Fedele et al., 2017; Petit-Boix and Apul, 2018) (La Notte et al., 2017).

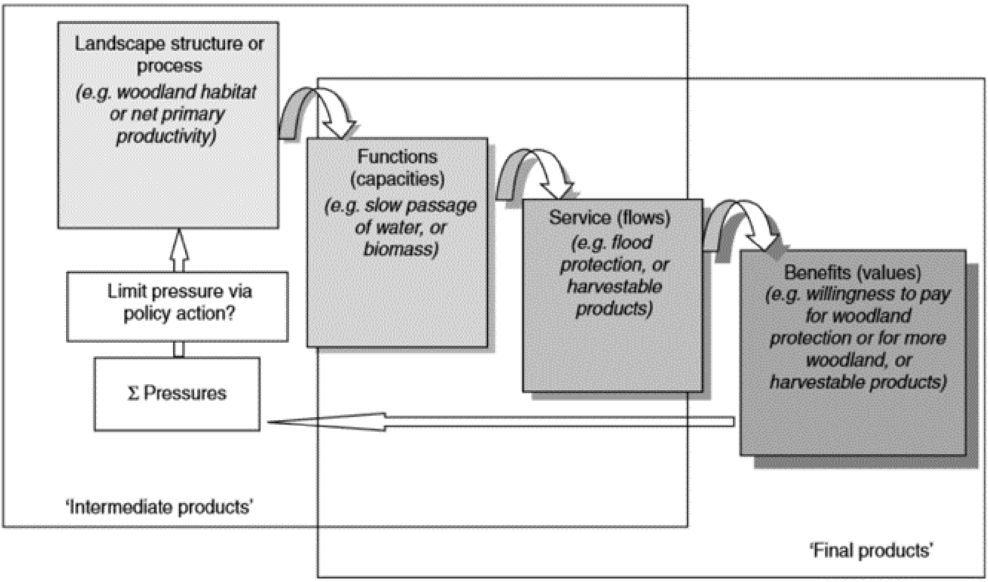

Figure 1-1. ES cascade of Haines-Young and Potschin (2010) depicting the relationship between biodiversity, ecosystem function and human well-being.

Another example is the IPBES conceptual framework (**Figure 1-2**) based on previous influential conceptual frameworks (National Research Council, 2004; Ostrom, 2009), most notably the one of MA (MA, 2005) (Díaz et al., 2015). The IPBES framework emphasizes the multiple knowledge systems, the co-production of benefits between nature and various assets built by people, the drivers affecting nature directly and the central role of institutions, governance and decision-making in the links between nature, NCP and quality of life (Díaz et al., 2015). Other examples are the conceptual framework of MA (MA, 2005), TEEB (TEEB, 2010b), MAES (Maes et al., 2013) or EPPS (Bastian et al., 2012).

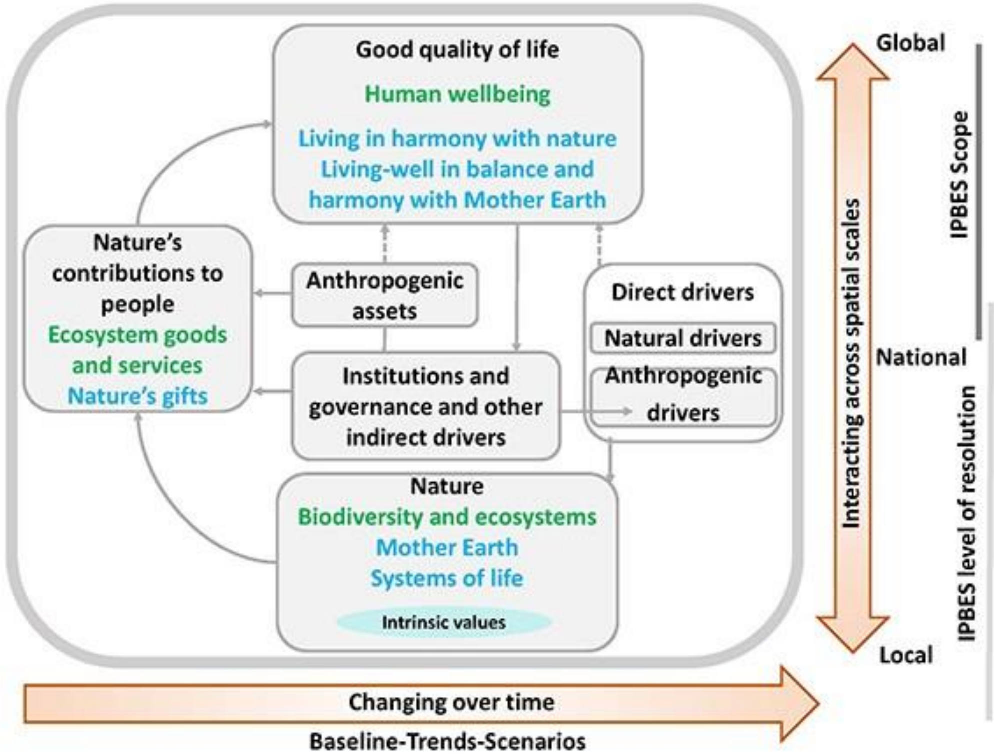

Figure 1-2. IPBES Conceptual Framework of Díaz et al. (2015). In the central panel, delimited in grey, boxes and arrows denote the elements of nature and society that are at the focus of the Platform. In each of the boxes, the headlines in black are inclusive categories that should be intelligible and relevant to all stakeholders involved in IPBES and embrace the categories of western science (in green) and equivalent or similar categories according to other knowledge systems (in blue). The thick coloured arrows below and to the right of the central panel indicate that the interactions between the elements change over time (horizontal bottom arrow) and occur at various scales in space (vertical arrow). The vertical lines to the right of the spatial scale arrow indicate that, although IPBES assessments is at the supranational-subregional to global-geographical scales (scope), they will in part build on properties and relationships acting at finer (i.e. national and subnational) scales.

From these multiple conceptualizations, we selected the conceptual framework of Wal-ES (**Figure 1-3**). This framework was built from the most influential ES frameworks (e.g. MA, IPBES, ES cascade, MAES) to illustrate the different components of the SES and their interactions. The ecosystem is represented as a functional entity resulting of the interactions between its structure, biological composition and processes (Elmqvist et al., 2010) performing numerous functions. Some of these functions are useful to human society and provide services often with human output (e.g. labor, intellectual or energy inputs) (Munns et al., 2015; Reyers et al., 2013). Ecosystems supply the potential services but ES exist only if there is a demand from individuals or groups to have them (Munns et al., 2015). People get individual or collective benefits from these ES, improving their well-being (Bouma and Van Beukering, 2015). The importance of the ES are recognized by humans through valuation processes (Muraca, 2011). Different stakeholders attach distinct values to these benefits (Hein et al., 2006). These manifold values (e.g. ecological, economic, cultural, social values) expressed in many different ways are captured during the integrated assessment (Gómez-Baggethun et al., 2014). These values influence the decisions and the governance system resulting on human interventions on the ecosystem.

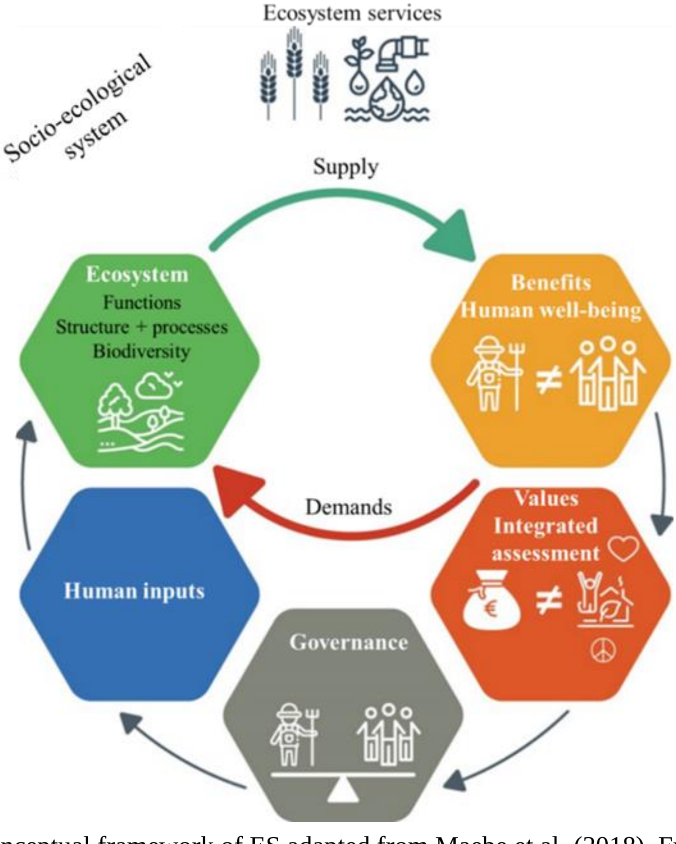

Figure 1-3. Conceptual framework of ES adapted from Maebe et al. (2018). From the variety of functions performed by the ecosystem, some respond to a demand of human society and become ES. These ES provide benefits to human society which in turn assigns values to them. These values influence the decision-making process and thus human interventions on ecosystems.

2.2.3 Typologies

Numerous ES classifications have been developed to list the different ES provided by ecosystems. ES typologies can be classified into three types: (1) human-need-oriented which focuses on humans needs for ES (e.g. Boyd and Banzhaf, 2007; Staub et al., 2011; Wallace, 2007), (2) beneficiary-oriented which focuses on beneficiaries and how they use ES (e.g. Landers, 2015; Landers and Nahlik, 2013), and (3) functional which aggregates ecological functions and processes into ES (e.g. CICES, 2018; de Groot et al., 2002; Díaz et al., 2018; MA, 2005; TEEB, 2010) (Willot et al., 2019). An example of human-need-oriented typology is the one of Wallace (2007) which classifies the services, according to the specific human values they support, into four categories: (1) adequate resources, (2) benign physical and chemical environment, (3) protection from predators, disease and parasites, and (4) sociocultural fulfillment. An illustration of a beneficiary-oriented classification is the FEGS-CS which arranges the ES at the intersection of two main classification dimensions: (1) environmental classes (i.e. ecosystems producing ES), and (2) beneficiary categories (Landers and Nahlik, 2013).

The functional classifications cluster ES into three or four main categories. Some classifications differentiate only provisioning services, regulating services and cultural services (e.g. CICES, 2018) while others distinguished a fourth category: supporting or habitat services (de Groot et al., 2002; MA, 2005; TEEB, 2010a) Provisioning services are the goods provided by the ecosystems and used by people (e.g. food, timber, water, medicinal plants and firewood). They are the most direct link between nature and human society and thus generally receive the most attention (Chapin, 2009). Regulating services are the regulation functions of the ecosystem directly useful to human society (e.g. improvement of air or water quality, noise mitigation, regulation of extreme events, pollination, and climate regulation). Regulating services are largely invisible and often ignore by managers but maintaining them is crucial to avoid devastating consequences (Chapin, 2009). Cultural services are the opportunities of cultural practices ensured by ecosystems (e.g. recreation, education, wildlife watching, spiritual values, and heritage). The values assigned to cultural services are influenced by various factors and differ often from one stakeholder (group) to another making them difficult to assess (Ardoin, 2006; Yung et al., 2003). Supporting services are the services necessary to produce all other ES (e.g. primary production, nutrient cycling, and soil formation). Other classifications (e.g. de Groot et al., 2002; TEEB, 2010) use the term of ‘habitat services’ in place of or as a synonym of supporting services to describe the provision by ecosystems of a living space for all wild plant and animal species on Earth (e.g. habitats for species and maintenance of genetic diversity). In the NCP classification, three categories were differentiated: (1) material contributions (i.e. substances, objects or other material elements from nature that directly sustain people’s physical existence or material assets), (2) non-material contributions (i.e. nature’s effects on subjective or psychological aspects underpinning people’s quality of life), and (3) regulating contributions (i.e. functional and structural aspects of organisms and ecosystems that modify environment conditions experienced by people and/or regulate the generation of material and nonmaterial contributions) (Díaz et al., 2018).

These numerous ES typologies reflect, in their meaning and structure, the principles and concepts of the theoretical framework from which they originate (La Notte et al., 2017). The human-need-oriented and beneficiary-oriented classifications arise from the economic viewpoint focusing more on the benefits while the functional classifications emerge from the ecological viewpoint emphasizing the impacts on nature and pressures from the socio-economic side (La Notte et al., 2017). Furthermore, each ES classification refers to a certain context. For instance, CICES was created at the European context and was adapted by members states to their local context (e.g. CICES-Belgium (Turkelboom et al., 2013) and Wal-ES typology for the Walloon region (Wal-ES, 2016)). Each ES typology has its own advantages and limitations. For instance, the MA classification creates a problem of double-counting because the supporting services underlie all other ES. To address this problem, FEGS-CS focuses on final services. However, double-counting can still arise in FEGS-CS as the beneficiary of one ES benefits also from other ES. Hence, the selection of ES classification depends on the context (e.g. vision, goals, scale) and the embedded vision and notions they state without losing sight of their limitations (La Notte et al., 2017).

We considered the Wal-ES typology that differentiates 61 ES provided by the Walloon ecosystems and regroups them into three main categories: (1) provisioning ES, (2) regulating ES, and (3) cultural ES (Wal-ES, 2016).

2.3 Ecosystem services assessment

ES assessment is the process of analyzing, assessing and understanding ES values and their interactions (i.e. coexistences, synergies and trade-offs) (Gómez-Baggethun and Martín-López, 2015). ES have multiple values (e.g. intrinsic, instrumental, relational, ecological, economic values) (see for example Arias-Arévalo et al. (2018) or Jacobs et al. (2018) who detailed different types of ES values).

2.3.1 Value pluralism

Value pluralism recognizes this multiplicity of values by stating that different and often conflicting value domains are neither reducible to each other, nor to some ultimate value (Chang, 2015; O’neill, 2008). For this reason, ES assessment should not be narrowed down to one value domain as is often the case with economic valuation but instead should open up to the different possibilities for identifying and valuing the role of ecosystems in human societies (Lyytimäki and Petersen, 2014).

This value pluralism was translated by IPBES (2022) into a values assessment typology to guide decision makers on understanding and engaging with the diverse ways in which people relate to and value nature. This typology encompasses five values dimensions and types. The first four values dimensions and types express the many ways people relate to nature:

1. The world-views: the lenses through which people perceive, make sense of and act upon the world. They shape people's values in their relationships with other people and with nature;
2. The knowledge systems: dynamic bodies of knowledge, practices and beliefs, pertaining to the relationships of people with one another and with nature, embedded in world-views;
3. Broad values: general moral guiding principles and life goals informed by people's world-views and beliefs that can underpin people's specific values of nature;
4. Specific values: judgements regarding nature's importance in particular situations. Three types of specific values can be distinguished: (1) instrumental (i.e. things that are a means to a desired end and tend to be associated with nature (e.g. as asset, capital, resources)), (2) intrinsic (i.e. values of nature expressed independently of any reference to people as valuers and include entities such as habitats or species that are worth protecting as ends in and of themselves), and (3) relational (i.e. meaningfulness of people-nature interactions, and interactions among people through nature). (IPBES, 2022)

The last values dimensions and types are the quantitative measures and qualitative descriptors (i.e. value indicators) that reflect the nature's importance to people. These indicators are generally categorized into three groups: (1) biophysical, (2) economic, and (3) socio-cultural. (IPBES, 2022)

To organize and reflect on the richness of the relationships between people and nature, four life frames (i.e. living from, with, in and as) are also represented on the values assessment typology of IPBES (2022).

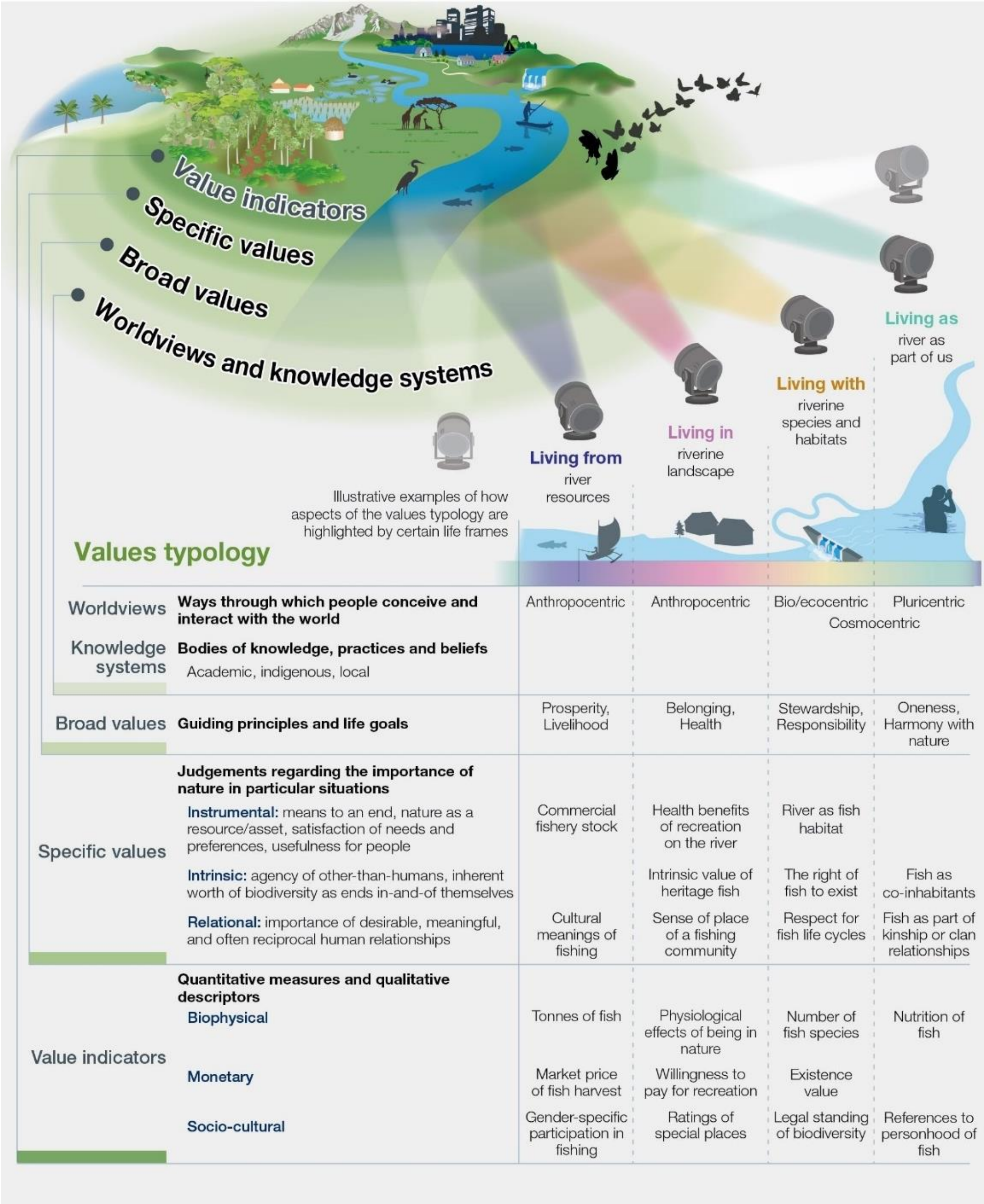

Figure 1-4. The values assessment typology of IPBES (2022) that highlights the keys concepts and their interrelationships to understand the diverse values of nature.

2.3.2 Integrated assessment of ES

To account for value pluralism, the integrated assessment of ES integrates different disciplinary approaches as well as introduces diverse positions on how value should be defined and expressed (Arias-Arévalo et al., 2018). However, the operationalization of value pluralism in ES assessments has remained largely elusive (Arias-Arévalo et al., 2018) and monetization is still the dominant valuation language (Abson et al., 2014; Christie et al., 2012) despite the demand from stakeholders including policy makers for other value dimensions (Laurans et al., 2013; Ruckelshaus et al., 2015) and the critics on economic valuations (see for example Farrell, 2007; Martinez-Alier et al., 1998; O'neill, 2008; Spash, 2007).

ES integrated assessment requires using a variety of methods to depict a more complex picture of why and how people value ES (Arias-Arévalo et al., 2018), including for instance market price-based approaches, revealed preference methods, benefit transfer, deliberative monetary valuation surveys, interviews, deliberative methods, modelling and field experiments (see Arias-Arévalo et al. (2018), Bagstad et al. (2013), Grêt-Regamey et al. (2017), Harrison et al. (2018) and Jacobs et al. (2018) for reviews on ES assessment methods). Each method meets specific objectives, has its own advantages and disadvantages, requires, to a certain extent, a significant investment in data collection and processing, has its own uncertainties and addresses some of the value dimensions (Maebe et al., 2019). The choice of the methods depends on the context of the study (e.g. goals, spatial and temporal scales, availability of data, financial resources) (Dick et al., 2011) and is as relevant as the results of the assessment (Martín-López et al., 2014).

To improve the inclusion of nature's values in decisions, IPBES (2022) proposed a 5-step valuation framework (**Figure 1-5**) (Termansen et al., 2023):

1. Establish a legitimate valuation process;
2. Define the purpose of valuation;
3. Establish the scope of valuation;
4. Choose and apply relevant valuation methods;
5. Articulate and communicate valuation outcomes to inform decisions.

For each of the five steps, questions are given to guide the valuation process. At each step, choices need to be made considering the trade-offs in valuation regarding relevance (i.e. ensuring that different values can be considered), robustness (i.e. reliable and theoretically consistent evidence following a transparent, and socially inclusive and legitimate value elicitation process) and resource efficiency (i.e. time, financial, technical and human resources) (Termansen et al., 2023).

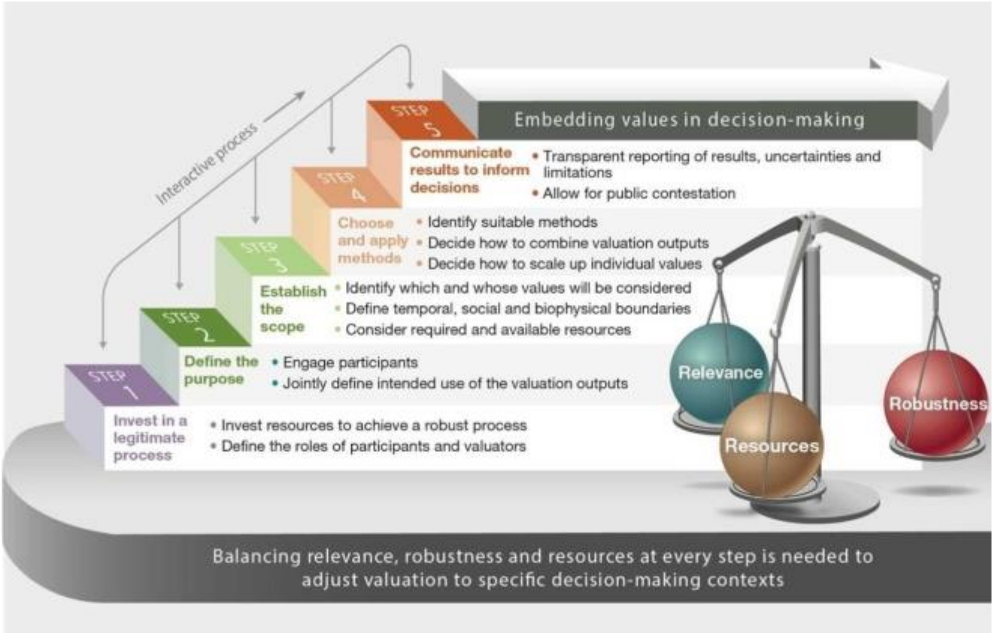

Figure 1-5. The 5-step valuation framework to embed values in decision-making of IPBES (2022). At each step, choices need to be made considering the trade-offs in valuation regarding relevance, robustness and resource efficiency. (Termansen et al., 2023)

2.3.3 ES matrix

We will know discuss one specific ES assessment method: the ES matrix to give an example of an efficient, fast and flexible method that can be easily used in the integrated assessment of the ES (Jacobs et al., 2018). We will also discuss some improvements that we made on this matrix to assess more accurately the ES. This two-dimensional matrix links the different land cover classes with their capacities to supply ES (Burkhard et al., 2009). These capacities are assessed on a scale, generally ranging from 0 (no relevant capacity to supply the ES) to 5 (very high relevant capacity), based on statistics (e.g. Kandziora et al. 2014), model results (e.g. Nedkov and Burkhard 2012), expert opinion (e.g. Kopperoinen et al. 2014), interview results (e.g. Kaiser et al. 2013), monitoring and/or other data sources (e.g. Baral et al. 2013). This matrix can then be linked to spatial data to map the supply of ES in the territory (Jacobs et al., 2018).

The matrix model is one of the most popular ES assessment methods (Jacobs et al., 2015) for several reasons. It is a simple way to obtain an overall spatially explicit picture of ES (Jacobs et al., 2018) which allows combining several data sources (Jacobs et al., 2015). In particular, the maps derived from the matrix bring to light the potential areas of opportunities and conflicts to guide spatial planning and management (Burkhard et al., 2014) and help to implement ES into decision-making

(Daily and Matson, 2008). The scaling system facilitates the comparison between ES, land cover classes and scenarios (Jacobs et al., 2015).

Nevertheless, the ES matrix also has disadvantages. First, it disregards landscape heterogeneity in the supply of ES by considering only individual land cover classes (Eigenbrod et al., 2010; Stoll et al., 2015). On one hand, by assuming land cover and management is in accordance with the abiotic conditions, land use intensity is neglected (Lavorel et al., 2017) leading to discrepancies between land cover and the capacity of the ecosystem to provide ES (Van der Biest et al., 2015). On the other hand, more extreme values are masked by using an average value for each land cover that does not take into account the varying capacity of an ecosystem to provide ES depending on the abiotic conditions and its management (Van der Biest et al., 2015). Then, the use of qualitative or semi-quantitative data such as expert opinion or interview results can be subjective, simplistic and error prone because they depend on the knowledge and experience of experts and respondents (Jacobs et al., 2015; Paudyal et al., 2015). Finally, uncertainty lies in various levels: ES concept (i.e. high complexity of the concept), data and methods used to assess the ES, land cover data, integration of various data etc., but most of these uncertainties are not specific to the matrix method (see Hou et al. (2013) for a list of all uncertainties of the ES matrix).

In response to these critics, Jacobs et al. (2015) offered four guidelines to improve the ES matrix: (1) to include other physical factors to better capture landscape heterogeneity, (2) to analyse uncertainties (e.g. measures of confidence and of model reliability, validation with other data), (3) to describe transparently the methods used to assess ES, and (4) to validate the ES scores by experts and stakeholders to provide legitimate results. Specific recommendations were also discussed by Schröter et al. (2014) on how and where to map supply and demand of ES for policy-relevant outcomes and by Hou et al. (2013) regarding how to manage uncertainties related to the ES matrix. Furthermore, Campagne and Roche (2018) provided a 7-step methodology to build the matrix, based on expert opinion.

Some improvements have been made on the matrix model since the first publication of Burkhard et al. (2009). Some authors added other data to the land cover. For example, Yapp et al. (2010) applied vegetation data from the VAST dataset to better capture the spatial heterogeneity and discrepancies between land cover or management and abiotic conditions. Other authors discussed the scoring of the matrix, based on expert opinion. For example, Campagne et al. (2017) compared three approaches to estimate the means and standard errors of the matrix scores.

Nevertheless, the ES matrix can still be improved in the integration of other determinants rather than land cover (Burkhard et al., 2012). Indeed, the supply of ES is largely determined by three main components (**Figure 1-6**): (1) biotic factors (e.g. species, land cover and vegetation, habitats) (Smith et al., 2017), (2) abiotic factors (e.g. precipitations, rock formations, soil texture, slope), the combinations of which determine different ecological contexts, and (3) human activities (e.g. management practices, land use intensity, pollution) (Burkhard et al., 2012).

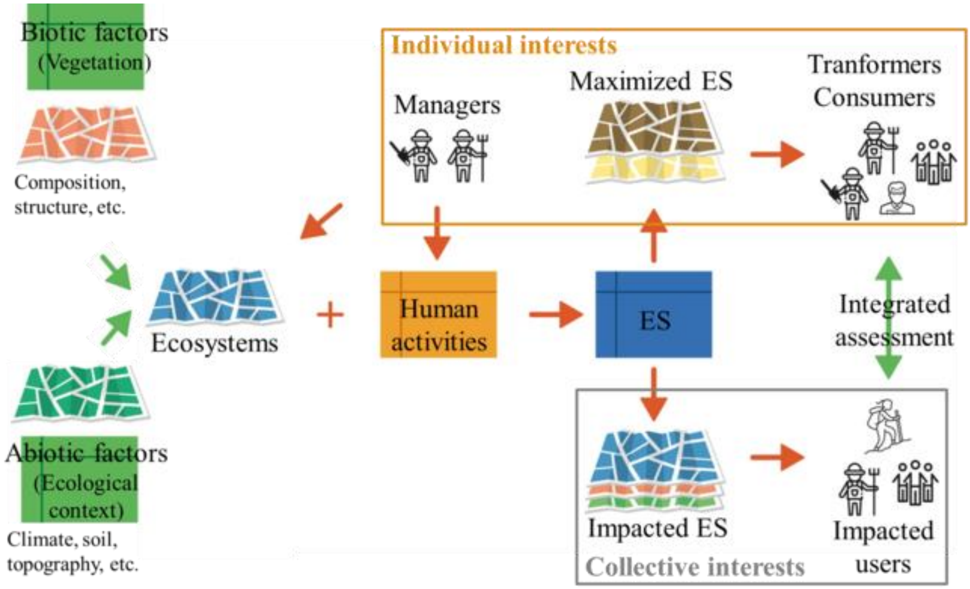

Figure 1-6. Schematic representation of the integrated assessment of Ecosystem Services (ES). The supply of ES is determined by three main components: (1) biotic factors, (2) abiotic factors, and (3) human activities. Ecosystems result from the interactions between biotic and abiotic factors. The managers shape the ecosystem to maximise the supply of some ES (i.e. maximised ES) which benefit some stakeholders (i.e. transformers and consumers) and which, in turn, impact the supply of other ES (i.e. impacted ES) and other stakeholders (i.e. impacted users). The integrated assessment should consider the different ES and stakeholders to balance the collective and individual interests. Adapted from Maebe et al. (2018).

The biotic and abiotic factors interact together to shape the ecosystem (Smith et al., 2017). The abiotic factors influence ES supply in varying manners (e.g. food production is highly influenced by abiotic factors while, for aesthetic landscapes, there is much less evidence) (Smith et al., 2017). They do not only reflect the capacity of an ecosystem to provide ES but also provide information on the risks to impact ES supply by human activities (e.g. a clear cutting has a priori a higher negative influence on soil erosion on a steep slope than on a flat soil (Bansept and Fiquepron, 2014)). Biotic factors also affect ES supply. In their review, Smith et al. (2017) found an influence of biotic factors (e.g. community, habitat, diversity, functional group and population dynamics) on ES. For example, larger trees in a forest store more carbon, intercept and absorb more water (Smith et al., 2017). Finally, human activities influence both deliberately some ES (i.e. maximised ES) and inadvertently others (i.e. impacted ES) (Schägner et al., 2013). Human activities can have both a positive and negative influence (Smith et al., 2017). For example, clear cutting provides wood (i.e. deliberate and positive influence) but causes nutrient loss that can pollute water (i.e. inadvertent and negative influence) (Bansept and Fiquepron, 2014; Fiquepron et al., 2012).

By adding information on abiotic factors and human activities in the ES matrix, this method gives up some of its simplicity and some of its utility in data scarce situations, but it considerably improves its accuracy by considering the landscape heterogeneity. It is true that other tools which allow systematically taking into account abiotic factors and human activities such as InVEST (Kareiva et al., 2011) or ECOPLAN-SE (ECOPLAN, 2016) can be easily and transparently used. However, these tools remain more complex and time-consuming and require more data than the matrix. Furthermore, in general, they do not systematically present all the advantages of the matrix (i.e. fast and simple, spatially explicit, allowing combining different types of data, easy comparison between ES, and worldwide use).

Therefore, we proposed an amended ES matrix with two improvements: the inclusion of (1) the ecological context (i.e. the physical and chemical conditions of the environment mainly determined by the elevation, topography and soil according to its texture, moisture, nutrient availability, etc.) to synthesise abiotic factors, and (2) the management to represent human activities (Maebe et al., 2019).

This amended matrix was applied on one class of land cover (i.e. forest) to exclusively test the influence of abiotic factors and human activities on the supply of ES and their relationships. The forest was chosen because of its particular importance in ES supply, diversity and trade-offs (Roces-Díaz et al., 2017). Six ecological contexts were differentiated: (1) mesic brown forest soils (i.e. good soils that are not constraining in terms of productivity or because they do not have a high ecological significance), (2) steep slopes (slope ≥ 15°), (3) alluvial soils, (4) wet soils, (5) podzolic soils, and (6) peat soils. Human activities were considered by differentiating two contrasting forest management strategies, the two most common in Wallonia: (1) uneven-aged broadleaved forests (natural regeneration, no clear cutting), and (2) pure even-aged spruce plantations (clear cutting, residue grinding, wet soil drainage, plantation). Six ES were selected from the classification of the Walloon platform on ES (Wal-ES, 2016): (1) wood production, (2) global climate regulation by sequestration of GES, (3) flood protection, (4) erosion protection, (5) water purification and oxygenation, and (6) natural areas for outdoor recreation. They were chosen by considering their representative nature to represent the three main categories of ES (i.e. provisioning, regulating and cultural ES) and some of the main ES provided by forests (according to Swanson and Chapin (2009), Landsberg and Waring (2014)).

The capacity of the forest to supply ES, depending on the forest management and the ecological context, was assessed on a scale consisting of: 1 = minimal capacity to supply the corresponding ES, 2 = very low capacity, 3 = low capacity, 4 = medium capacity, 5 = high capacity, 6 = very high capacity, and 7 = maximal capacity. This usual scale ranging from 0 to 5 was adapted by replacing 0 by 1 to avoid mathematical issues (i.e. empty product) and by adding a seventh score to enlarge the scale to further separate close capacities in the supply of ES. These scores indicate relative magnitudes rather than values (Maynard et al., 2010). The scores were gathered from master student works (Master bioengineer in Nature and Forest Management, GxABT, ULiège, Belgium) over five years (2013–2017). They scored the six ES by group from a literature review (47 references) according to a single supply indicator (**Table 1-1**) for the Ardenne ecoregion (southern part of Wallonia). The literature allowed discriminating the capacity of the forest to supply ES (i.e. ES potential) depending on the management and the ecological context. These scores were collectively compared. For each ES, students concerned in each group presented the arguments that allowed them to score the ES. Then, the students discussed the variability in ES scores and arguments to reach a consensus. Finally, they presented the new scores with revised arguments. The consensus scores from the five years were averaged and rescaled to have a minimal and maximal score for each ES. Finally, these scores were validated by the co-authors with some minor modifications. (**Figure 1-7**)

Table 1-1. The six ecosystem services according to the classification of the Walloon Platform on ES (Wal-ES), with their code name and their corresponding name in the CICES-BE classification (Turkelboom et al., 2013), assessed in the amended ES matrix with their corresponding supply indicator, references and arguments.

ES (Wal-ES)	**ES code**	**ES (CICES-BE)**	**Indicator**	**References**	**Uneven-aged broadleaved forests**	**Pure even-aged spruce plantations**
Wood production	Wood	Plant fibres and materials	Volume of mobilizable wood	Alderweireld et al., 2015; Rondeux and Thill, 1989; Thill et al., 1988; Weissen et al., 1991	Less yield and volume due to slow growth	More yield but the volume produced is not stable over time (clear cutting)
Global climate regulation by sequestration of GES	Carbon	Global climate regulation by reduction of GES concentrations	Amount of carbon sequestered in forest vegetation (BOC) and soils (SOC)	Alderweireld et al., 2015; Broadmeadow and Matthews, 2003; Hargreaves et al., 2003; Jandl, 2007; Laitat et al., 2004; Latte et al., 2013; Lettens et al., 2008; Lindsay, 2010; Minkkinen et al., 2008; Schulp et al., 2008; Stevens and van Wesemael, 2008; Vesterdal et al., 2013; Wiesmeier et al., 2013	BOC: less volume but larger wood density, larger volume of the tree (above- and below-ground) and more understory vegetation	BOC: more yield but lower wood density, lower volume of tree (above- and below-ground) and almost no understory vegetation
					SOC: higher due to leaf decomposition and increasing carbon stocks on wet and peat soils	SOC: lower despite a biomass accumulation in the first stages but clear cutting and soil drainage induce high mineralization

Flood protection	Flood	Natural flood protection & sediment regulation	Capacity of soil infiltration and evapotranspiration of vegetation	Armbruster et al., 2004; Aussenac, 1968; Aussenac and Boulangeat, 1980; Carnol et al., 2014; Hein, 2011; Nisbet and Thomas, 2008; Nisbet et al., 2011; Piégay et al., 2003; Rotherham, 2015; Wastiaux, 2008	Lower tree evapotranspiration and interception of rainwater (deciduous trees) but continuous presence of vegetation cover and deep rooting allowing better infiltration. No drainage and even slowdown effect of water flows in alluvial zones thanks to vegetation	Higher tree evapotranspiration and interception of rainwater but clear cutting and the absence of understory vegetation have a negative impact. Existing huge drainage networks on wet and peat soils highly intensify floods
Erosion protection	Erosion	Buffering and attenuation of mass flows + Protection against water and wind erosion	Soil and sediment retention capacity	Armbruster et al., 2004; Augusto et al., 2000; Aussenac, 1968; Bansept and Fiquepron, 2014; Carnol et al., 2014; Fontecilla Lechuga, 2012; Gillijns et al., 2005; Grosclaude, 1999; Marty and Bertrand, 2011; Nisbet et al., 2011	High erosion protection in all ecological contexts thanks to deep rooting allowing better infiltration and the presence of a permanent vegetation cover especially on alluvial soils where the understory vegetation captures sediments	Low erosion protection on all sensitive soils: steep slopes (clear cutting), wet and peat soils (drainage networks) and alluvial soils (absence of understory vegetation)

Water purification and oxygenation	Water	Water purification and oxygenation	Denitrification and phosphorus retention capacity	Armbruster et al., 2004; Augusto et al., 2000; Aussenac and Boulangeat, 1980; Bansept and Fiquepron, 2014; Broadmeadow and Nisbet, 2004; Fiquepron et al., 2012; Fontecilla Lechuga, 2012; Gagkas et al., 2006; Hegg et al., 2006; Hein, 2011; Joosten and Clarke, 2002; Lavabre and Andreassian, 2000; Marty and Bertrand, 2011; Nisbet and Thomas, 2008; Nisbet et al., 2011, 1995; Nys, 1981; Piégay et al., 2003; Reddy, 1976; Rothe et al., 2002	Vegetation filters pollutants with lower effects on podzolic soils where nutrients leaching is high	Spruce plantations increase soil acidification and have a higher N deposition. The mineralisation of the litter induced by the clear cutting is a very high source of pollutants for surface water especially, in the presence of drains or slopes
Natural areas for outdoor recreation	Recreation	Landscape for outdoor recreation	Forest landscape attractivity	Bodson, 2005; Church et al., 2014; Colson, 2009; Standaert and De Claevel, 2011; Willis et al., 2003	Broadleaved forests are very much more preferred to spruce plantations for their naturality, complex structure, tree diversity, lighting, colours in autumn welcoming, etc., as well as the presence of surface water (in Wallonia)	Spruce plantations are in general less popular, particularly in the presence of clear cutting and signs of intensive exploitation (e.g. ruts) (in Wallonia)

Forest Management	Ecological Context	Ecosystem Services **Wood** Volume of mobilizable wood	**Carbon** Amount of carbon sequestered in forest vegetation and soil	**Flood** Capacity of soil infiltration and evapotranspiration of vegetation	**Erosion** Soil and sediment retention capacity	**Water** Nitrates and phosphorus retention capacity	**Recreation** Forest landscape attractivity
Pure even-aged spruce plantation	Mesic brown soil	7	6	6	5	4	4
	Steep slope	5	4	3	2	3	2
	Alluvial soil	7	4	3	1	1	3
	Wet soil	4	3	2	2	2	2
	Podzolic soil	5	4	4	3	2	4
	Peat soil	1	1	1	1	1	1
Uneven-aged broadleaved forest	Mesic brown soil	5	7	7	6	7	6
	Steep slope	4	5	6	5	6	5
	Alluvial soil	5	7	7	7	7	7
	Wet soil	3	4	6	6	6	6
	Podzolic soil	4	5	6	6	4	6
	Peat soil	1	5	5	6	6	5

Scale of the ES scoring

1	Minimal capacity
2	Very low capacity
3	Low capacity
4	Medium capacity
5	Good capacity
6	Very good capacity
7	Maximal capacity

Figure 1-7. Amended ES matrix illustrating the capacity of the different combinations of a forest management strategy with an ecological context to supply the six ES. The meaning of the code name of the six ES can be found in Table 1-1. The supply indicator of each ES is provided.

The amended ES matrix (**Figure 1-7**) confirms the importance of systematically considering both abiotic factors and human activities in the ES assessment. This matrix shows a strong influence of the ecological context on ES supply and their relationships. Indeed, on mesic brown soils, all the ES are generally well provided while, on sensitive soils, the ES are mostly lower, particularly in pure even-aged spruce plantations. These results are in accordance with literature, which also found a difference in ES supply amongst different types of soil and landform (Smith et al., 2017; Willemen et al., 2012). The same conclusions can be drawn for the management strategies. Forest management strongly influences ES supply and their relationships both by the tree species composition of the stand and by the level of artificialisation of the management practices. The more artificial the management is, the higher is the provisioning ES and the lower are the regulating and cultural ES (see Baral et al. (2013), Burkhard et al. (2014), Roces-Díaz et al. (2017) for similar conclusions).

Even if the influence of the ecological context and the management is, on average, strong, it varies in intensity. For example, ES supply on alluvial soils is more variable than on mesic brown soils and is, on average, more constant for uneven-aged broadleaved forests than for pure even-aged spruce plantations. Smith et al. (2017) also found that the influence of abiotic factors and of human activities is highly variable.

The impacts of the ecological context and the management on ES supply interact with each other. For example, the impacts of intensive management on regulating and cultural ES are exacerbated on sensitive soils. It is thus important to consider together the ecological context and the management in the assessment of ES supply.

This simple and fast method can be easily used to assess numerous ES considering both the ecological context and the management (Maebe et al., 2019) but it is not enough to truly perform an integrated assessment. Other methods should complement this approach to assess the different value domains (see Chapter 2 6 Ecosystem services assessment for example of other ES assessment methods). Stakeholder engagement is also essential to ensure the legitimacy of the results and to diversify the value domains considered (see Chapter 2 4 Stakeholder engagement for example of methods to engage with the stakeholders). In particular, the socio-cultural values (i.e. the opinion of the stakeholders on the importance of the ES (Breyne et al., 2021)) should be also assessed along with the ES performance (i.e. ES indicators) to align the ecosystem management with social expectations (Breyne et al., 2021) (see Chapter 2 4.2.2 Second participatory workshop: the needs of the stakeholders and Chapter 2 4.3 Surveys of the forest users for examples of methods to assess the socio-cultural values). Finally, the temporal dimension should be considered to understand the dynamics of the ES (Carpenter et al., 2009; Renard et al., 2015) and of the SES (Biggs et al., 2012; Brand and Jax, 2007). The inclusion of the resilience concept in the analysis helps understanding such dynamics (see Chapter 2 8 Resilience assessment for examples of methods to assess resilience together with the ES).

2.4 Critical analysis of ecosystem services

The ES concept and its application have both strengths and weaknesses that need to be recognized and deal with (Abson et al., 2014; Evans, 2019; Kull et al., 2015; Norgaard, 2010; Schröter et al., 2014). The ES concept is a central connector and mediator between social and ecological systems to make clearer and more direct the connections people have with ecosystems and with each other (Biggs et al., 2015; Munns et al., 2015; Ruhl and Chapin, 2014). This awareness creates novel understanding and ideas, inspiration and genuine enlightenment (Lyytimäki and Petersen, 2014; Ruhl and Chapin, 2014). It also brings forward the biophysical boundaries of the Earth system that should not be exceeded to ensure the functioning of the ecosystems that provide ES (Arias-Arévalo et al., 2018; Schröter et al., 2017). By highlighting the impacts of human activities on ES and their stakeholders, the ES concept allows for a more complete assessment of the impacts of any given management intervention or policy decision (Munns et al., 2015).

Numerous conceptualizations of the ES concept have flourished since its introduction expressed through the diversity of definitions, classifications and frameworks (La Notte et al., 2017). Many of ES definitions are vague and necessitate further interpretation, resulting in inconsistencies (e.g. the mix up of processes and end-state benefits or the confusion with environmental services or landscape multifunctionality (Lamarque et al., 2011)) and multiple interpretations and uses that could be totally opposed (Kull et al., 2015; La Notte et al., 2017). Indeed, this boundary object is simultaneously a technical (i.e. scientific use), pedagogic (i.e. used for communication), policy (i.e. used to justify conservation, social or agricultural policies) and political notion (i.e. used to help solve conflicts or engage stakeholders) (Kull et al., 2015). Even within the same type of use, its usages are diversified (e.g. in the policy use of ES, this concept is both applied for biodiversity conservation or to justify public policies focusing on social welfare or farm support) (Kull et al., 2015).

The manifold conceptualizations of the ES concept are intrinsically linked to its transdisciplinary nature where misunderstandings and inconsistencies are common and inevitable (Munns et al., 2015). To accommodate its transdisciplinary and holistic nature, some plurality and flexibility are essential (Costanza, 2008; Munns et al., 2015). Furthermore, the complexity of the concept makes impossible to classify ES in completely independent categories or to provide unambiguously definitions (de Groot et al., 2002; Munns et al., 2015). However, some standardizations would not hurt to advance research (e.g. improve comparability among ES studies), to promote collaboration and communication, and to better inform decision making (see La Notte et al., 2017; Munns et al., 2015; Polasky et al., 2015 for examples of ES standardization). Haines-Young et Potschin (2009) even suggested avoiding spending too much time on this issue and rather focusing on ensuring the rigor of the outputs of the ES concept. However, the conceptualizations of the ES concept are still being discussed, notably in the frame of IPBES (see Chapter 1 2.2.1 Definitions).

The ES concept is intrinsically normative (Abson et al., 2014). The terms 'ecosystem' and 'service' carry a certain vision: ecosystems are viewed as agents with intentions and reciprocal relationships with other agents such as humans while they do not provide intentionally services (Lyytimäki and Petersen, 2014) and originally, the term 'service' refers to a transaction (usually paid for), this meaning occults other types of interactions such as spiritual or experiential (Turnhout et al., 2013). Moreover, this anthropocentric concept frames the way humans view ecosystems as important to preserve for the benefits they provide them (Schröter et al., 2017) and focuses only on some of the many functions of an ecosystem that do provide benefits (Bouma and Van Beukering, 2015). In more economic viewpoints of ES, this concept is also criticized because it may reflect and reinforce certain market-based models of society and underlying ideologies leading to reinforcement of dominant power relations and exclusions as well as the commodification of nature (Gómez-Baggethun et al., 2010; Kull et al., 2015; McAfee, 2012). In that sense, ES may serve only as a façade to legitimize old approaches (Lyytimäki and Petersen, 2014) and sidelines other approaches to environmental management such as stewardship or spiritual one (Turnhout et al., 2013). The ES concept is thus highly political in the way it frames society-environment relationships, creating new market, property and power relations (Kull et al., 2015).

The normativity of the ES concept has positive sides too. This normativity is essential to ensure the meaningfulness of the ES concept in the context of achieving the societal goals (Turnhout et al., 2013). This concept highlights the role and importance of ecosystems in human well-being, facilitating communication on nature conservation and sustainable use (Bouma and Van Beukering, 2015; Schröter et al., 2014). Indeed, its anthropocentric nature provides additional arguments to address the ongoing ecological crisis (Reid et al., 2006; Skroch and López-Hoffman, 2010). It builds bridges between different interests groups, disciplines and the science policy interface (Kull et al., 2015; Lyytimäki and Petersen, 2014; Reyers et al., 2010). Indeed, the ES concept offers a 'platform' for bringing people and their different views and interests together, especially if the existence aspects are acknowledged (Schröter et al., 2014).

This concept induces implicitly many choices in terms of classification, weighting, scale and quantifiability (Kull et al., 2015). The selection of ES is particularly of concern as analyzing one ES instead of another can fundamentally change the resulting assessment (e.g. Grimaldi et al. (2014) showed that in the Amazon, it was possible to either justify deforestation or conservation policies in the name of ES) (Kull et al., 2015). ES studies follow many different goals and even if they may intent to assess the same things, they instead measure them differently or even measure different things (Munns et al., 2015). It is thus difficult to assess the credibility of these studies but also to understand and use them especially for the policy makers and managers (Seppelt et al., 2011). Numbers need to be debated and the innumerable things need to be acknowledged by the stakeholders (Kull et al., 2015).

ES assessment is not a simple exercise giving the high complexity of the topic itself (Burkhard et al., 2014), the diversity of assessment methods (Baral et al., 2016), the large amount of data necessary (Stoll et al., 2015), the risk of double counting overlapping ES (La Notte et al., 2017) and the cross-scales interactions (Kull et al., 2015). As a result, many ES remain undervalued and underappreciated (Biggs et al., 2015). Simplifications and assumptions are made to address knowledge gaps and to ensure the feasibility of the study (Hein et al., 2006; Norgaard, 2010). ES assessment is also political because the choice of methods and values they convey influences policy conclusions as it frames which data is relevant, how it should be produced (Farrell, 2007), and who can participate and in which role (Vatn, 2005). The choices induce uncertainties and an accidental rejection of relevant information that need to be recognized (Lyytimäki and Petersen, 2014). For example, the ES concept may exclude biodiversity issues leading to overlook the trade-offs between ES and biodiversity (Maes et al., 2012).

Because of the pressure of quantification, there is a tendency to select the most accessible and measurable variables and to create aggregate measures that facilitate comparison or use in markets (Kull et al., 2015). In that sense, most ES studies have been focusing on ecological and economic aspects while socio-cultural aspects (e.g. engagement, motivation, communication and education) have received less attention (Abson et al., 2014; Lyytimäki and Petersen, 2014). As a consequence, ES research benefited little from tools in social sciences and humanities (Díaz et al., 2018). However, this trend is gradually changing: in the recent years, more and more ES studies incorporate the socio-cultural aspects (e.g. Bernués et al., 2019; Chan et al., 2012; Dawson et al., 2017; De Vreese et al., 2019; Díaz et al., 2018).

Nevertheless, ES assessment remains useful to build knowledge among stakeholders and decision makers to better inform their decision, design appropriate implementation mechanisms and implement these mechanisms to improve human well-being (Ruckelshaus et al., 2015). However, decision-makers may find the ES concept complicated, difficult to understand and rather odd for communicational purposes (Söderman et al., 2012). On the other hand, Norgaard (2010) argued that this concept is too simplistic to be used by decision-makers as it hides great uncertainties that need to be better understood (Bouma and Van Beukering, 2015). Furthermore, the application of the ES concept has social and environmental consequences including environmental justice or distributional consequences, that may even exacerbate social inequalities between different social groups but also between current and future generations (Jacobs et al., 2016; Schoon et al., 2015; van den Belt and Stevens, 2016). Indeed, ES assessments tend to focus on the instrumental values of nature (IPBES, 2022). To solve this issue, IPBES (2022) designed a values assessment typology (see Chapter 1 2.3.1 Value pluralism) to include more explicitly other values dimensions and types such as responsibility, reciprocity and respect for nature; as well as to embrace other knowledge systems (e.g. people are part of nature). The exclusion of stakeholders but also disciplines can create active opposition toward the ES concept often because of the perceived risks of nature commodification (Lele et al., 2013) and social equity concerns (Pascual et al., 2014). These issues are too seldom taken into account (Abson et al., 2014; Schröter et al., 2017) despite the potential of this concept to reveal the hidden costs and multiple contradictory benefits (individual and collective interests) of a policy or management decision on stakeholders (Howe et al., 2014; Schoon et al., 2015).

3. Resilience

First, the evolution of the different conceptualizations of resilience is described. Then, its assessment is discussed. Finally, its advantages and limitations are given.

3.1 History of the resilience concept and its multiple conceptualizations

The theory of resilience has a long history in many disciplines. Its development in ecology is represented in **Figure 1-8** to understand how this concept has evolved over time. Its development is not linear: a new conceptualization of resilience can have multiple origins and can advance in parallel with previous conceptualizations.

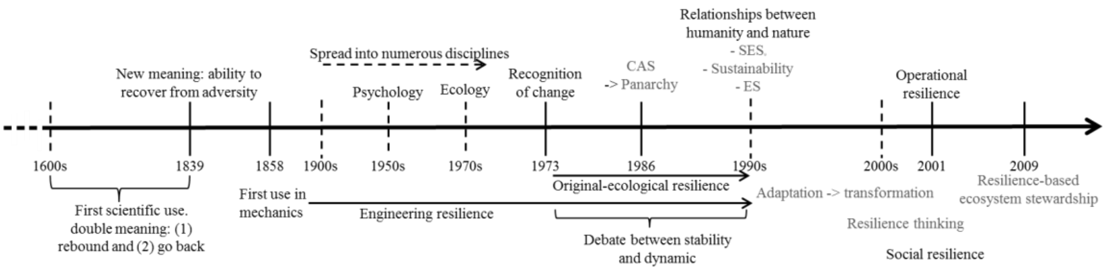

Figure 1-8. Evolution of the resilience concept adapted from Yaman Galantini et Tezer (2018). The words in grey refer to the concepts that gave rise to resilience thinking and resilience-based ecosystem stewardship.

The first scientific use of resilience can be traced back in the 17th century where it already had a double meaning: to rebound or to go back (Alexander, 2013). In the 19th century, resilience gained another meaning as the ability to recover from adversity (Alexander, 2013). At the same time, it began to be used in mechanics to describe the resistance properties of materials such as wood, metal or textile (Alexander, 2013; McAslan, 2010).

In the 20th century, resilience spread into numerous disciplines. For example, it was introduced in psychology in 1950s, first to study the vulnerability of children to trauma and how it impacts their adulthood (Alexander, 2013; Thorén and Persson, 2015). Resilience has thus a long history of multiples, interconnected and sometimes conflicting meanings in humanities, sciences and engineering: each discipline appropriates the concept of resilience for its own needs (Alexander, 2013; Brand and

Jax, 2007). But even in a same discipline, resilience has evolved and has different meanings.

From the 1970s, two conflicting conceptualizations of resilience appeared in ecology: (1) engineering resilience, and (2) original-ecological resilience. The first one views ecosystems as stable systems responding to disturbances in a linear manner and operating in one stability domain (Folke, 2006; Holling, 1973). **Engineering resilience** is thus defined as the recovery of the ecosystem to its previous state (Carpenter et al., 2001; Holling and Gunderson, 2002). This definition emphasizes efficiency, predictability, control and stability: ecosystems can be controlled, the impacts of their changes can be predicted and the highest productivity can be achieved (Holling and Gunderson, 2002; Longstaff, 2005). **Original-ecological resilience** considers that ecosystems are profoundly affected by changes and continually confronted by the unexpected in the ever-changing world (Holling, 1973). The ecosystems are viewed as dynamic systems, most of the time far from their equilibrium and having multiple stable states (i.e. stability domains) (**Figure 1-9**) (Gunderson, 2000; Holling, 1973). This conceptualization, introduced by Holling (1973), defines resilience as the ability of a system to absorb changes and still persist (i.e. continue to function). This definition underlines persistence (i.e. the system does not change fundamentally), adaptive capacity, variability and unpredictability to face the uncertainty, non-linearity and versatility of the system (Holling and Gunderson, 2002; Standish et al., 2014).

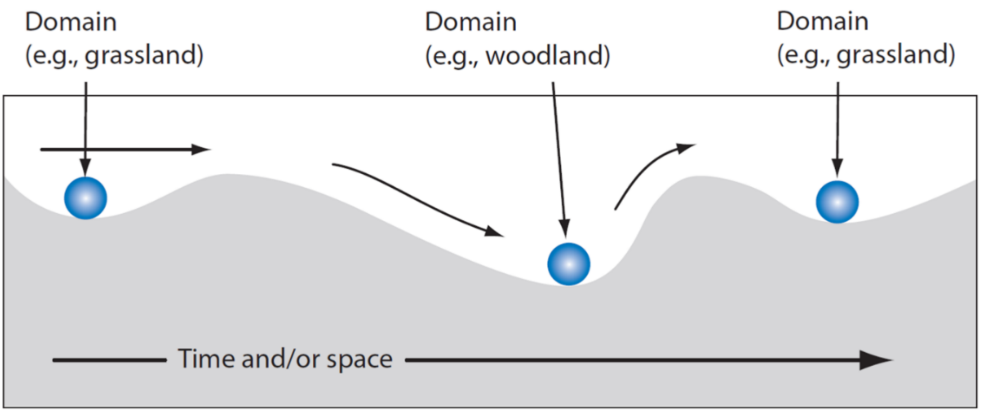

Figure 1-9. Representation of the multiple stability domains of an ecosystem (Campbell et al., 2009).

These two conceptualizations of resilience were much discussed between 1970s and 1980s in the ecology field (e.g. Connell and Sousa, 1983; Holling, 1973; May; Pimm, 1984). Now, it is commonly accepted that engineering resilience does not adequately describe alone most of the current (social)-ecological systems, especially in the ever-changing world. Engineering resilience is now mainly seen either as a component of resilience called resistance (Fuller and Quine, 2016) or as an important property of a system, namely stability (Holling, 1973).

In late 1980s and in the 1990s, the conceptualization of resilience took a turn (Folke, 2006) in particular in the light of complexity science and of the interrelationships between humanity and nature. Complexity science investigates how relationships among individual parts can give rise to collective behaviors of the whole system that cannot be predicted by its individual parts (Puettmann et al., 2009a). This science, introduced in numerous disciplines (e.g. physics, neurology and economy), is more a set of theoretical frameworks to study systems than a discipline in itself (Puettmann et al., 2009a). Quite recent in ecology (Puettmann et al., 2009a), complexity science changed the way (semi-)natural systems are perceived and studied (Levin and Levin, 2000; Mitchell, 2009; Waldrop, 1992).

This science gave rise to the theory of CAS defined as a complex system in which the individual parts are constantly reacting to one another, thus continually modifying the system and allowing it to adapt to altered conditions (Levin, 1998). CAS are characterized by eight properties, four structural properties:

1. Openness: exchange of material, energy or information with the external environment, the system is never totally at equilibrium (Puettmann et al., 2009a);
2. Heterogeneity and diversity: diversity of components with heterogeneous responses to the same stimulus and redundancy (Parrott and Lange, 2013);
3. Memory: prior states influence present and future ones (Puettmann et al., 2009a);
4. Hierarchy: the behavior of interacting components at one level gives rise to other emergent components at a higher level which feedback upon the components at lower levels (Parrott and Lange, 2013).

leading to four dynamic properties:

1. Self-organization: spontaneous configuration of the system (Dawson et al., 2010; Puettmann et al., 2009a);
2. Emergence: the unexpected occurrence of structures, processes or functions at one scale that are the aggregate result of interactions between components at a finer scale (Hartvigsen et al., 1998; Parrott and Lange, 2013)
3. Uncertainty due to the non-linear dynamics of the system;
4. Adaptation: the system can adjust its structure or configuration in response to external drivers thanks to its capacity to learn (Coetzee et al., 2016), heterogeneity, redundancy and flexibility (Parrott and Lange, 2013).

Resilience and CAS theory have nurtured each other from late 1980s (e.g. Clayton and Ratcliffe, 1996; Costanza et al., 1993; Hartvigsen et al., 1998; Holling, 1985) (Brand and Jax, 2007; Folke, 2016). On one hand, CAS theory is particularly useful for analyzing and understanding dynamic concepts such as resilience (Coetzee et al.,

2016) and for guiding management (Drever et al., 2006; Holling and Meffe, 1996). On the other hand, resilience has enabled to apply CAS theory in natural management (Puettmann et al., 2009a). This merge of these two theories resulted in two new conceptualizations of resilience: (1) **extended-ecological resilience** defined as the capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks and therefore identity (Walker et al., 2006), and (2) the **panarchy** theory, also named systemic-heuristic resilience.

Panarchy is a nested set of adaptive cycles operating at different temporal and spatial scales (Drever et al., 2006; Holling, 2001). Each adaptive cycle evolves in four different phases regrouped into two opposing modes: (a) a development mode (i.e. the fore or front loop characterized by stability, relative predictability and conservation) with two phases: (1) exploitation (phase r) recently disturbed areas are rapidly colonized, and (2) conservation (phase K) where energy and materials are accumulated and stored, and (b) release and reorganization mode (i.e. back loop characterized by uncertainty, novelty and experimentation) with two phases: (3) release (phase Ω) where the accumulation of energy and materials are released by agents (e.g. fire, pests, economic shock), and (4) reorganization (phase α) of the system (e.g. expansion of pioneer species or innovation and restructuring of a society) (**Figure 1-10**) (Holling and Gunderson, 2002). Three main system dimensions: (1) resilience, (2) potential, and (3) connectedness, vary along the four stages (Holling and Gunderson, 2002; Quental et al., 2011). For example, when the system goes from the exploitation phase to the conservation one, the potential (i.e. accumulated capital opens the door to other states) and the connectedness increase as well as the stability leading to a decrease in resilience (i.e. the system becomes more and more sensitive to unknowns) (Holling and Gunderson, 2002). CAS are inherently characterized by panarchy: they are influenced by changes that emerge within or from outside the system and can adapt to these changes (Folke et al., 2004; Holling and Gunderson, 2002).

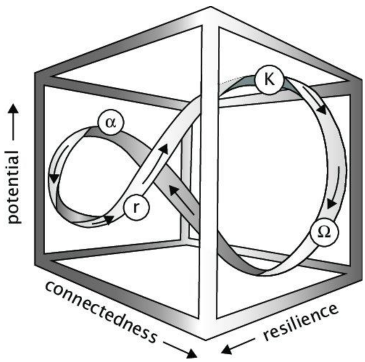

Figure 1-10. Representation of the panarchy theory with the four phases of the adaptive cycle: exploitation (phase r), conservation (phase K), release (phase Ω) and reorganization (phase α) as well as the three dimensions: potential, connectedness and resilience, adapted from Holling et Gunderson (2002) in Hogan et al. (2021).

Resilience benefits in several ways from the panarchy theory. This theory enables the visualization and understanding of hierarchies across social, economic and ecological dimensions and across spatial and temporal scales (Dick et al., 2011) as well as their interactions (Holling, 2001). Moreover, this theory shows that perturbations can be crucial for the continuous development of the system as the system collapse is viewed as creative destruction (Carpenter and Gunderson, 2001; Walker et al., 2006). Finally, the analysis of the system in its adaptive cycle can guide management interventions (Burkhard et al., 2011).

However, several authors pointed out some limitations of the panarchy theory. Gotts (2007) argued that this theory cannot be applied at the global scale because it is not possible to translate planetary SES into the different phases of the adaptive cycle. Moreover, Burkhard et al. (2011) found that connectedness is limited to internal connections, thereby omitting significant external relations while most systems are open. Finally, Carpenter et al. (1999) emphasized the difficulties in applying data to characterize the three dimensions (i.e. resilience, connectedness and potential). In response to these critics, Holling et Gunderson (2002) suggested to view panarchy more as a metaphor which can be used to generate hypotheses on system dynamics but which should not be exploited for detailed system analysis or over-interpreted. Furthermore, Walker et Salt (2012a) stated that the cyclic pattern is not absolute: they are many variations in human and natural systems.

In the 1990s, several papers (e.g. Gadgil et al., 1993; Hammer et al., 1993; Perrings et al., 1992) started to incorporate resilience as a significant feature for human and environmental interactions. These interactions were integrated into the resilience concept by the lens of SES, ES, and sustainability.

In the lens of SES, humans are seen as part of the ecosystem, meaning that natural and human systems should not be studied independently(Anderies et al., 2006; Folke et al., 2002). The resulting **social-ecological resilience** is the capacity of the system to reorganize and adapt through the multi-scale interactions between its social and ecological components (Carpenter et al., 2001; Holling and Gunderson, 2002). Furthermore, SES are CAS as they have critical thresholds, multiple drivers of change and reciprocal feedbacks between social and ecological components (Folke, 2006; Levin et al., 2013).

In mid-1990s, **ecosystem services** were integrated into the resilience concept. The ES-related definition of resilience is the capacity of the SES to continue providing the desired set of ES in the face of a fluctuating environment and human use (Biggs et al., 2015; Folke et al., 2002). The relationships between resilience and ES are further developed in the Chapter 1 4 Bringing together ecosystem services and resilience.

Resilience and **sustainability** have been jointly considered over the past three decades (Thorén and Persson, 2015) to advance our understanding on how to promote human well-being together with a healthy planet (Redman, 2014). On one hand, resilience is used to understand or construct sustainability (Anderies et al., 2013;

Ludwig et al., 1997) because resilience analyzes the capacity of coupled systems to continue to function under change (Perrings and Kinzig, 2018; Sterk et al., 2017) and promotes learning and adaption (Anderies et al., 2013; Yaman Galantini and Tezer, 2018). Moreover, resilience introduces a dynamism based perspective by accounting for uncertainty, changes, complexity, long-term and adaptation (Lew et al., 2016; Wu, 2013; Yaman Galantini and Tezer, 2018). Resilience is also useful in understanding the effects of individual actions on the system level to avoid situations where a sustainable action decreases the sustainability of the global system (Anderies et al., 2013). Finally, resilience provides a set of tools to operationalize sustainability, for example by measuring the performance of achieving sustainability (Anderies et al., 2013). On the other hand, sustainability provides a framework to translate resilience into meaningful actions (Anderies et al., 2013). Furthermore, advances in sustainability research can provide input for resilience research (Wise et al., 2014). For instance, sustainability science can inspire transformative strategies (Redman, 2014).

From the 1990s and 2000s, two concepts: adaptation and transformation have been interacting with resilience. **Adaptation** is a process of deliberate change in anticipation or in reaction to disturbances (Nelson et al., 2007) and the adaptability or adaptive capacity is the capacity to adapt (Folke et al., 2010; Shahadu, 2016; Walker et al., 2004). This concept is at the heart of resilience from 1990s in many of the resilience representations discussed earlier in this chapter. For example, in the panarchy, the system is going through adaptive cycles and in CAS, the system is defined as able to adapt and one of its four dynamic properties is adaptation.

The concept of **transformation** appeared later, in the 2000s, as incremental adaptation did not challenge current systems and paradigms by enabling the continuity of current objectives under changed conditions (Pelling, 2010; Smith et al., 2011). Transformation is a cross of threshold into a new stability domain, in other words, a radical reorganization of the system (Redman, 2014; Yaman Galantini and Tezer, 2018) while transformability is the capacity to transform (Shahadu, 2016; Walker and Salt, 2012a). The concept of transformative adaptation combines the two notions to emphasize the need to adapt not only with incremental change but also through transformation. Transformation addresses the root of the problem and avoids the persistence of unsustainable practices (Pelling, 2010). This concept of transformation is subject to a growing interest in practice and research (e.g. Chapin et al., 2010; Geels, 2006; Olsson et al., 2014; Westley et al., 2007). For instance, IPBES (2019) highlighted that transformative change across economic, social, political and technological factors is necessary to achieve sustainability. Therefore, transformation became an international policy goal that is currently being analyzed by IPBES to examine the determinants of transformative change and options for achieving the 2050 Vision for Biodiversity (IPBES, In review).

The concepts of resilience, adaptation and transformation intertwine in several ways depending on their conceptualizations. First, when resilience is considered as a property of the system, adaptation is seen as a way to face disturbances (Miller et al., 2010). For example, Walker et Salt (2012a) defined adaptability as the capacity of the system to manage resilience and Parrott et Lange (2013) showed that most of the literature on resilience (e.g. Brown et Westaway (2011), Nelson et al. (2007) or Chapin et al. (2009b)) stressed the importance of maintaining the adaptive capacity of the system. However, there is no obvious connection between resilience and adaptive capacity: if the system is maladapted (i.e. poorly functioning), resilience is not necessarily a desirable property (Parrott and Lange, 2013). Secondly, resilience is viewed as being part of adaptation, especially when resilience is defined in the narrow sense of maintaining a similar functioning of the system. For example, Colloff et al. (2017) classified resilience as one of the numerous adaptation approaches. Pelling (2010) framed adaptation as a continuum of resilience (i.e. stability), transition (i.e. incremental social change) and transformation. Thirdly, adaptation and transformation are included into the resilience concept. For instance, Fuller et Quine (2016) defined four properties of resilience: (1) resistance by absorbing the disturbance and continuing to function in the same state, (2) recovery to the pre-disturbance state or to an alternate state having essentially the same structure and function, (3) transformation to a new state, and (4) adaptation allowing recovery or transformation (**Figure 1-11**).

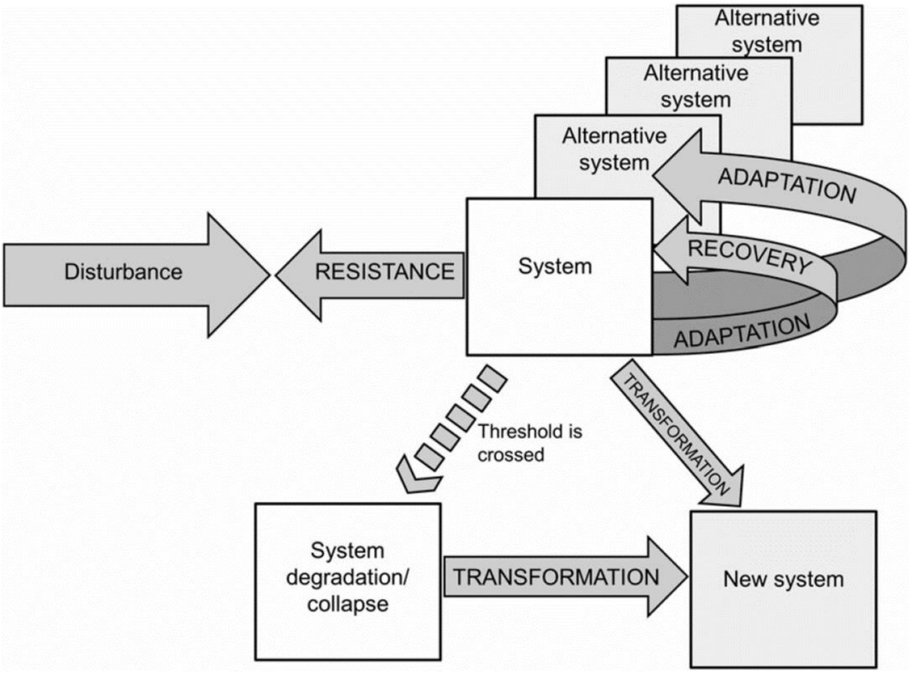

Figure 1-11. Representation of resilience with its four properties in uppercase: resistance, recovery, transformation and adaptation (Fuller and Quine, 2016).

In 2001, Carpenter et al. (2001) realized that most studies exploring resilience, used it as a metaphor or a theoretical construct, only few studies defined resilience operationally (e.g. Carpenter et al., 1999; Janssen et al., 2000; Peterson et al., 1998). Therefore, when analysing the dynamics of a system in relation to its regime shifts, the resilience of what to what should be specified (Carpenter et al., 2001). This specified resilience or **operational resilience** is the resilience of specific parts of the system to one or several disturbances. In opposition, general resilience is the resilience of any or all parts of the system to a full range of disturbances including the new ones, it is about coping with uncertainty in all ways (Folke et al., 2010). In operational resilience, the state of the system (i.e. of what), the temporal and spatial scales (i.e. when and where), the disturbance(s) (i.e. to what), the point of view (i.e. for whom) and the implementation (i.e. by whom and how) need to be defined (Carpenter et al., 2001; Lebel et al., 2006). Management options are influenced by the way resilience is specified (e.g. specific trees species will be preserved if management aims at sustaining a particular type of forest while species composition can vary if the aim is to sustain the supply of a particular ES) (Carpenter et al., 2001). The increase in the resilience of specific parts of the system to particular disturbance may decrease the general resilience of the system (Folke et al., 2010; Walker and Salt, 2012a). General resilience should also be preserved as it buys insurance against unknowns (Folke, 2016; G. D. Peterson et al., 2003; Polasky et al., 2011a). However, preserving general resilience has a cost and should be balanced with the actions needed to meet the immediate needs of society and the ecosystems (Folke, 2016).

Another concept close to operational resilience is robustness. **Robustness** is the system ability to recover or maintain its social-ecological functions in the face of disturbances (Dawson et al., 2010). This concept describes the ability of the system to resist change by absorbing the impacts (Cañizares et al., 2021). Robustness focuses on designing fail-safe systems within a defined range of uncertainty (Anderies et al., 2013). Its focus on a specific system coping with a particular set of disturbances having a clear policy objective in mind (i.e. performance indicator) makes it similar to operational resilience (Hoekstra et al., 2018). By looking at the inherent hidden fragilities of the system, robustness provides a systematic approach to explore the trade-offs between robustness and fragility (Anderies et al., 2013).

In a world increasingly changing, resilience has been more and more studied since 2000 (Folke, 2016). Between 2000 and 2015, the number of scientific publications on resilience in relation to the environment has increased from about 250 to more than 6000 publications (Folke, 2016). Resilience entered in politics, business and practice in response to numerous challenges ranging from poverty alleviation to strategies to anticipate and respond to change and crises (Folke, 2016). From this boom in resilience, two approaches: (1) Resilience thinking, and (2) Resilience-based ecosystem stewardship were developed in the 2000s from previous advances in resilience (i.e. SES, ES, sustainability, CAS theory, panarchy, adaptation and transformation).

Resilience thinking is defined as a collection of ideas and theories to study the dynamics and the development of SES (Rist and Moen, 2013) as well as to find strategies to manage the system in the face of disturbances in such a way that humans live within planet boundaries (Biggs et al., 2015). Resilience thinking is also called resilience perspective by Folke (2006) or by Anderies et al. (2006) or resilience approach by Brand et Jax (2007). Walker et Salt (2012a) formalized ten principles in resilience thinking:

1. The system is a CAS and is thus self-organizing;
2. Thresholds are a core component of the system dynamics: they represent the system self-organizing capacity;
3. Social, economic and biophysical domains are interlinked within the SES: a change in one domain will often lead to a change in the others with feedbacks that can cause further change in the first domain;
4. The system moves through adaptive cycles (i.e. panarchy);
5. The system operates across multiple and interacting spatial and temporal scales, each characterized by its own adaptive cycle;
6. Specified resilience and general resilience have to be considered together as they interact with each other;
7. Resilience involves both adapting and transforming as they are complementary processes (i.e. if the system is caught up in an undesirable state, sometimes it is not possible to adapt, the system needs to be transformed);
8. Maintaining or building resilience has a cost: direct costs of the actions and indirect costs of opportunities lost;
9. Resilience does not presume knowing everything but to have sufficient information to manage the system;
10. Resilience is about acknowledging change, embracing and working with it and not about keeping the system in the exact same conditions.

Resilience-based ecosystem stewardship follows the same principles as resilience thinking but while resilience thinking focuses more on system understanding, resilience-based ecosystem stewardship is more action-oriented. Resilience-based ecosystem stewardship is a framework to manage holistically SES in order to sustain their long-term capacity to provide multiple ES to support equitable human well-being under conditions of uncertainty and change (Chapin et al., 2009a). This definition focuses on the human side: the ultimate goal is sustaining human well-being and the notion of stewardship implies a sense of responsibility for the state of the system of which we are part (Chapin et al., 2009a). Resilience-based ecosystem stewardship recognizes that humanity and nature interact within SES at multiple spatial and temporal scales (Chapin et al., 2009a). Furthermore, SES are part of a rapidly changing world where change is inevitable and affects SES leading to great uncertainty where failure is possible and no one-fits-all solution exists (Chapin et al., 2011; Hansen, 2014) (Chapin et al., 2009a). In response, resilience-based ecosystem stewardship advocates understanding the SES (e.g. its history, the ecological and social drivers, the institutional context, the multiple interacting spatial and temporal scales) with a variety of approaches in an integrative and transdisciplinary way by engaging multiple disciplines and stakeholders (Chapin et al., 2010, 2009a; Hansen, 2014). Furthermore, multiple collective solutions as opposed to one-fits-all solution should be implemented with a proactive governance which embraces and shapes changes (Chapin et al., 2010, 2009a).

From the 2000s onward, the social dimensions of resilience has gained interest as it is necessary to conceptualize how individuals and social systems respond to changes in the environment (Morse et al., 2013). **Social resilience** is the ability of groups or communities to cope with disturbances as a result of social, institutional, political and environmental change to sustain their well-being (Adger, 2000; Hall and Lamont, 2013). To include the social dimension, resilience research expands in four directions to study:

1. The role of institutions, organizations, networks, and agency as well as their cross-scales interactions in enhancing and undermining resilience (e.g. Berkes, 2009; Bodin and Crona, 2009; Dietz et al., 2003; Galaz, 2005; Tompkins, 2005);
2. Adaptive governance (i.e. process of resolving trade-offs and charting a course for sustainability as defined by Boyle et al. (2001)) (e.g. Chaffin et al., 2014; Folke et al., 2005; Huitema et al., 2009; Karpouzoglou et al., 2016);
3. Social learning, cultural aspects and knowledge systems (e.g. Fazey et al., 2007; Forbes, 2013; Hegmon et al., 2008; Pahl-Wostl et al., 2007; Redman and Kinzig, 2003);
4. Issues of inequality, power and politics in resilience (e.g. Boonstra, 2016; Lebel et al., 2006; Smith and Stirling, 2010; Stone-Jovicich, 2015; Thomas and Twyman, 2005) (Folke, 2016; Folke et al., 2010).

Moreover, resilience is increasingly having an impact on development research from individual to society as whole (Folke, 2016). Researches are conducted on poverty, adaptability, food security, social protection, and resilience of individuals, households and groups in the face of environmental change (e.g. Béné et al., 2016; Boyd et al., 2013; Davies et al., 2013; Nayak et al., 2014) (Folke, 2016). Resilience is also studied at the community level to study the adaptation and sometimes transformation of the community in the face of changes (e.g. Amundsen, 2012; Berkes and Ross, 2013; Magis, 2010) (Folke, 2016). Finally, the broader scale is also analyzed to understand the interactions between communities and their dependencies on global economic (e.g. Crona et al., 2015; Scholes et al., 2013; Wilson, 2012) (Folke, 2016).

However, resilience has not been that much integrated in social sciences for several reasons detailed by Olsson et al. (2015). On one hand, this concept creates a tendency to depoliticize social changes when for example, poverty is seen as a stochastic process rather than the outcome of political and structural processes. Moreover, poverty cannot be solved only by building resilience and might even work against the interests of people who are poor. On the other hand, the resilience vocabulary does not fit into the social sciences (e.g. feedbacks alone are not enough to explain the interactions between social entities in norm-based processes) while core theories of social sciences are absent from resilience (e.g. the self-organization property excludes agency, power and conflict, which are core concepts in social sciences). So, the application of resilience in social sciences requires more solid theoretical grounding (Davidson, 2010). Moreover, Olsson et al. (2015) and Thorén et Persson (2015) advocated for pluralism to highlight the subtle differences between disciplines and to acknowledge that resilience conceptualizations are not compatible with all ontologies.

The history of the resilience concept is fundamental to understand how this concept has been built from the mechanics to ecology to be then integrated into SES, complexity, sustainability, adaptation, transformation and social research (Yaman Galantini and Tezer, 2018). During the development of the resilience concept, multiple conceptualizations were born to answer new challenges and to integrate research advances. Resilience is a boundary object with different meanings for various users but at the same time allows for interdisciplinary communication (Brand and Jax, 2007). Resilience can either be viewed as a property of a system (e.g. original-ecological resilience or engineering resilience) or as an approach and set of assumptions for analyzing, understanding and managing change in a system (e.g. resilience thinking or resilience-based ecosystem stewardship) (Biggs et al., 2015). Resilience as an approach can be further split into three conceptualizations:

1. Intellectual framework to understand complex systems (e.g. social-ecological resilience, systemic-heuristic resilience or extended-ecological resilience) (Anderies et al., 2013; Yaman Galantini and Tezer, 2018);
2. Collection of ideas (e.g. self-organization, non-linearity, regime shifts, adaptability) each one related to the dynamics of the system (e.g. resilience thinking) (Anderies et al., 2013);
3. A way to face the current and future challenges of the ever-changing world (e.g. sustainability related resilience or resilience-based ecosystem stewardship) (Lew et al., 2016). In this last sense, resilience has a prescriptive attribute implying that resilience is desirable (Olsson et al., 2015).

No conceptualization is superior to the others but depending on the context, one or several conceptualizations can be more suitable.

3.2 Resilience assessment

Before assessing the resilience, the studied system should be described (Walker and Salt, 2012a). This step aims at collecting just enough information to understand the system knowing that it will only ever be a rough approximation of the actual system (Walker and Salt, 2012a). The necessary information to describe the system is:

1. The scales: the focal scale and the smaller and larger scales influencing that scale in both the biophysical and social domains;
2. People and governance: the stakeholders, the governance system, the rules and regulations;
3. The resilience of what: the values (i.e. what people want and do not want) and the issues (i.e. what people are worried about);
4. The resilience to what: the disturbances;
5. The drivers and trends: the past and the possible futures (Walker and Salt, 2012a).

This step is important because in order to manage correctly the system, where the resilience lies, when and how the resilience can be lost or gained, what are the challenges and opportunities associated with the current changes and what are the possible futures and changes should be understood (Chapin et al., 2009a; Walker et al., 2002). This step benefits from involving the stakeholders to get a better picture of the system (Walker and Salt, 2012a).

Then, to assess resilience, a variety of methods exists depending on its conceptualization. On one hand, if resilience is viewed as a property of the system, methods to measure this property are used. Some of these methods focus on the specified resilience by analyzing specific parts of the system in the face of one or several particular disturbances (Rist and Moen, 2013). They measure, for example, the degree to which a system is unaffected by disturbances or the speed of returning to its equilibrium to assess engineering resilience (Folke et al., 2004). For assessing the (social-)ecological resilience, the stability domain such as its area or the height of the lowest point (Holling, 1973), the extent of disturbance that the system is able to absorb without changing fundamentally (Gunderson, 2000; Walker et al., 2004), the probability of a specific state to be maintained during a given time (Peterson, 2002) or the critical thresholds of regime shifts (Walker and Salt, 2006) are measured.

To quantify these measures, a variety of methods and models are carried out. To find signals of regime shifts, critical slowing down, increased autocorrelation, decreasing recovery rates and increased variance are assessed (e.g. Dakos et al., 2008; Scheffer and Carpenter, 2003; Scheffer et al., 2012) (Folke, 2016). To determine the location of the thresholds, disturbances are simulated experimentally or retrospective analysis of previous disturbances that caused regime shifts are performed (e.g. Bestelmeyer et al., 2013; Connell and Sousa, 1983; Schill et al., 2015; Thrush et al., 2009) (Standish et al., 2014). Conceptual models such as the STM are also used to understand the different states of the system, the transitions between these states and the conditions inducing these transitions as well as the possible thresholds (e.g. Lavorel et al., 2015; Peinetti et al., 2019; Peri et al., 2017). For example, López et al. (2011) proposed an improved version of STM: the SFSTM to assess resilience based on two axes: ecosystem structure and functions. Analytical models such as the fuzzy cognitive mapping are implemented to represent the important features and their relationships to the central issue (e.g. Gray et al., 2015; Olazabal and Pascual, 2016; Singh and Chudasama, 2017). Dynamics models ranging from simple mathematical models of linked differential equations to more complex models, attempting to mimic real-world feedback loops to assess the values of variables and parameters needed for the threshold to occur or to monitor changes in key system variables, are performed (e.g. Biggs et al., 2009; Blackwood et al., 2018; Schlüter et al., 2019) (Lew et al., 2016; Walker and Salt, 2012a). Network models show the connections between the variables to indicate the weak points or change points (e.g. Oshima and Leaf, 2018; Villano et al., 2019). Agent-based models depict the actors (i.e. agents) and the rules of their decision process to explore the outcomes of various policy decisions when changes occur (e.g. Dressler et al., 2018; Egli et al., 2018; Van Strien et al., 2019) (Walker and Salt, 2012a).

Measuring specified resilience does not provide a holistic view of the system: general resilience should also be assessed to understand the resilience of the whole system to multiple threats over the long term (Rist and Moen, 2013; Walker and Salt, 2012a). It is difficult, if not impossible, to quantify general resilience in absolute terms, so trends and changes and their possible effects are examined thanks to surrogates (Brand, 2009; Walker and Salt, 2012a). Some examples of surrogates are:

1. Diversity that encompasses indicators of functional diversity, response diversity, (functional) redundancy, connectivity, spatial heterogeneity, etc. (e.g. Craven et al., 2016; Leslie and McCabe, 2013; Mouillot et al., 2013; Nyström et al., 2008; Peterson et al., 1998) (Elmqvist et al., 2003; Standish et al., 2014; Walker and Salt, 2012a);
2. Reserve generally measured by the loss of reserve such as the loss of habitat patches, seed banks, social memory, local of knowledge or savings (e.g. Ma et al.; Sharp and Angelini, 2019; Tidball et al., 2010) (Walker and Salt, 2012a);
3. Level of capital assets estimated for example by indicators of ES (e.g. Guerry et al., 2015; Nord-Larsen et al., 2019; Seidl et al., 2016) (Folke, 2016; Walker and Salt, 2012a);
4. System discontinuities (i.e. scale breaks) (e.g. Allen et al., 2005; Angeler et al., 2011; Barichievy et al., 2018) (Allen et al., 2005; Folke, 2016).

However, surrogates have high uncertainty because of the lack of evidence supporting surrogates and the dynamics, the complexity and the multidimensionality of the relationships between resilience and its surrogates (Carpenter et al., 2005). Thus, a set of complementary surrogates should be considered to represent jointly the different key aspects of resilience (Carpenter et al., 2005). To select them, Bennett et al. (2005), for example, suggested to use simple systems models.

Another approach to assess general resilience is to study the sources of resilience (e.g. Adger et al., 2005, 2011; Goulden et al., 2013) (Folke, 2016). For example, the role of cultural landscapes, linked to the sense-of-place and deep identities, in adaptations and transformations are currently studied (e.g. Lyon, 2014; Tidball and Stedman, 2013; Turner et al., 2003). Another example is the work on cultural resilience emphasizing cultural features such as resilience pivots or ancestral contracts that persist despite adaptation or even transformation and support the persistence of the system's identity (e.g. Forbes, 2013; von Heland and Folke, 2014; Rotarangi and Stephenson, 2014) (Folke, 2016).

On the other hand, resilience is measured from the different concepts underlying its conceptualizations. To assess adaptation and adaptive capacity, surrogates are used such as biodiversity, heterogeneity of landscape mosaics, social networks or the balance of power between interest groups (e.g. Loreau, 2000; Peterson et al., 1998; Scheffer et al., 2000) (Carpenter et al., 2001). Other methods focus on the adaptation of human communities to change by analyzing the vulnerability of a region or people, their adaptive capacity, the potential effects of adaptation initiatives or the adaptation processes (e.g. Brooks et al., 2005; Kelly and Adger, 2000; O'Brien et al., 2004; Rayner and Malone, 2001) (Smit and Wandel, 2006). Panarchy theory is applied to assess resilience either by quantifying indicators derived from this theory such as the total number of connections (Burkhard et al., 2011) or by analyzing the dynamics of the alternative states (e.g. Angeler et al., 2016; Beier et al., 2009; Yang et al., 2018). Complexity is assessed by a variety of approaches such as field and greenhouse experiments, indicators (e.g. mean information gain obtained from time series of different variables describing the dynamics of the system or fractal dimension to measure the spatial complexity of patterns), network analysis, modelling methods such as individual-based models or agent-based models to investigate cross-scale interactions within complex systems and scenarios to explore the range of probable future states (e.g. de Haulleville et al., 2018; Meloche, 2006; Parrott, 2005) (Parrott, 2010; Parrott et al., 2012; Parrott and Lange, 2013).

Finally, if resilience is considered as an approach, scenarios are used to articulate multiple alternative futures using qualitative or quantitative data and methods and by engaging diverse stakeholders in the process (e.g. Peterson et al. 2003a, Swart et al. 2004, Plieninger et al. 2013, Oteros-Rozas et al. 2015) (Chapin et al., 2009c; Folke, 2016). Furthermore, many methodologies have also been developed for implementing resilience such as the US Climate Resilience Toolkit (US Government, 2015), the Resilience Alliance's Workbook for practitioners (Resilience Alliance, 2010) or the resilience implementation framework developed by Fuller et Quine (2016).

In conclusion, numerous methods exist to assess resilience and no accepted method has currently emerged (Field and Parrott, 2017). In response, Hodgson et al. (2015)

called for the standardization of the resilience assessment methods across systems and fields. Furthermore, as each method has its own strengths and weaknesses and captures only some aspects of resilience, different methods should be combined (Cantarello et al., 2017; Folke, 2016; Seidl et al., 2016). For example, Standish et al. (2014) recommended linking thresholds to surrogate indicators of resilience (e.g. functional diversity) whilst incorporating measures of connectivity and scales. As another example, Diaz et al. (2011) linked functional diversity with social actors strategies. Finally, the development of methods and knowledge on the dynamics of the systems should be pursued to answer current challenges in the assessment of resilience such as the shortage of knowledge on slow variables (i.e. slow variables determine the underlying structure of SES, whereas the dynamics of the system typically arise from interactions and feedbacks between fast variables that respond to the conditions created by the slow variables. For instance, the slow variables of drinking water are soil composition and phosphorous concentrations in lake sediments) (Biggs et al., 2012)) and thresholds, the limited consideration of spatial and temporal scales and the lack of feasibility of some methods (Folke, 2016; Rist and Moen, 2013; Standish et al., 2014).

3.3 Critical analysis of resilience

Resilience focuses on the functioning of the system and its transformational dynamics (Holling and Gunderson, 2002; Walker et al., 2006). Therefore, resilience can help answering the current challenges characterized by high uncertainty, globalized and interconnected systems, increasing disparities and limited choice (Brown, 2015). Resilience is a mean to understand and to assess how a complex interconnected system responds to disturbances (Moberg and Hauge Simonsen, 2014; Standish et al., 2014). Resilience aims at increasing natural and social capital, preparing for cascading impacts of actions, adjusting to mismatched cross-scale linkages and moving the system out of undesirable states by either enabling the system to respond to disturbances whilst maintaining its functioning, enhancing adaptive capacity to cope with unknown futures or transforming the system toward a new configuration (Anderies et al., 2013; Folke et al., 2010; Redman, 2014).

However, as resilience is just one among many possible policy goals for ecosystem management, it is seldom seen as a priority compared to other goals such as food production or endangered species protection (Ruhl and Chapin, 2014). On the other hand, resilience is over-interpreted in the attempt to make it a full-scale paradigm or even a science (Alexander, 2013). The risk of misuse of resilience increases with its popularization in policies because of its vagueness, normativity and current application difficulties (Newton, 2016).

Indeed, there is no unique, clear and universal definition of resilience (Fuller and Quine, 2016). The definition varies within a discipline as well as from a discipline to another and different concepts are linked to resilience (e.g. resistance, adaptation, transformation) (Brand and Jax, 2007; Shahadu, 2016). The vagueness of resilience results in a diversity of applications (Folke, 2016; Standish et al., 2014) with different intentions leading to contrasting policies and actions that may be counter-productive (Brand and Jax, 2007; Fuller and Quine, 2016). Furthermore, the contrasting conceptualizations of resilience among stakeholders and disciplines lead to misunderstanding and miscommunication (Fuller and Quine, 2016; Gallopín, 2006), causing misuses of resilience (e.g. resilience is used as a hook to attract an audience rather than being a truly meaningful concept) (Brand and Jax, 2007). Finally, this confusion in the meaning of resilience hampers its application and operationalization (Brand and Jax, 2007; Walker et al., 2004). In response to these critics, McAslan (2010) and Shahadu (2016) stressed the commonalities between the definitions of resilience. Furthermore, Shahadu (2016) suggested to identify specific definitions and concepts and to use them consistently across disciplines. To clarify its meaning, resilience can also be specified (i.e. resilience of what to what for whom) as suggested by Carpenter et al. (2001) and Sarkki et al. (2017). The multi-faceted aspect of resilience is also an asset because it creates a bridging concept that integrates different theories and perspectives to develop a better understanding of the dynamics of complex SES within varied context (Anderies et al., 2006; Baggio et al., 2015; Fuller and Quine, 2016). For instance, the multiple meanings of resilience are useful to understand and to incorporate how different stakeholders view resilience (Strunz, 2012; Wise et al., 2014).

Secondly, resilience is normative. First, the use of resilience is normative: the application of resilience results in actions that have real social consequences (Olsson et al., 2015). Then, determining when resilience is on a desirable or undesirable path, when the system is crossing a threshold and for whom is subjective and a political question (Folke, 2016) especially when trade-offs occur (e.g. trade-offs between the resilience of an ecosystem and the resilience of ecosystem management) (Ruhl and Chapin, 2014). In that sense, resilience can viewed as negative if it maintains the system in a undesirable state (Folke, 2016; Seidl et al., 2016). Thus, it is important to consider how helpful or unhelpful is the resilience in the managements options and to have in mind that resilience is not an outcome but a mean (Standish et al., 2014). Finally, the evolution of resilience from a descriptive concept to a system thinking increases its normativity (Olsson et al., 2015). Indeed, depending on the conceptualization of resilience, its normativity varies: specified resilience drives more choices than general resilience (Anderies et al., 2013). Brand et Jax (2007) advised to make transparent and to justify ethically the normative choices when using resilience.

Finally, even if resilience provides heuristics for living in a complex world, its operationalization and assessment are not easy because of its complexity and the difficulty in translating its conceptual models into practice (Anderies et al., 2013; Lew et al., 2016). For example, Shahadu (2016) showed that the methodologies developed to measure the components of the SES are either complex or applicable to only large research projects. However, resilience proposes new management and policy approaches such as adaptive management and adaptive governance, more consistent with the evolving and complex nature of the system (Holling and Meffe, 1996; Westley et al., 2002). Resilience helps defining the decision-making context and providing understanding of how this context may change or transform (Anderies et al., 2013). For instance, the use of scenarios to develop indicators and predict future desirable and undesirable states of the system improves decision-making capabilities (Folke et al., 2002). Moreover, resilience informs management by understanding the social-ecological dynamics of the system and by developing principles to guide interventions aiming at improving the long term performance of the system (Anderies et al., 2006; Folke, 2016).

4. Bringing together ecosystem services and resilience

The added values of pairing ES and resilience are first discussed. Then, the different ways these two concepts can be paired are presented.

4.1 Why putting together the resilience and ecosystem services concepts?

ES and resilience have been both proposed to answer the current environmental crises in a sustainable way. Each of the two concepts makes their own inroads into the environmental issues. The ES are an assessment tool while resilience is a full-system perspective. Therefore, we propose to pair these two distinct concepts to bring together their unique added values.

ES are used to specify resilience by defining the resilience of what, to what, for whom and who should contribute to building resilient SES. This characterization of resilience makes it an operational tool (Carpenter et al., 2001; Lebel et al., 2006; Sarkki et al., 2017) while the operationalization of resilience, especially in SES, is still rare (Nikinmaa et al., 2020). As a central connector and mediator between social and ecological systems, ES are particularly suited to help us understanding what we have to do in the SES to ensure its sustainability (Biggs et al., 2015; Munns et al., 2015; Ruhl and Chapin, 2014). Moreover, since the very essence of ES is to be assessed to make visible the interactions between society and nature (MA, 2005), numerous frameworks and guides exist (see for example Baral et al. (2016) for ES assessment framework, IPBES (2022) or Barton et al. (2017) for guides).

We propose to consider resilience to bring the dynamic perspective because this concept acknowledges uncertainty, changes and the need for adaptation or even transformation while broadening the analysis to the entire SES and its external influencing factors (Folke et al., 2010; Walker et al., 2006). Resilience provides an understanding of the spatial-temporal dynamics of ES (Carpenter et al., 2009; Renard et al., 2015). The analysis of resilience enables detecting and anticipating losses or changes of ES or even catastrophic failure in the SES (Feld et al., 2010). Resilience is not limited to the dynamics of the ES but also encompasses every other part of the SES (e.g. resilience of an ecosystem per se, a community) to have a system perspective (Biggs et al., 2012; Brand and Jax, 2007). Furthermore, resilience broadens the analysis to not only examine what people get from nature (i.e. the ES) but also what nature gets from people (e.g. actions that society can take to maintain the natural capital over the long term (Brand and Jax, 2007)).

4.2 How can resilience and ecosystem services be paired?

They are multiple ways of pairing ES and resilience. We categorized these different pairings into four types: (1) resilience is incorporated into ES, (2) ES are incorporated into resilience, (3) the resilience of ES, and (4) ES and resilience are part of a common framework (**Table 1-2**).

Table 1-2. Types of pairing of resilience and ES.

Pairing type	Pairing
Resilience incorporated into ES	Resilience as an ES in ES typology
	Resilience as a determinant of human well-being
	Adaptation services
ES incorporated into resilience	ES assessment to measure resilience
	Resilience theories applied to ES
Resilience of ES	Resilience defined by ES
	Assessing the resilience of ES
	Managing the resilience of ES
ES and resilience in a common framework	ES and resilience integrated into a common conceptual framework
	ES and resilience integrated into a common assessment framework

In the first type of pairing, **resilience is incorporated into ES**. First, **resilience** is integrated **as an ecosystem service** in ES typologies (see for example the ES “resilience and future options” mentioned in Nahlik et al. (2012) or the NCP “Maintenance of options” (Díaz et al., 2018)). Resilience is also considered as an **important determinant of human well-being** when it is defined as the ability of individuals or communities to adapt to change (Kretsch and Stange, 2015). Finally, **adaptation services** are the benefits people derive from the capacity of ecosystems to moderate and adapt to the effects of environmental change, either by persisting and supplying existing services or by transforming and supplying new ones (Colloff et al., 2016; Lavorel et al., 2015).

In the second type of pairing, **ES are incorporated into resilience**. **ES assessments** are performed to measure resilience (e.g. amount of ES to measure the level of capital assets (e.g. Polasky et al. 2011, Lin et al. 2019) or connectivity of ES through network analysis (e.g. Field and Parrott 2017)) (Walker et al., 2006). Secondly, **resilience theories** can be applied to better understand ES (e.g. ES are viewed as complex because they are the emergent results of interactions between the ecological and social factors at various spatial and temporal scales (Reyers et al., 2015), or ES are incorporated into the adaptive cycle of the panarchy theory (Burkhard et al., 2011)).

In the third type of pairing, the focus is on the **resilience of ES**, namely the dynamics of ES. Firstly, the **resilience** is **defined** according to the **ES** as the ability of the system to sustain the diversity and supply of ES as well as the opportunities of their use in the face of disturbances (Biggs et al., 2012; Chapin, 2009). The resilience of what can be specified in terms of ES (Walker and Salt, 2012a). The **resilience of ES** can be **assessed** by numerous methods (e.g. modelling (e.g. Bradford and D’Amato 2012, Sutherland et al. 2016), social network analysis (e.g. Kilonzi and Ota 2019), or scenario analysis (e.g. Temperli et al. 2012, Cantarello et al. 2017)). Finally, the **management of the resilience of ES** implies maintaining desirable states while decreasing the resilience of states that do not provide the desired ES or do so at low levels (Gunderson and Holling, 2002; Walker et al., 2002). Principles such as the seven principles developed by Biggs et al. (2015, 2012) have been built to sustain ES.

Finally, **ES and resilience** are integrated into a **common framework**. ES and resilience are integrated into a common **conceptual framework** to represent the effects of drivers on the SES and the multiple interactions between the components (e.g. Collins et al. 2011, Hansen 2014). For instance, Collins et al. (2011) proposed the PPD framework which links the ecosystems to society through the ES concept and the disturbances to analyse the dynamics of the SES. ES and resilience are also integrated into a common **assessment framework** to jointly assess ES and resilience (e.g. Sarkki et al., 2017). For example, Sarrki et al. (2017) combined the DPSIR framework with social-ecological indicators (including ES indicators) and scenario building to assess the resilience of a SES.

The way ES and resilience are paired has consequences as each of their pairings brings together some of their strengths and creates some pitfalls. When incorporating resilience into ES, the strengths of ES are integrated into resilience (e.g. ES bring significance, a gathering point and operationalization to resilience). Furthermore, ES are broadened to include resilience either directly as an ES, as a determinant of human well-being, or as adaptation services. Nonetheless, through the prism of ES, some strengths of resilience are left behind: its systems perspective and its biocentrism. When resilience is assessed with measures of ES, it helps operationalizing resilience but the system perspective is lost by looking only at the ES. When the theories of resilience are applied to the ES concept, a better understanding of the dynamics of the ES is gained but again, the system perspective is lost. The analysis of the resilience of ES ensures an understanding and an assessment of the dynamics of the ES, essential for the long-term supply of ES and a definition of the resilience of what: which ES are desired and for whom. However, the decision of which ES to sustain is inherently political, inevitably entails trade-offs between ES and their beneficiaries and has distributional implications. Another limitation is the focus on the resilience of ES putting aside the other forms of resilience and its systems perspective. When resilience and ES are integrated into a common framework both their strengths complement and supplement each other. Furthermore, the risk of having one concept overriding the other is low because they are considered equally.

This is why we propose, in this thesis, the Navigate framework, a conceptual and operational framework that pairs closely ES and resilience.

5. Research questions

The central hypothesis of this doctoral research is:

The concepts of ES and resilience are better able to answer the current crises toward sustainability when they are paired than used separately.

From this perspective, ES and resilience are viewed as tools to meet sustainability which is the goal to reach.

From this central hypothesis, three assumptions are tested:

1. When ES and resilience are paired, they mutually reinforce each other;
2. Various methods including stakeholder engagement are needed to capture the multiple dimensions of ES and resilience;
3. One-fits-all solution does not exist: multiple solutions and compromises are the way forward.

6. Positioning of the research

My underlying motive is the protection and preservation of nature for itself (biocentric worldview). I believe that protecting nature without considering the people interacting with it may be counterproductive, especially in highly populated countries like Belgium. This is why I found the concept of ES so attractive to make the links between nature and people. Since the beginning of my professional career, I have been working on this concept.

I also know this concept is not perfect. So, I have been trying to improve it in several ways. First, its anthropocentric nature can put aside other values dimensions and types (i.e. intrinsic and relational). I perform integrated assessment together with stakeholder engagement to account for value pluralism. Stakeholder engagement was not only a way to broaden the assessment of the values dimensions and types, it also struck me as essential to design solutions that are right for the stakeholders. Secondly, the ES concept does not consider the dynamics of the system while we are facing stronger and stronger polycrises. I turned to the concept of resilience to ensure that nature and the services it provides can be sustained in the long term.

Even if I tried to broaden the scope of the ES concept, the use of this concept strongly influences my doctoral research (see Chapter 4 2.3 Step 3: Establish the scope of valuation). The same goes for resilience (see Chapter 4 . I could have used other related concepts (e.g. NCP, adaptation services, adaptation/transformation) that would have given another perspective to my research.

Finally, I wanted to provide a framework that would advance the scientific knowledge and be useful in the civil world to solve real-life issues. Therefore, I performed an action research (i.e. this type of research aims at both answering practical concerns of people in an immediate problematic situation and providing theoretical contributions to scientific research (Chiasson et al., 2009)). In this type of research, two cycles constantly interact and nourish each other: (1) the research cycle (i.e. the pairing of ES and resilience and the corresponding Navigate framework), and (2) the practice cycle (i.e. the implementation of the Navigate framework in the municipal forest of Sivry-Rance) (Chiasson et al., 2009). These incessant back and forths refine the answers to my research questions and the management solutions of the municipal forest of Sivry-Rance. My research was not only an action research but also an intervention research (i.e. the researcher formalizes the change and designs tools to help executing the corresponding change (Gonzalez-Laporte, 2014)). Indeed, I provided tools to better consider the ES and the resilience in forest management plans.

To perform intervention research, I needed to be more than an observer researcher (i.e. I observed my research environment to answer my research questions) but also an immerser researcher. I worked closely with the stakeholders to understand their issues and to gather their knowledge to find an acceptable and reasonable change (Perez, 2008). In that sense, I was a partner of the project, being responsible with the stakeholders for carrying out the project. I also was a facilitator who provides the resources (e.g. survey, participatory workshop) to the stakeholders to notably express their opinions, discuss and learn from each other. I, therefore, influenced the stakeholders and the outputs of the project by bringing knowledge to the process and by driving the information collected from the stakeholders (see Chapter 4 2.1.3 Reflections on the participatory methods that discusses the impacts of the participatory methods on the results).

Chapter 2

Methodology

1. Navigate framework

First, the methods used to build the Navigate framework are detailed. Then, the conceptual part of the Navigate framework is presented. Next, its operational part is discussed. Finally, we describe how this framework was applied to the case study of the municipal forest of Sivry-Rance.

1.1 How the Navigate framework was built?

The Navigate framework was built from three different sources of information: (1) a literature review, (2) interviews with experts, and (3) a case study.

The framework was designed based on a broad literature survey of peer-reviewed papers in scientific journals in English (cut-off date: September 24th, 2021). This literature review was conducted using the bibliographic database of Scopus to understand the interrelationships between ES and resilience and to review their existing frameworks. The literature search was based on the following keywords: resilien*, adapt* and ecosystem services, in ‘Title, abstract or author-specified keywords’. To identify the existing framework of ES and/or resilience, the following keywords were added: framework OR design. Because the terms ES and resilience are widely used, a significant proportion of articles identified only used them as a buzzword. So, we screened all the identified abstracts to select only the papers which really explore ES and resilience, preferably with a framework. A total of 87 papers were selected, 61 papers on the concepts of ES and resilience and 26 discussing ES or/and resilience frameworks. From the papers on ES and resilience, we gained information on their existing relationships and pairings, what one of the two concepts can bring to the other, and their drawbacks (**Table 2-1**).

Table 2-1. Synthesis of the 61 papers on the concepts of resilience and ES from the literature review.

Thematic		References
Relationships between the ES and resilience concepts		Burkhard et al. 2011, Wu 2013, Ruhl and Chapin 2014, Horcea-Milcu et al. 2020
Pairing of the ES and resilience concepts	Resilience is an ES	Díaz et al., 2018; Nahlik et al., 2012
	Resilience of ES	Robards et al. 2011, Biggs et al. 2012, 2015, Bradford and D'Amato 2012, Temperli et al. 2012, Schoon et al. 2015, Sutherland et al. 2016, Cantarello et al. 2017, Kilonzi and Ota 2019
	Resilience to sustain ES	Walker and Salt 2006, 2012b, Fischer et al. 2006, Lebel et al. 2006, Chapin et al. 2009b, 2010, 2011, Dawson et al. 2010, Rist and Moen 2013, Guerry et al. 2015
	Dynamics of nature, society and their interactions (including the ES)	Carpenter et al., 2009, 2005; Enfors, 2013; Folke et al., 2002; Lade et al., 2020; Nelson et al., 2009; Renard et al., 2015; Runting et al., 2017; Thom and Seidl, 2016, 2016; Walker et al., 2006
	Adaptation services	Colloff et al., 2017, 2016; Lavorel et al., 2019, 2015
	ES to assess resilience	Polasky et al. 2011a, Field and Parrott 2017, Lin et al. 2019, Nikinmaa et al. 2020
	ES to manage for resilience	Reyers et al. 2015, Hogan et al. 2021
Critical analysis of ES and resilience	ES	Norgaard 2010, Abson et al. 2014, Schröter et al. 2014, 2017, Kull et al. 2015, Munns et al. 2015, Evans 2019
	Resilience	Brand and Jax 2007, Moberg and Hauge Simonsen 2014, Standish et al. 2014, Olsson et al. 2015, Baggio et al. 2015, Folke 2016, Newton 2016, Shahadu 2016

We used the framework papers to review the existing frameworks, to analyze their added values and limits, and to understand how they integrate the ES and/or resilience concept (**Table 2-2**). Most of the existing frameworks are conceptual and not easily applicable. Furthermore, only few of them closely pair the ES and resilience concepts or have a social perspective. We thus designed the Navigate framework to be truly operational and comprehensive (ES and resilience together with a social perspective). We also took inspiration from these frameworks to design ours (**Table 2-2**).

Table 2-2. Synthesis of the 26 papers on the ES and/or resilience frameworks with their added values, limits and how we drew on them.

References	Framework's name	Concepts	Added values	Limits	Source of inspiration
Baral et al., 2016	Simplified framework for planning the assessment of ES from planted forests	ES	Framework easily applicable	Focus on ES Focus on planted forest	ES assessment
Boesing et al., 2020	Temporal dynamics of ES supply and demand	ES	ES dynamics Distinction between ES supply and demand	Focus on ES	ES supply and demand ES dynamics
Breyne et al., 2021	Socio-cultural importance-performance approach	ES	Social perspective	Focus on ES	Socio-cultural values of the ES
Cavender-Bares et al., 2015	Framework to analyse the ES trade-offs	ES	Social perspective Interactions between ES	The framework does not provide steps to follow	Socio-cultural values of the ES ES dynamics
Díaz et al., 2015	IPBES conceptual framework	ES	Interactions between nature and society Multiple scales and their interactions are depicted	Focus on ES Conceptual framework that does not provide a method to assess the system	Different terms to describe a concept to reveal the plurality of conceptualizations
Duraiappah et al., 2014	A multi-scale conceptual framework on nature, the productive base of societies and human well-being	ES	Interactions between nature and society Multiple scales and their interactions are depicted	Focus on ES Conceptual framework that does not provide a method to assess the system	Multiple scales Co-production from natural and anthropogenic capital
Fedele et al., 2017	Framework on mediating mechanisms and factors in ecosystem service delivery	ES	Roles and interactions of the different stakeholders	Focus on ES Conceptual framework that does not provide a method to assess the system	ES cascade Stakeholders

Ikematsu and Quintanilha, 2020	Conceptual framework to illustrate the linkages between scenarios, models, and relationships among ES for informing policy and decision-making	ES	Framework easily applicable	Focus on ES	Scenarios
Fuller and Quine, 2016	Resilience implementation framework	Resilience	The framework provides different steps to follow to assess resilience	Focus on resilience	Different steps to follow
Lauerburg et al., 2020	Conceptual framework of the vulnerability of a SES, the assumed connectivity of its sub-systems and the potential point of action of a tipping point	Resilience	Interactions between the ecological, social and economic spheres	Conceptual framework that does not provide a method to assess the system Focus on resilience	SES
Li et al., 2020	Analytical framework for resilience in regional management	Resilience	The framework provides different steps to follow to assess resilience	Focus on resilience	Different steps to follow
Turner et al., 2003	Vulnerability framework	Resilience	Multiple scales and their interactions are depicted	Conceptual framework that does not provide a method to assess the system	Multiple scales
Baskent et al., 2020	Conceptual framework components indicating the organization and connections to ecosystem planning process	ES, resilience	Framework easily applicable Social perspective	Focus on forest ecosystems	Different steps to follow
Bretagnolle et al., 2019	The conceptual framework of the SES within the French long-term social ecological research platforms	ES, resilience	Interactions between nature and society Social perspective Examples of implementation of this framework	The framework does not provide steps to follow	ES assessment Stakeholder engagement

Chapin et al., 2009a	Diagram of SES	ES, resilience	Framework that combines ES and resilience Interactions between nature and society are depicted	Conceptual framework that is not easily applicable	SES Drivers
Chapin et al., 2009a	Conceptual framework linking human adaptive capacity, vulnerability, resilience and transformability	ES, resilience	Framework that combines ES and resilience Different forms of resilience are considered	Conceptual framework that is not easily applicable	Different forms of resilience Pathways
Collins et al., 2011	Press–Pulse Dynamics framework	ES, resilience	Framework that combines ES and resilience Interactions between nature and society are depicted	The framework does not provide steps to follow	Drivers Interactions between nature and society
Hansen, 2014	Example of application of the Press–Pulse Dynamics framework	ES, resilience	Example of application	The framework does not provide steps to follow	Multiple scales and their interactions Drivers Interactions between nature and society
Colloff et al., 2017	TARA approach	ES, resilience	Framework that combines ES and resilience Different forms of resilience Examples of implementation of this framework	Based on the resilience concept as we defined it in this thesis but this concept is not used in the framework	Pathways
Dick et al., 2011	Review of a range of analytical framework to study ES	ES, resilience	Frameworks that pair ES and resilience	Mainly conceptual frameworks not so easy to operationalize	ES and resilience consider together in a same framework

Enfors-Kautsky et al., 2021	Wayfinder framework	ES, resilience	The framework provides different steps to follow Different forms of resilience	ES are not assessed	Planetary and social boundaries Pathways Different steps to follow
Peter, 2020	Integration of the results from the perspective of sociological theory of risk into the existing ES framework	ES, resilience	Interactions between nature and society	Conceptual framework that does not provide a method to assess the system	Interactions between nature and society
Raworth, 2017	Doughnut framwork	ES, resilience	Planetary and social boundaries	Conceptual framework that does not provide a method to assess the system	Planetary and social boundaries
Sarkki et al., 2017	Combined DPSIR-Indicator-Scenarios approach for assessing the resilient provision of ES by SES	ES, resilience	Framework that combines ES and resilience Framework easily applicable	Focus on the resilience of ES	Scenarios
Walker et al., 2002	Framework for analyzing social-ecological resilience	ES, resilience	The framework provides different steps to follow to assess resilience Social perspective	Social uncertainty	Different steps to follow
Weise et al., 2020	The use of the resilience trinity framework to guide the identification of suitable actions to ensure sustained ES provisioning to society	ES, resilience	Framework easily applicable	ES are not assessed	Different steps to follow

Thirty-five interviews with leading experts on the resilience and ES concepts were then conducted. The experts were selected based on their extensive experience as reflected in the literature review (i.e. main and relevant authors of the papers), their participation in organizations on ES or resilience (e.g. Resilience Alliance, IPBES, PECS), or a recommendation from another expert. A semi-structured interview was conducted with each expert based on a common questionnaire. This form of interview offers the double benefit of asking common questions to all the experts and thus obtaining comparable information, and the possibility of rephrasing questions and asking for clarification. The interviews, lasting about one hour, were conducted face-to-face in the office of the interviewee whenever possible, otherwise they were conducted via Skype © or Zoom ©, during summer 2019. The interviews were recorded after obtaining permission from the respondent. The questionnaire includes questions on the interviewee's position; their use of the two concepts; their definitions of resilience and ES; the origin, strengths, and weaknesses of these two concepts and their relationship with sustainability; the added values and limitations of pairing the two concepts; the ways to pair them; and any recommended experts and literature. Each interview advanced our understanding of the two concepts while sharing ideas to bring the framework to maturity (e.g. an expert suggested to use the concept of resilience to consider the drivers and the ES concept to identify the impacts of the disturbances). These interviews made us realize how the ES and resilience concepts could have very different meanings. Having a conceptual framework that explains these two concepts and their relationships is thus needed to get a common understanding before applying ES and resilience.

To test the framework and to make it more operational, it was applied to a case study. This implementation started at the beginning of the framework design and continued throughout its entire development, so the framework and the case study continuously gave feedback to each other. The Navigate framework was continuously adjusted thanks to an agile project management (i.e. the project is managed in an iterative way depending on the needs of the stakeholders). This type of management is highly responsive and flexible, two qualities needed in real and complex environment (Steiner, 2014).

The selected case study is the municipal forest of Sivry-Rance. The reasons of this choice are explained in the Chapter 2 2.7. Why the municipal forest of Sivry-Rance?. The case study is presented in the Chapter 2 2. Case study: the municipal forest of Sivry-Rance.

1.2 Conceptual part of the Navigate framework

The conceptual part of the Navigate framework, illustrated in **Figure 2-1**, synthetizes many of the recent advances in the resilience and ES concepts, embedded in a clear and coherent process to set the stage for their joint implementation.

1.2.1 Six key elements

The key elements of the framework are: (1) the SES, (2) the ES, (3) the disturbances, (4) the scales, (5) the social and biophysical boundaries, and (6) resilience.

The **SES** consists of three components: (1) nature, (2) society, and most importantly, (3) the dynamic coupling of social and ecological subsystems (Cannon and Müller-Mahn, 2010) (**Figure 2-1A**). This representation is fundamental to understanding the influence of humans on ecosystems, how society deals with and is affected by environmental impacts (Peter, 2020) and changes through interconnected social and natural processes (Colding and Barthel, 2019; Folke, 2006).

The SES is thus characterized by the dynamic interactions between its various components which means that these components are themselves not fixed (Brown, 2021; Tozzi, 2021). Each component influences the next one and provides feedback based on the previous one. Among the multiple interactions between nature and society, we focus on the **ES**. The ES are the functions, performed by the structures and processes of the ecosystem and its biodiversity, generally together with anthropogenic capital (i.e. various forms of social, human, financial and technological capital) (Kachler et al., 2023; Palomo et al., 2016), that meet people's needs. This co-production of the natural and anthropogenic capital generates the ES supplies. The flows from society to the ecosystem are the ES demands. From these ES, humans obtain benefits, increasing their well-being. The importance of these benefits generates a diversity of values. In turn, these values influence decision-making, translated into human actions on the SES that will influence the ES for which the actions are taken but also the other ES. To keep the conceptual framework easily readable, the human actions are depicted at the intersection between the nature and society curves while they can be carried out at different levels on the SES (e.g. nature-based solutions or restoration take place on the natural structures and processes) and generate the anthropogenic capital. (Díaz et al., 2015; Haines-Young and Potschin, 2010)

Biophysical drivers (i.e. drivers that are not the result of human activities and whose occurrence is beyond human control such as weather patterns or volcanic eruptions) and social drivers (i.e. drivers that result from human actions such as climate change or payment for ES) cause **disturbances** that have a cascading effect on the SES (Cavender-Bares et al., 2015; Chapin et al., 2009; Lauerburg et al., 2020) (**Figure 2-1B**). For instance, a change in the ecosystem results in changes in ecosystem functioning and consequently in the provision of ES, implying societal impacts (Díaz et al., 2015).

The components of the SES, the drivers and the disturbances occur and interact at different **scales** (Díaz et al., 2015; Duraiappah et al., 2014). By scale, we refer to the usual spatial and temporal scales but also to any other scale such as the scale of jurisdiction, the hierarchy of knowledge or institutional scale that are generally less recognized (Cash et al., 2006).

Two boundaries are illustrated. First, the **biophysical boundaries** ensure that the natural system functions properly. At the Earth scale, these boundaries are composed of nine global biophysical processes regulating the stability of Earth beyond which large-scale and potentially irreversible environmental change is expected (i.e. planetary boundaries) (Persson et al., 2022; Rockström et al., 2009; Steffen et al., 2015). At finer scales, these boundaries are the limits beyond which the natural system does not provide the ES needed. Secondly, the **social boundaries** ensure that each person of the SES has the ability to meet their basic human rights (Raworth, 2012). Combining the biophysical and social boundaries creates a doughnut-shaped space within which humanity can thrive and ensure trajectories that are safe and just (i.e. a sustainable space) (Enfors-Kautsky et al., 2021; Raworth, 2017).

From the multiple conceptualizations of **resilience**, we choose the Resilience-based ecosystem stewardship definition of resilience, given the frame of our research: the ability of the SES to sustain its long-term capacity to provide multiple ES to support equitable human well-being within the planetary boundaries under conditions of change and uncertainty (Chapin et al., 2009). This conceptualization of resilience captures the interactions between the social and ecological spheres and stresses that adaptation or even transformation are necessary to ensure a sustainable future (Folke et al., 2010). In that sense, resilience is the mechanism by which the SES can continue to provide the multiple ES we humans need. We distinguish three forms of resilience: (1) persistence, (2) adaptation, and (3) transformation.

These three forms of resilience are schematized in different pathways. The pathways represent multiple possible futures (more or less) distinct from each other (Enfors-Kautsky et al., 2021) that integrate feedbacks and trade-offs across temporal and spatial scales helping to address particularly complex challenges and guide decision making (IPBES, 2016). We represent two examples of pathways. In the first pathway (i.e. the one above), the system persists and moves closer and closer to the biophysical boundaries to eventually cross them. The natural part of the system is then represented by dotted line to illustrate that it does not perform well knowing that if it continues to stay outside the biophysical boundaries, the SES and the society will be negatively impacted too and finally the entire system will crash. To come back into the safe operating space, the system transforms. In the second pathway, the system persists and crossed the social boundaries and then adapts twice to come back into the just space.

To keep these pathways easily readable, three simplifications were made:

1. We only consider one form of resilience of the overall SES even if, in reality, some parts of the SES may persist while other parts may adapt and/or transform (Enfors-Kautsky et al., 2021);
2. We only represent two examples of the combinations of the different forms of resilience while others are possible;
3. We did not change the depiction of the SES while in reality when the SES adapts or transforms, it changes.

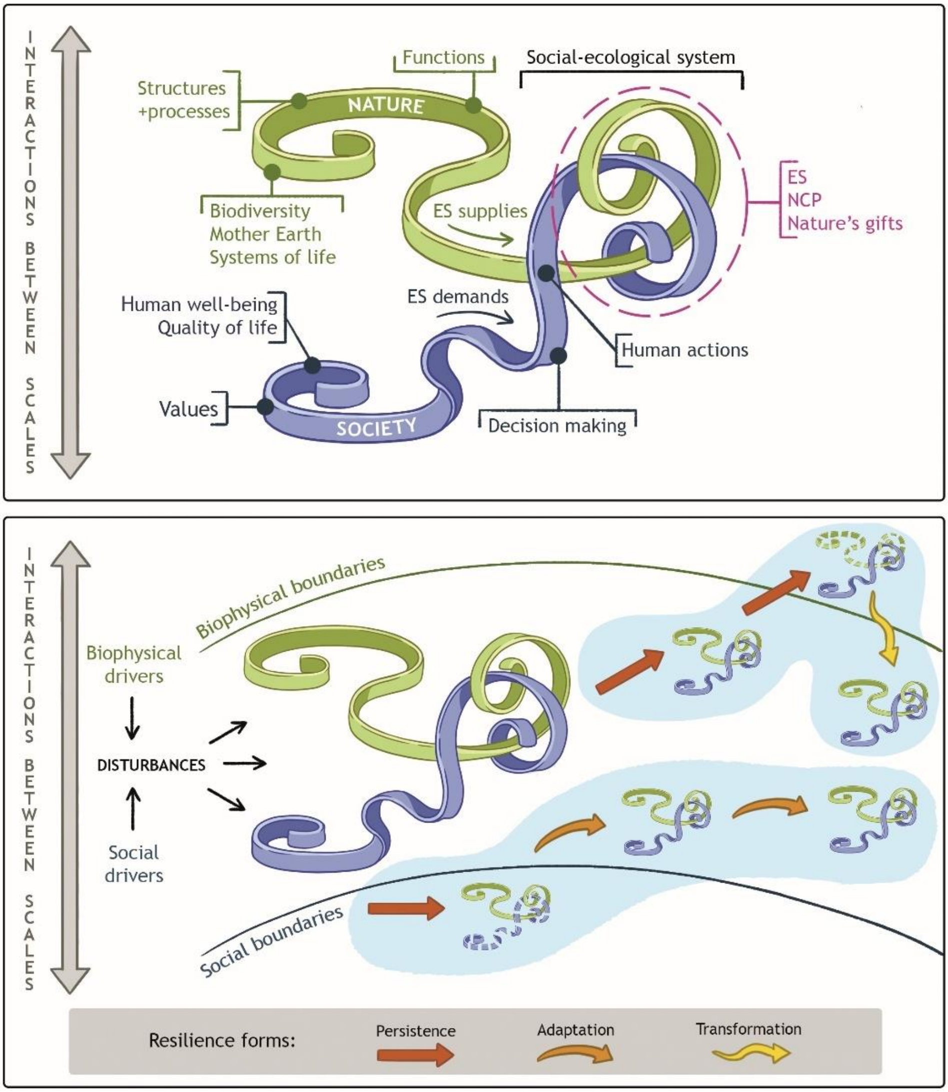

Figure 2-1. The conceptual part of the Navigate framework.
A. Representation of the socio-ecological system (SES) and its multiple interactions by two intertwined curves. The first curve represents nature with its biodiversity that generates structures and processes performing functions. The functions used by people to improve their well-being are the ecosystem services (ES) or nature contribution to people (NCP). The second curve depicts society characterized by people's quality of life, their values, and the decisions they make. Their subsequent actions to improve the ES they need have also an influence on the other ES. The first arrow symbolizes the supplies of ES from the ecosystem functions generally together with anthropogenic capital, and the second arrow schematizes the demands from society. The double arrow, on the left, depicts the different scales at which the components of the SES occur.

B. Representation of the dynamics of the SES and its biophysical and social boundaries. Disturbances, caused by biophysical and social drivers, affect the SES. The SES responds either by persisting, adapting, or transforming (i.e. three forms of resilience) in different pathways. Two examples of pathways are given.
This schematic representation of the conceptual part of the Navigate framework is inspired by Turner et al. (2003), Chapin (2009), Collins et al. (2011), Dick et al. (2011), Hansen (2014), Díaz et al. (2015), Colloff et al. (2017), Lade et al. (2020), Peter (2020) and Enfors-Kautsky et al. (2021).

1.2.2 Three principles

The framework is underpinned by three principles.

The first principle is pluralism. Taking inspiration from the IPBES conceptual framework (Díaz et al., 2015), we used several terms to describe a same part of the framework to highlight that the choice of a concept is a cultural debate between different worldviews, reproducing a particular social order (Peter, 2020). The terms ‘supply’ and ‘demand’ are in plural to account for the multiplicity of supplies depending on the ecosystem and its management (Maebe et al., 2019) and the diversity of demands depending on the preferences and values of people (Breyne et al., 2021; Peter, 2020).

The second principle is the openness and indeterminacy of the SES boundaries. It brings in actors, ecological processes, scales, etc. that may seem peripheral and considered as external influences (e.g. population growth, globalization), but can have important consequences on the SES (Brown, 2021).

The third principle is the multi-scale and cross-scale perspective. This perspective supports the identification of trade-offs within and across scales. For instance, by making clear how ES can be supplied, used, valued and managed at different scales (Duraiappah et al., 2014), we can understand how a decision can affect nearby, faraway or futures services (Rodríguez et al., 2006).

1.3 The operational part of the Navigate framework

From the conceptual part of the Navigate framework and the nature of the resilience concept (i.e. a broad concept with a full-system perspective), we might have been expected that the resilience concept conceives the ES concept. The opposite happened when the Navigate framework was operationalized because of the operational nature of the ES concept. Indeed, the integrated assessment of the ES was used to evaluate the resilience.

The six steps of the operational part of the Navigate framework are presented below.

1.3.1 Step 1: Define the system

This first step represents the application of the conceptual part of the Navigate framework where the different components of the system, its scales, its interactions and dynamics are studied. This step is divided into three sub-steps: (1) define the ‘territory’, (2) define the SES dynamics, and (3) identify the interactions and scales.

In the first sub-step, the ecosystems, the stakeholders and their relationships are described (Oikonomou et al., 2011). In the second sub-step, the biophysical and social drivers impacting the SES are identified (Carpenter et al., 2001). These two first sub-steps allow defining the resilience of what (i.e. the system), to what (i.e. the drivers) and for whom (i.e. the stakeholders). In the third sub-step, the various links between the components of the SES and the scales are analyzed (Cavender-Bares et al., 2015; B. L. Turner et al., 2003). These three sub-steps are performed by collecting information from various sources: review of existing information (e.g. management plans, administrative documents, scientific reports), field data, stakeholders and interviews with experts, etc. This definition of the system is a simplification of reality and should be validated by the stakeholders.

1.3.2 Step 2: Define the problem, the stakes and the goals

From the analysis of the system, we can characterize, with the stakeholders the stakes. Based on these stakes, the problem that needs to be solved and the goals of the study are defined.

1.3.3 Step 3: Define the pathways

We propose selecting the pathways with the stakeholders as a set of desired futures, each pathway representing the preferences of a certain group of stakeholders (see for example Tompkins et al. 2008, Palomo et al. 2011, Ruiz-Mallén et al. 2015 for participatory scenario planning). These preferences are translated into management interventions to create management scenarios. The most prominent drivers identified in the first step are then combined with the management scenarios. For example, several climate change scenarios from IPCC (IPCC, 2022) can be integrated into each management scenario. Therefore, the factors that can shape the SES (i.e. the management and the drivers) are studied to understand the impacts of different changes on the SES.

1.3.4 Step 4: Assess the ES

The ES are assessed to gain a comprehensive view of the SES (Ikematsu and Quintanilha, 2020). This perspective has been chosen for four reasons:

1. ES are an accessible feature of the SES to analyze (Enfors, 2013);
2. They embrace the different perspectives as their contribution to human well-being varies among and across different groups of people (Arias-Arévalo et al., 2018; Daw et al., 2011);
3. They clarify the causes of ecosystem change as well as the relationships between and within natural and human systems (Ikematsu and Quintanilha, 2020);
4. They explicitly consider multiple dimensions because they perform at different scales (Atkins et al., 2011; Bastian et al., 2012).

The following four sub-steps guide the assessment of ES: (1) understand the social preferences, (2) select the ES, (3) select the methods, and (4) assess the ES. In the first sub-step, the opinions of the different stakeholders, expressed by their preferences regarding the ES, are considered to give meaning to the ES values (Breyne et al., 2021). These preferences are expressed in two ways: (1) the importance they give to the different ES, and (2) the minimal and satisfactory levels that the ES should have. Participatory workshops or surveys can be used to collect these preferences. In the second sub-step, the relevant ES are selected based on the analysis of the system (Step 1), the social preferences of the stakeholders and the selected pathways (Step 3) to consider only the ES at stake in the current state and in the pathways. In the third sub-step, the proper methods to assess the ES are selected based on the resources at hand (e.g. time, money, data) from the existing ES assessment methods (see for instance Grêt-Regamey et al. (2017), Harrison et al. (2018) and Jacobs et al. (2018) for a review of ES assessment methods). For each ES, several methods should be used following the principles of the ES integrated assessment to capture the diversity of ES values (Arias-Arévalo et al., 2018; IPBES, 2022). In the four sub-step, based on these methods, the ES are assessed for the current state and in the different pathways.

1.3.5 Step 5: Assess resilience

The resilience of what (i.e. the ES needed by the stakeholders, step 4) to what (i.e. the drivers considered in the pathways, step 3) and for whom (i.e. the stakeholders, step 1) can be defined from the previous steps.

Then, we propose assessing the resilience of the different pathways in two different ways. First, the resilience of ES (i.e. the capacity of the SES to provide the ES needed by the stakeholders) is captured by analyzing the diversity of ES that answer the needs of the stakeholders (defined in the step 4). Secondly, the social resilience is studied. The preferences of the stakeholders (defined in the step 4) are changed several times to see how the variation in societal demand modifies the preferred pathway(s). By varying the preferences of the stakeholders, we account for uncertainty in future social demands that can change drastically within short time frames (Seidl and Lexer, 2013).

1.3.6 Step 6: Take action

In the sixth step, based on the comparison of the pathways, some pathways are selected because they are more desirable than others in the sense of being more ecologically sustainable and socially just (Enfors-Kautsky et al., 2021). These selected pathways are translated into concrete actions with the stakeholders. The action plan is made of flexible measures that maintain existing available actions and keep options open for now and the future and create new options when old ones close (Lade et al., 2020). This process is iterative as new insights based on the observation and experience from the process are generated and reflected upon, and the solutions found may trigger or unveil new problems (Grima et al., 2017).

1.4 Implementation of the Navigate framework to the municipal forest of Sivry-Rance

The Navigate framework was applied to the municipal forest of Sivry-Rance following the six steps described in the operational part of the Navigate framework (**Figure 2-2**).

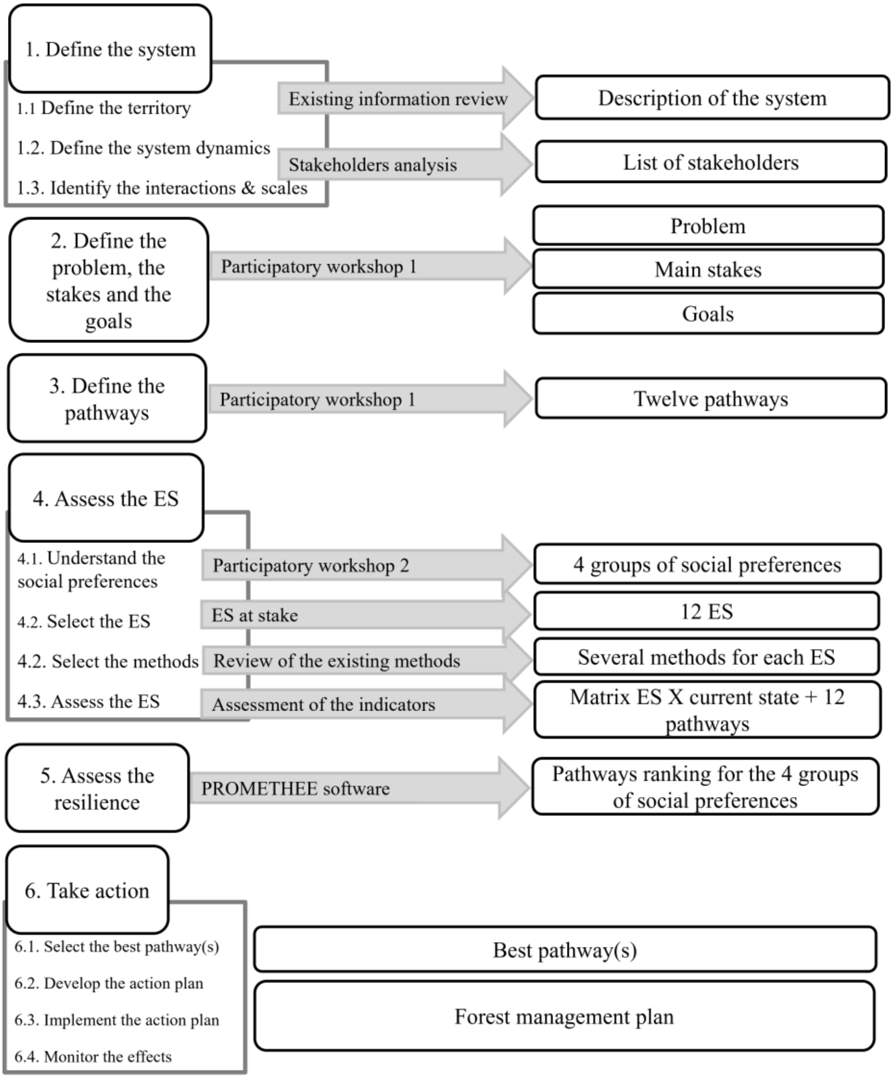

Figure 2-2. Operational part of the Navigate framework applied to the municipal forest of Sivry-Rance with the six steps, the methods, and results of these steps.
This part of the Navigate framework is inspired by Baral et al. (2016), Sarkki et al. (2017), Baskent et al. (2020), Ikematsu and Quintanilha (2020), Li et al. (2020) and Enfors-Kautsky et al. (2021).

The methods used to implement this framework to the municipal forest of Sivry-Rance are detailed in the next sections (from the Chapter 2 3. Review of existing information to Chapter 2 8. Resilience assessment).

The results are presented step by step in Chapter 3.

Finally, the Navigate framework and its implementation to the municipal forest of Sivry-Rance are discussed in Chapter 4.

2. Case study: the municipal forest of Sivry-Rance

We selected the municipal forest of Sivry-Rance as a case study. After describing this forest in terms of its owner, management (forestry, nature conservation, recreation activities), ecological context and health state, this choice is justified.

2.1 Owner and manager

The municipal forest of Sivry-Rance, of about 2200 ha, is located in the municipality of Sivry-Rance (Belgium), in the province of Hainaut, on the French border (**Figure 2-3**). This forest is owned by the municipality of Sivry-Rance.

The municipal forest of Sivry-Rance is managed by the DNF in charge of the management of the public forest. The forest is divided into four forest management units, each of them managed by a forest officer from the DNF. Three municipal workers perform the daily forest work. The four forest officers are overseen by a coach officer and the head of the forest district of Thuin (i.e. 'Cantonnement de Thuin'). They are supported by an administrative officer. The forest equipment is owned by the municipality of Sivry-Rance and maintains by the three municipal workers.

The forest management plan of the municipal forest of Sivry-Rance began to be reviewed in 2018. The first step of this revision was the analysis of the current state of the forest in terms of the ecological and human context, natural habitats, management, nature conservation and rentability based on four sources of information: (1) existing data (e.g. administrative, soil, hydrological data, forest inventory, economic statistics), (2) review of grey literature, (3) field measurements (e.g. biological inventory, field trip), and (4) experts (i.e. DNF, municipality of Sivry-Rance, Fishery Service[1]). Then, the management aims were defined for the four functions of this forest (i.e. ecological, social, economic and hunting functions). Finally, the means to reach these aims were described (e.g. silvicultural practices, restoration actions, development of the recreation infrastructures). This plan was reviewed by the municipality of Sivry-Rance, the Natura 2000 committee, *Pôle Environnement* (i.e. an advisory body that gives opinions on the environmental issues upon the request of the government, the regional administration, the municipalities or other initiatives) and the public. Finally, the final version of this plan was adopted by

[1] Service de la Pêche of the SPW who oversees the management and the development of the freshwater in Wallonia.

the municipality in 2022. This forest management plan is presented in the Chapter 3 3.5. Multifunctional Forest of Chapter 3.

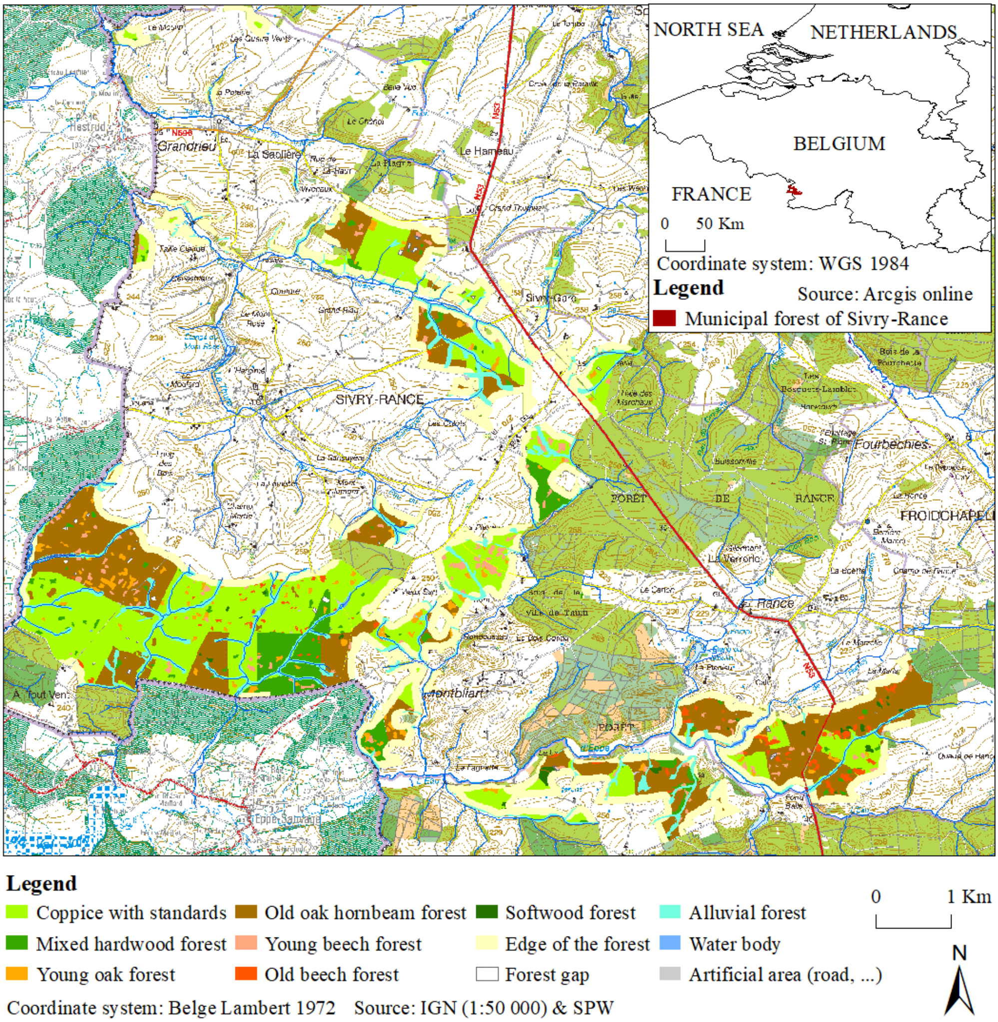

Figure 2-3. Map of the municipal forest of Sivry-Rance depicting its localization, the water network and the different forest stands.

2.2 Ecological context

The area, culminating at 250m high, is characterised by a temperate climate (i.e. relatively cool and wet summer and relatively mild and rainy winter) with a mean annual rainfall of 976 mm and a mean annual temperature of 9.5°C (Colson and Baix, 2021).

The forest is in the watershed of Sambre. It is gouged by numerous streams, tributaries of Thure (North), Eau d'Eppe (South) and Hantes (East) (**Figure 2-3**).

Several ponds were excavated on Eau d'Eppe and Ri de Fromont because they have a stronger river flow. This river system shaped the topography of this forest where the plateaus follow slopes (5% of the forest has a slope ranging between 15° and 30°) and river bottoms. (Colson and Baix, 2021)

The loamy stony soils, mainly present, create water deficit, especially on the southern slopes. Loamy soils, are present in one third of the area, some of them are hydromorphic (one quarter of the forest area) and create waterlogging. Waterlogging is also present on the clay soils (1% of the forest area). (Colson and Baix, 2021)

2.3 Forest stands and their management

The municipal forest of Sivry-Rance is mainly composed of hardwoods mostly oaks and hornbeams accompanied by beeches and other deciduous trees (e.g. maple, birch, alder, cherrywood). One-quarter of the hardwood forest is composed of mixed irregular stands, one-half is former coppice with standards under conversion to irregular stands (**Figure 2-4A**) and 10% is still coppice with standards. The softwood stands (1% of the forest area) mainly consist of spruce (**Figure 2-4B**) or larch in regular stands. (**Figure 2-3**) (Colson and Baix, 2021)

The hardwood forest is managed according to continuous cover forestry (Pommerening and Murphy, 2004). This management aims at promoting a durable and profitable forest using forest practices inspired by the natural processes: continuity of forest cover, natural regeneration, selective thinning, diversity of forest species and ages. After logging, for three years, the area is allowed to regenerate naturally (**Figure 2-4C**). Then, the species mix is managed to promote the best quality wood species (i.e. oak, cherrywood, maple). If the natural regeneration is not enough (e.g. due to a very strong competition of the bramble or the ferns), small enrichment plantings are done with a variety of hardwood species (e.g. oak, cherrywood, maple) (**Figure 2-4D**). This planting method has four advantages:

1. The natural regeneration is used to "educate" the seedlings;
2. It promotes a mixed forest stand with a better resilience (species and genetic diversity);
3. It reduces the costs (from 20% to 30% less than the costs of a full planting);
4. The natural regeneration protects the plants from the sun and the game.

Then, the management continues to promote the mix of tree species and ages with selective thinning to harvest mature wood, to let grow freely the best quality trees and to promote natural regeneration. In the last decade, 3.6 m^3/ha*year of timber was on average harvested, which roughly corresponds to the theoretical annual growth (i.e. 3.9 m^3/ha*year). The forest is thus at its equilibrium. Almost half of the harvested timber volume is composed of oak. A quarter of the harvested timber volume is thinning wood from various best quality tree species, half of them being hornbeam. (Colson and Baix, 2021)

The few softwood stands are managed with regular dynamic thinning (every six years) to ensure a girth annual growth of 2.5 cm a year. In the harvested softwood stands, the natural regeneration is promoted to obtain mixed hardwood-softwood irregular stands. (Colson and Baix, 2021)

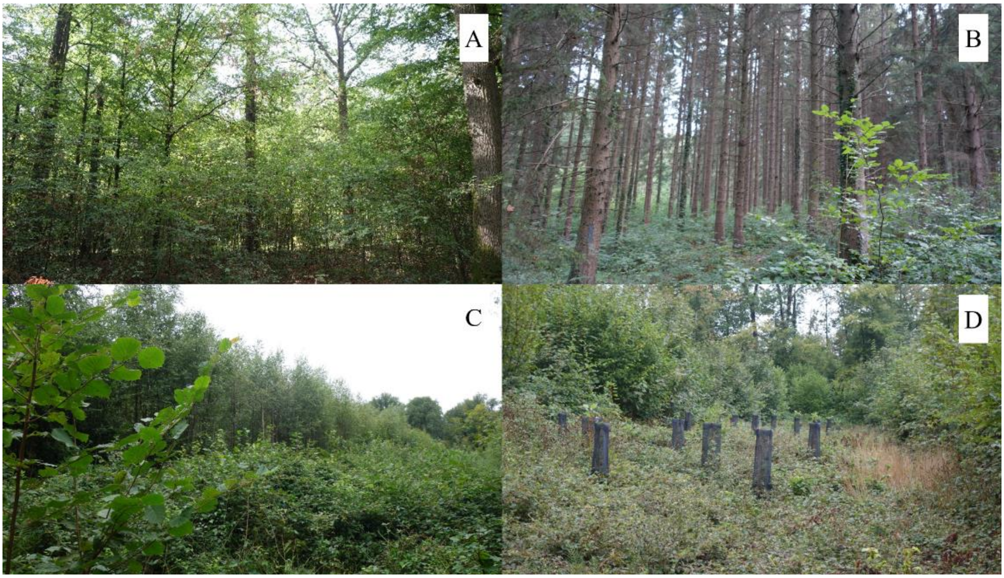

Figure 2-4. Four pictures illustrating the forest stands and their management in the municipal forest of Sivry-Rance: an irregular oak-hornbeam stand (A), a regular spruce stand (B), the natural regeneration (C) and the small enrichment planting (D).

2.4 Nature conservation and restoration

Most of the forest is an old-growth forest (83% of the forest area) and is part of the Natura 2000 network (95%). These natural forest habitats have a high biodiversity with typical forest species, some of which are pretty rare (e.g. black woodpecker, honey buzzard, black stork). The river system increases the biodiversity by providing natural wetland habitats (e.g. alluvial forest, wet meadow, tall forb habitat) alongside with several ponds. Bats are present in several caves. Deadwood and biological interest tree are still poorly represented (0.5/ha deadwood tree and 0.2/ha biological interest tree). (Colson and Baix, 2021)

Because most of the forest is part of the Natura 2000 network, biodiversity restoration actions are taken. Forest ponds are excavated (**Figure 2-5A**) and wetlands are restored (**Figure 2-5B**) as part of the Life BNIP (i.e. project aiming at reaching the Natura 2000 goals and the European Nature Conservation goals). The Galot pond (**Figure 2-5C**) and upstream and downstream sections of the valley bottom of the Ermitage river of this pond are a ZHIB. This pond was brought to light in 2011. The owner would like to give the ZHIB status to another pond, the pond of Ostenne (**Figure 2-5D**). (Colson and Baix, 2021)

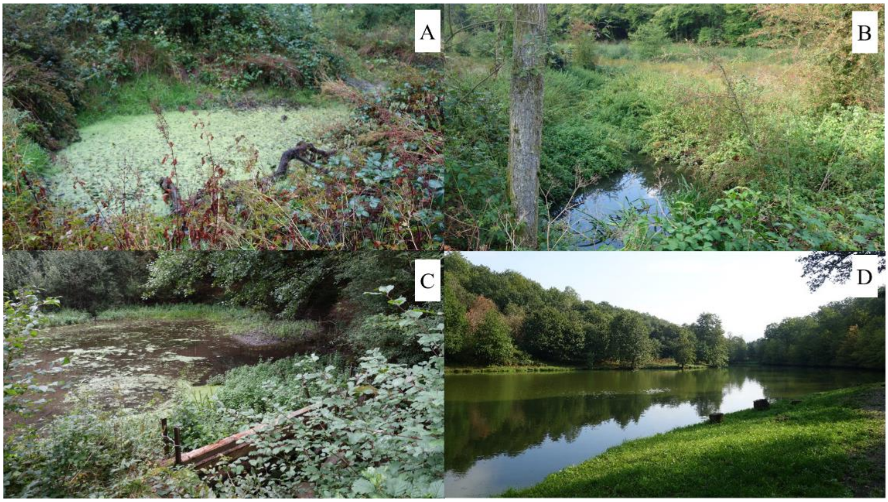

Figure 2-5. Four pictures illustrating the nature conservation and restoration actions of the municipal forest of Sivry-Rance: a forest pond (A), a wetland under restoration (B), the Galot pond (C) and the pond of Ostenne (D).

2.5 Recreation activities

This forest is socially important for the local community for the different activities it offers (e.g. walking, biking, mushrooms picking, fishing, hunting). Every year, 60 to 80 firewood lots (±15 cubic meters for a lot) are sold to the inhabitants (**Figure 2-6A**). Since 2011, mushrooms picking has been regulated to answer the over-harvesting by organised groups. Mushroom picking is now restricted to the inhabitants who have a picking permit. Two local fishing associations (Gaule Chevrotine and Gaule Rançoise) share the fishing rights on the three municipal fishing ponds (**Figure 2-6B**). (Colson and Baix, 2021)

For several years, the municipality of Sivry-Rance has developed the tourism by promoting its natural and cultural heritage and by building tourism infrastructures (190 km of marked routes in the Sivry-Rance region, 6 equestrian paths, 1 bivouac area, 1 RAVeL, educational panels, benches and picnic tables) (**Figure 2-6C**). This well-developed recreation infrastructures is regularly maintained. (Colson and Baix, 2021)

The forest has a good game habitat quality thanks to the continuous cover forestry (i.e. irregular mixed stands and natural regeneration combined with small planting enrichments improve game habitat quality), the maintenance of the grass strips as well as the river system and the ponds. The populations of the roe deer and the wild boar are well regulated by the hunters. The forest is divided into sixteen hunting areas leased by the municipality of Sivry-Rance to the hunters with a nine-year contract. This contract specifies that the individual protection of the tree plants must be met by the hunters. The hunting activities are announced in advance on the walking paths in the forest (**Figure 2-6D**) and on the municipal website. (Colson and Baix, 2021)

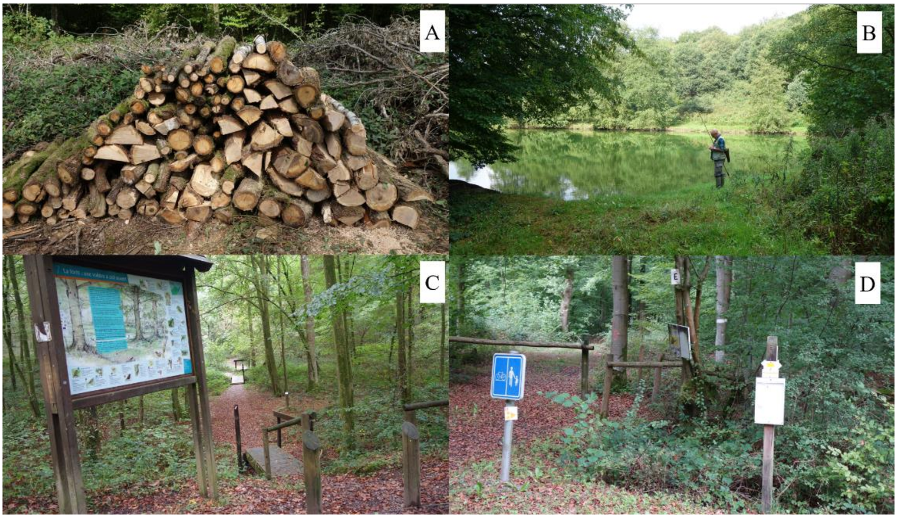

Figure 2-6. Four pictures illustrating the recreation activities in the municipal forest of Sivry-Rance: firewood harvesting by inhabitants (A), a fisher (B), a walking path with an educational panel (C) and a walking path with information on the hunting dates (D).

2.6 Health state of the forest

Several health issues affect various wood species of the municipal forest of Sivry-Rance. First, the oak dieback has been more and more frequent in the last few decades and is caused by a combination of numerous factors: climate change, pests, management such as soil compaction or site unsuitability. The ashes are decimated by chalara caused by the fungus, *Hymenoscyphus fraxineus* (T. K.) B., Q., H. Since the summer 2017, a worrying hornbeam dieback has been observed without knowing the cause. The recent and successive hot and dry summers (2017, 2018, 2019, 2020, 2022) have caused numerous diebacks affecting various wood species, especially on the southern slopes and the superficial soils (**Figure 2-7A**). Those climate conditions alongside with the weakening of the trees were beneficial to some pests such as the *Ips typographus* L. which decimated spruce stands. Storms, aggravated by climate change, are responsible for increasing falling trees (**Figure 2-7B**). (Colson and Baix, 2021)

Figure 2-7. Two pictures illustrating the health state of the municipal forest of Sivry-Rance: dieback due to the several consecutive dry summers (A) and a fallen tree (B).

2.7 Why the municipal forest of Sivry-Rance?

First, we chose to study the forests because they are currently facing increasing known and unknown threats caused by human activities (e.g. climate change, novel pests and diseases due the increase in international trade) (Millar et al., 2007; Rist and Moen, 2013). On the other hand, the demand increases for the numerous ES the forests provide (e.g. wood, recreation, pest control, water purification, climate regulation) (Aerts and Honnay, 2011; Thom and Seidl, 2016). To answer these unprecedented biological, political, social and climate challenges (Messier et al., 2015), novel tools and approaches such as the Navigate framework are needed to ensure that forests still provide the ES we need in the future (Rist and Moen, 2013)

We selected the municipal forest of Sivry-Rance because it is a good example of a multifunctional forest with a diversity of stakeholders coping with multiple pressures.

Furthermore, the timing was perfect as its forest management plan started to be reviewed by the DNF. The DNF wanted to go further in the analysis of the social-cultural aspects that are generally poorly studied compared to the economic and ecological functions of the forest. The municipality of Sivry-Rance was also interested in engaging more the stakeholders in the forest management and in better understanding their uses of the forest.

3. Review of existing information

To understand the municipal forest of Sivry-Rance, its drivers, dynamics, interactions and scales, a review of scientific and grey literature was performed.

First, we reviewed scientific literature to have broad information on forests, their drivers and dynamics (Alderweireld et al., 2015; Attiwill, 1994; Blanco et al., 2017; FAO, 2018; Landsberg and Waring, 2014; Messier et al., 2013; Millar and Stephenson, 2015; Puettmann et al., 2009b; Seidl et al., 2013; Swanson and Chapin, 2009; Thom and Seidl, 2016).

Then, we focused on the context of the municipal forest of Sivry-Rance by reviewing its forest management plan (Colson and Baix, 2021) that provides a comprehensive analysis of this forest.

These two sources of information were not enough to fully understand the municipal forest of Sivry-Rance. They were supplemented by the stakeholder analysis (see Chapter 2 4.1 Stakeholder analysis), the first participatory workshop (see Chapter 2 4.2.1. First participatory workshop: the future of the municipal forest of Sivry-Rance) and field measurements (the surveys of the forest users (see Chapter 2 4.3. Surveys of the forest users) and the cameras traps to assess the forest attendance (see Chapter 2 6.3. Forest attendance assessment).

4. Stakeholder engagement

Stakeholder engagement is the active involvement and participation of stakeholders in some aspects of a research project. Four levels of engagement can be defined from the lowest to the highest one: (1) inform (i.e. share information about the research project), (2) consult (i.e. ask for opinions or information), (3) involve (i.e. the stakeholders provide resources or data), and (4) collaborate (i.e. stakeholders are effectively partners with the research team). (Durham et al., 2014)

The stakeholder engagement, in our research, aimed at:

- Understanding the stakeholders, the relationships between them and with the forest, their uses of the forest, their needs and expectations;
- Building a forest management plan of the municipal forest of Sivry-Rance consistent with the needs and expectations of the stakeholders;
- Opening the mind of the stakeholders to the constraints of the forest management (e.g. legislation, the reality on the ground), to the needs and expectations of the other stakeholders and the impacts of a management action on the ES and resilience.

Several participatory methods (i.e. stakeholder analysis, participatory workshop, survey, information session), with different levels of engagement, were used to engage with the stakeholders throughout the research project (**Figure 2-8**). Each of them is detailed in the next sections.

Figure 2-8. The different participatory methods used in the stakeholder engagement of the municipal forest of Sivry-Rance on a timeline and with their corresponding level of engagement. The stakeholder analysis was used to define the stakeholders to be invited to the two participatory workshops.

To develop these participatory methods, we used several sources of information: (1) scientific literature, (2) experts to discuss our methodology and have their advice, and (3) tests on the ground to make them better suited to the stakeholders (**Table 2-3**).

Table 2-3. Different sources of information used to develop the participatory methods.

Thematic	Scientific literature	Experts	Test
Overview of stakeholder engagement and methods	Pretty et al. 1995, Kerkhof 2001, Walker et al. 2002, Narayanasam 2009, Boedhihartono 2012, Durham et al. 2014, Ratner et al. 2014	Team on Nature and Society of INBO	/
Stakeholder analysis	Reed et al. 2009, Lovens et al. 2014, Raum 2018	Team on Nature and Society of INBO	Tested with the first interviewees
1st participatory workshop	Bohnet and Smith, 2007, Carlsen et al., 2013, Oikonomou et al., 2011, Oteros-Rozas et al., 2015, Palomo et al., 2011; Plieninger et al., 2013, Ruiz-Mallén et al., 2015	GTSE[2], professor specialized in stakeholder engagement at GxABT, DNF, municipality of Sivry-Rance	/
2nd participatory workshop	Kodikara et al. 2010, Seidl and Lexer 2013, Fontana et al. 2013, Saarikoski et al. 2016, 2019, Diaz-Balteiro et al. 2017	DNF, municipality of Sivry-Rance	Two trials with the general public
Surveys	/	Agreta project[3], professor specialized in surveys at GxABT	Tested with the first interviewees
Public information session	/	DNF, municipality of Sivry-Rance	Tested with the municipality and DNF

In each step of the stakeholder engagement, participant observation was undertaken to be as closed as possible to the stakeholders to understand and analyse their expectations and needs (Dupont et al., 2015). The interns[4] and I interacted with the stakeholders according to our predefined interviewer (in the stakeholder analysis and the surveys) or facilitator (in the participatory workshops) role while observing the situation (Arnould, 2021).

[2] This group aims at sharing information and initiating joint projects on ES at GxABT, ULiège.

[3] The Agreta project aims at increasing attractiveness of the cross-border Ardenne region.

[4] The list of interns who took part in the different participatory methods is given in each corresponding participatory method.

4.1 Stakeholder analysis

The general definition of a stakeholder is: any person or group who influences or is influenced by the process or result of any kind of project or decision (Durham et al., 2014; Lovens et al., 2014). In the context of our research, a stakeholder is any group or individual who can affect or is affected by the ES provided now or in the future by the municipal forest of Sivry-Rance (Hein et al., 2006). A stakeholder analysis is a process that identifies individuals, groups or organization who are affected by or can affect the project and that prioritises these individuals and groups for involvement in the decision-making process (Reed et al., 2009).

The aim of our stakeholder analysis was to identify the stakeholders and who involve in which part of the participatory process. A second goal was to understand them (interest, influence), the relationships between them and with the ES.

From the OpenNESS manual on stakeholder analysis for environmental decision-making at local level (Lovens et al., 2014), the ecosystem services stakeholder matrix tool was selected because it is a reliable quite simple method linking directly the stakeholders to the ES depending on their types of interactions with the ES (see **Table 2-4** for a comparative analysis of different stakeholder analysis tools). This method perfectly answers our goal.

Table 2-4. Comparative analysis of the six stakeholder analysis tools provided in Lovens et al. (2014).

Stakeholder analysis tool	**Description**	**Relevance**	**Resources**	**Robustness**
Ecosystem services stakeholder matrix	Each stakeholder is linked to the ES he/she owns, manages, benefits from, is negatively impact by or influences using a combination of open interviews and a structured card game	Highly relevant: this method helps getting a better view on the stakeholders involved in a changing supply or use of ES and identifies a wide range of stakeholders and their relationships	Low resources: low-cost (i.e. 2-5 days, 1 person), low-tech (i.e. little equipment required and easily accessible)	Highly robust: the information is collected from different sources (i.e. interviews with different stakeholders and literature review)
Interest-Power matrix	The stakeholders are located on a matrix according to their relative interest and influence on a certain environmental issue based on information collected from interviews, questionnaires or focus groups	Moderately relevant: this method helps understanding the viewpoint and motivations related to ES of the stakeholders, predicting their possible reactions to contextual change, and providing information on which stakeholders must be handled with care and who should be empowered	High resources: high cost (i.e. 3-6 months, several persons), low-tech (i.e. little equipment required and easily accessible)	Highly robust: the information is collected from different sources (i.e. interviews, focus groups or questionnaires and literature review) in an iterative way
Interest-Power analysis	Assessment of the attitude and influence of the stakeholders to understand how they might interact with our intended goals	Relatively irrelevant: this method aims at identifying the stakeholders and underlying mechanisms that might resist the project and the amount of influence these opponents might exert	Low resources: low-cost (i.e. several hours, several person), low-tech (i.e. little equipment required and easily accessible)	Moderately robust: the information is gathered from 4 to 8 persons who cover various knowledge fields

Business Model Canvas	Tool to get a clear image of the business potential and societal relevance of our activities	Irrelevant: this method aims at identifying the commercial value of an activity and highlighting the possible partnerships, allies, and potential opponents	Low resources: low-cost (i.e. 4 days, several person), low-tech (i.e. little equipment required and easily accessible)	Moderately robust: the information is gathered from about 8 persons of different ages, representing multiple areas of expertise and various cultural backgrounds
Net-Map – Influence Mapping of Social Networks	Interview-based mapping tool that helps understanding, discussing, evaluating and improving situations in which many different stakeholders, with diverse interests and often conflicting goals	Moderately relevant: this method aims at ensuring key groups are not marginalised, identifying conflict between stakeholders, and selecting representatives	Low resources: low-cost (i.e. 3-5 days, several persons), low-tech (i.e. little equipment required and easily accessible)	Highly robust: the information is collected from different sources (i.e. interviews or focus groups and literature review) in an iterative way
Stakeholder map – Visualizing linkage between stakeholders	Descriptive-analytic tool to discover and visualize the relationship among the stakeholders	Moderately relevant: This method provides a graphical representation of the stakeholders relationships and their interests	Medium resources: medium cost (i.e. 13-15 days, 1 person), low-tech (i.e. little equipment required and easily accessible)	Highly robust: the information is collected from different sources (i.e. interviews and literature review)

The 'ecosystem services stakeholder matrix' tool, developed by Lovens et al. (2014), links the ES to the concerned stakeholders considering five categories of interactions: (1) owner, (2) manager, (3) user, (4) those who are hampered by ES, and (5) those who influence the rules of the delivery and use of ES. We did open interviews, in March and April 2019, using a structured card game to depict the different ES with ten key informants, persons with a specific knowledge on the focus area with a helicopter view (i.e. people who receive many different perceptions and thus have an oversight on what's going on in certain groups), with different expertise and opinions (e.g. forest manager, owner, local organization). To minimize the bias, the same interviewer undertook the ten interviews, using a common base of questionnaire (e.g. same explanation of the context of the questionnaire, same introductory questions, same structured card came).

From each of these interviews, we obtained an incomplete matrix based of their partial knowledge of the stakeholders (**Figure 2-9**). Each interview was adapted from the incomplete matrix of the previous interviewees to discuss in more details cells for which we got little information from the previous interviews (to have a relevant information in a cell, three different sources is a minimum) or cells with contradictory information. We then compiled these ten incomplete matrices to have a fuller picture of the stakeholders. We took advantage of these interviews to ask them if they had data that could be useful to assess the ES. Finally, a few empty cells remained while we knew from the literature review that stakeholders were concerned by these cells. They were thus fulfilled based on the literature review.

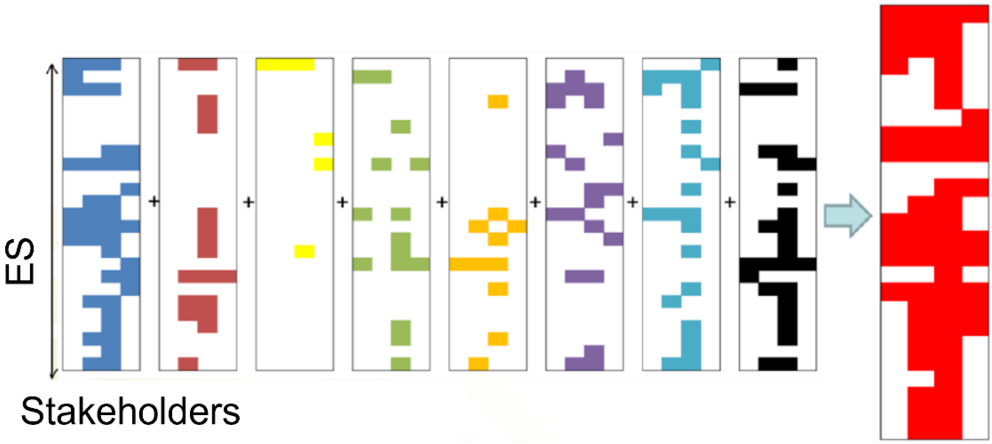

Figure 2-9. Visual representation of the incomplete matrix of each stakeholder and its compilation, adapted from Lovens et al. (2014).

4.2 Participatory workshops

Two participatory workshops were organized with the stakeholders identified in the stakeholder analysis. From the list of stakeholders identified during the stakeholder analysis, the municipality of Sivry-Rance invited personally persons representing each stakeholder.

These two participatory workshops aimed at collecting the expectations (first participatory workshop) and the needs (second participatory workshop) of the stakeholders. In a sense, they were independent from each other: the results of the first participatory workshop did not serve as a starting point of the second participatory workshop.

4.2.1 First participatory workshop: the future of the municipal forest of Sivry-Rance

The aim of this first participatory workshop was twofold:

- To identify the stakes of the stakeholders concerning the future of the municipal forest of Sivry-Rance (i.e. individual expectations);
- To co-build their ideal future forest (i.e. collective expectations).

In view of the values assessment typology of IPBES (2022) (see Chapter 1 2.3.1 Value pluralism), we obtained the individual and collective broad and specific values of the stakeholders.

This workshop used the method of participative scenario planning defined by Oteros-Rozas et al. (2015) as a process in which stakeholders, frequently guided by researchers, are engaged in a highly collaborative process and develop a leadership role within some or all stages of a scenario development process to investigate alternative futures. To design this workshop, we took inspiration from the methods developed in the literature on participative scenario planning. We did not follow one specific method; we combined and adapted some parts of the different methods proposed in the literature to our purpose (**Table 2-5**).

Table 2-5. Methods from which we took inspiration to design the first participatory workshop from the literature on participative scenario planning.

Reference	Method from which we took inspiration
Bohnet and Smith 2007	As Bohnet and Smith (2007), we asked the participants about the key issues or challenges that need to be addressed in the future as well as to provide their views on how their priorities could be effectively achieved. We took inspiration from Bohnet and Smith (2007) to design the groups: (a) ‘heterogenous’ groups to widen the exposure of viewpoints held by participants and provided opportunities for learning and capacity building that may not have arisen in more homogeneous groups, and (b) relatively small (between five and eight participants) to promote genuine input from each individual.
Palomo et al. 2011	We used some of the steps designed by Palomo et al. (2011): identification and prioritization of stakeholders (step 1), collection of information about those aspects of the system that were important to stakeholders (step 2), developing a set of scenarios (step 4), and proposing management strategies to achieve a desirable future (step 6). We also made ‘heterogeneous’ groups as Palomo et al. (2011).
Oikonomou et al., 2011	As Oikonomou et al. (2011), we asked the participants their wants and expectations and to propose potential actions.
Plieninger et al. 2013	We used some of the steps designed by Plieninger et al. (2013): identifying the driving forces (step a), building narratives about potential alternative futures (step b), discussing scenario impacts (step d), and (e) developing management strategies (step e). As Plieninger et al. (2013), the workshop was prestructured regarding their form and central aims, but remained completely open for the participants regarding content (no scenarios or drivers were predetermined by the researchers).
Carlsen et al. 2013	As Carlsen et al. (2013), the scenarios were built on the stakeholders’ own concerns, which make the scenarios relevant to the end-users and increase the likelihood of the scenarios actually being used. The three steps of the utilisation of the scenarios of Carlsen et al. (2013) were followed: identify future challenges (step a), identify options (step b), and assess the options (step c).
Ruiz-Mallén et al. 2015	As Ruiz-Mallén et al. (2015), we guided the stakeholders to think about how drivers would potentially impact the SES, according to their experience and knowledge of the area. We also asked participants to select the most preferred scenario.
Oteros-Rozas et al. 2015	We used some of tools described by Oteros-Rozas in their review: group discussions in small groups, individual reflections, drawings, and capturing ideas on post-its.

The workshop was held on Wednesday, the 12th of June 2019, from 7:15 pm to 10:30 pm, in the multifunctional room of the "Espace Nature de la Botte du Hainaut" asbl.

The facilitating team was composed of four persons, each having their specific role. Laura Maebe introduced the different parts of the workshop and guided the participants throughout the workshop. Alexis Gerard (teaching assistant at GxABT) took pictures, recorded the workshop, and helped with the practicalities (e.g. welcoming the participants, distributing the materials). Nolwenn Ogor and Ludivine Loizet (two interns on the doctoral research) managed the timing, took pictures, took notes on the content of the workshop and on the social processes (e.g. how the participants interact, behave), and helped with the practicalities. To limit the bias created by the different facilitators, a preliminary planning meeting was organized to precisely explain the conduct of the workshop and the role of each person. This information was transcribed in a document provided to each facilitator during the workshop. Finally, the questions of the participants were primarily answered by one person (i.e. Laura Maebe).

The municipality of Sivry-Rance helped with the practical organization (e.g. room booking, catering), introduced and concluded the workshop. The DNF presented the forest management plan.

Forty-five participants attended the workshop (from the 109 invitations sent) and thirty-nine of them stayed the entire workshop. They represented a broad range of stakeholders with a high number of hunters and recreation users/associations (**Table 2-6**). The men represented a small majority of the participants (about 60%). Old people held the majority.

Table 2-6. The different stakeholders who attended a part of the first participatory workshop and the entire workshop. For each participant, his/her main stakeholder type was identified.

	Number of participants	
Stakeholder	**Who attended a part of the workshop**	**Who attended the entire workshop**
Hunter	13	9
Recreation user	6	6
DNF	5	4
Municipality	5	5
Cultural center	3	3
Recreation association	3	3
Educational organization	2	2
Inhabitant	2	2
Farmer	1	1
Fisher	1	0
Historian	1	1
Local citizen	1	1
Rural development association	1	1
Touristic association	1	1
Total	**45**	**39**

After welcoming the participants, the workshop was introduced by the municipality of Sivry-Rance by explaining the history of the forest management, the actual management based on multifunctionality, the context of the forest management plan, and the different stakeholders invited to this workshop. Then, after thanking the participants for being there, we gave some practical information by presenting the facilitating team and asking permission to take pictures and to record the workshop.

Then, the first part of the workshop (i.e. individual expectations) was introduced. We asked the participants to write down, on two post-it notes, their main wish and fear concerning the future of the municipal forest of Sivry-Rance (**Figure 2-10A**). Each participant, in turn, explained his/her main wish and fear to the others and his/her post-it notes were grouped by thematic on two panels (one for the wishes and one for the fears).

The second part of the workshop (i.e. the co-building of their ideal future forest) began by presenting the background of the workshop (i.e. the doctoral research and the forest management plan), by giving the guidelines of their participation (e.g. collective exercise, everyone wears multiple hats, consultative workshop) and the instructions. First, we invited them to reflect individually on their dream future forest (in 65 years) and to write it down or draw it down. Then, the participants were grouped into six 'heterogenous' groups (i.e. a group having multiple types of stakeholders such as a hunter, a walker, a manager, the owner, an inhabitant, and a representative of a local association) of about six persons. These 'heterogenous groups' were made to encourage the participants to find a consensus between their various expectations (i.e. collective expectations). We asked each person of the group to briefly present their dream forest to the others to start the discussion. After, they discussed together to reach a common ideal future forest based on the consent principle (i.e. a decision is collectively taken when nobody has a fundamental objection) (**Figure 2-10B**). Next, we invited each group to reflect upon the drivers that could impact their future forest and which action(s) could be taken to answer these drivers. Finally, each group presented their ideal future forest with the drivers and actions to the other groups. We suggested them to vote for their preferred ideal future forest with a sticker.

The workshop was concluded by thanking the participants for their active participation, asking them for feedback on the workshop and by offering them a drink to close the evening.

Figure 2-10. Two pictures illustrating the first participatory workshop: the individual reflection on their main wish and fear concerning the future of the municipal forest of Sivry-Rance (A) and the collective discussion on their ideal future forest (B).

4.2.2 Second participatory workshop: the needs of the stakeholders

The aim of this second participatory workshop was to understand the needs of the stakeholders regarding the different ES provided by the municipal forest of Sivry-Rance. We collected the specific values from the IPBES values assessment typology with a focus on the instrumental values because we used the concept of ES.

To design this workshop, we took inspiration from the methods developed in the literature on the elicitation of stakeholders' preferences. We did not follow one specific method; we combined and adapted some parts of the different methods in the literature to our purpose (**Table 2-7**). For the weighting of the ES, we also took inspiration from the question on the socio-cultural values of the forest users' surveys (they had 100 points to distribute among the thirteen socio-cultural values, see Chapter 2 4.3.1 Content of the surveys) to force the stakeholders to make choices between the different ES.

Table 2-7. Methods from which we took inspiration to design the second participatory workshop from the literature on the elicitation of stakeholders' preferences.

Reference	**Method from which we took inspiration**
Seidl and Lexer, 2013	As Seidl and Lexer (2013), we accounted for uncertainty in future social demands by means of societal preference scenarios.
Saarikoski et al., 2016	In their review, Saarikoski et al. (2016) advised to illustrate the pros and cons of alternative courses of action from the perspective of stakeholders with similar values and preference structures (Munda, 2008, 2004). This is why we did ‘homogenous groups’ and compared their socio-cultural preferences.
Fontana et al., 2013	Because we had a lot of indicators, we also asked the stakeholders to weight the ES from a given list of ES as Fontana et al. (2013).
Saarikoski et al., 2019	As Saariskoski et al. (2019), we first asked the stakeholders to give their individual preferences and then, to discuss these preferences by group.
Diaz-Balteiro et al., 2017	As Diaz-Balteiro et al. (2017), we asked the stakeholders their acceptable values starting from the basis that not all the indicators can reach an optimal value for all forest management alternatives and climate change scenarios.
Kodikara et al., 2010	As Kodikara et al. (2010) stated there is hardly any literature on eliciting the preference thresholds and deriving preference functions for use in the PROMETHEE method. From their detailed description of their method, we were able to adapt it to our purpose.

The workshop was held on Thursday, the 16th of July 2020, from 7 pm to 10:30 pm, in the room of the cultural center[5] of Sivry-Rance.

The facilitating team was composed of three persons, each having their specific role. Laura Maebe introduced the different parts of the workshop and guided the participants throughout the workshop. Gwendoline Gérard (one intern on the doctoral research) facilitated the introductory game, took notes on the content of the workshop, and on the social processes and helped with the practicalities. Ludovic Pereira (another intern on the doctoral research) managed the timing, took pictures, took notes on the content of the workshop and on the social processes, and helped with the practicalities. The same measures as the first participatory workshop were taken to limit the bias of having different facilitators facilitating the workshop.

The municipality of Sivry-Rance helped with the practical organization (e.g. room booking, catering), introduced and concluded the workshop. The DNF presented the forest management plan.

[5] Cultural center aims at promoting culture in a local community by organizing shows, exhibitions, conferences, etc.

Nineteen participants attended the workshop (from the 109 invitations sent) and fifteen of them stayed the entire workshop. Seventeen of them also attended the first participatory workshop. They represented a broad range of stakeholders (**Table 2-8**). The men represented a small majority of the participants (about 60%). Old people held the majority.

Table 2-8. The different stakeholders who attended a part of the second participatory workshop and the entire workshop. For each participant, his/her main stakeholder type was identified.

	Number of participants	
Stakeholder	**Who attended a part of the workshop**	**Who attended the entire workshop**
Recreation assocation	3	2
Municipality	3	2
Hunter	3	3
DNF	2	2
Educational organization	1	1
Touristic association	1	1
Farmer	1	1
Inhabitant harvesting firewood	1	1
Fisher	1	1
Local citizen	1	1
Recreation user	1	0
Cultural center	1	0
Total	**19**	**15**

In the invitation to the workshop, the stakeholders were asked to give their opinion (i.e. Do they want to maximize, minimize or keep the ES at the same level?) and to weight the ES (i.e. they had 100 points to be allocated to the different ES depending on the importance they give to each ES) on a table gathering the ES assessed in the municipal forest of Sivry-Rance (see Chapter 2 6.1 ES selection which explains how the ES were selected) (Annex 1). A predefined list of ES was given to the stakeholders to gather the evaluation parameters of the assessed ES, needed in the PROMETHEE (see Chapter 2 7.2 Application of the MCA on the municipal forest of Sivry-Rance which explains how the results of the second participatory workshop were translated into the evaluation parameters). The order of the ES in the table was randomized to limit the impacts of this order on their weighting. From these tables, four 'homogenous' groups were formed, before the workshop, by manually regrouping together the persons who had similar opinions and weighting. We made 'homogenous' groups to gather distinct needs of different groups of stakeholders. We considered forming these groups with statistical classification methods to have a more rigorous and objective result. However, it was not practically feasible because half of the participants did not fill the table before the workshop, and we needed a fast method (i.e. the manual grouping) to review the groups during the workshop.

After welcoming the participants, the workshop was introduced by the municipality of Sivry-Rance by thanking the organizers of the workshop, the DNF for their excellent work on the forest management plan and the participants for being there, and by reminding them the health measures in the fight of the covid-19 pandemy. Then, we presented the facilitating team, we asked permission to take pictures, we explained how their anonymity would be maintained and the agenda of the evening. After, the DNF presented the forest management (i.e. how it is done and where we stand in the process). Finally, we presented the concept of ES and how it is assessed in the municipal forest of Sivry-Rance (**Figure 2-11A**). The results of the first participatory workshop were not presented because they were not needed to carry out this second participatory workshop.

We did a break during which we invited the participants, who did not fill the table in the invitation, to give their opinion and weighting of the ES. We reviewed the previously formed groups to create four 'homogenous' groups of about 4 persons.

To initiate the participatory process and show that everyone wears several hats, we did an introductory game. We asked them a dozen of questions (e.g. Who is going at least once week in the municipal forest of Sivry-Rance?, Who is a parent?, Who feels concerned by the future of the municipal forest of Sivry-Rance?) and they had to raise their hand when they would give a positive answer. Then, the guidelines of their participation (e.g. listen to everyone and speak freely, consultative workshop) were given.

After giving the instructions, the participants were asked to join their group to fill together the table of ES. They had to fill four columns: (1) their opinion, (2) their weighting, (3) their acceptable level of the ES (i.e. the minimal level that the ES should have), and (4) the satisfactory level of the ES (i.e. the level at which they feel satisfied by ES) (**Figure 2-11B**) (Annex 2). Then, we asked them to answer three questions in writing:

1. How to perpetuate the consultative process?
2. How satisfied are you with the group table?
3. Their socio-cultural values (they had to give 100 points to 13 socio-cultural values of the forest depending how important each value was to them, see Annex 3 for the question).

Finally, each group presented to the others their table and some propositions to perpetuate the consultative process.

Finally, a satisfaction survey (e.g. What did you like the most?; How satisfied are you by the different activities? How was the timing of the workshop?) was filled by the participants. We concluded the workshop and thanked them for their active participation. We closed the evening by offering a drink.

Figure 2-11. Three pictures illustrating the second participatory workshop: the introduction of the workshop (A) and the collective discussion to fill the table of their needs and expectations regarding the ES (two pictures) (B).

4.3 Surveys of the forest users

To understand the different cultural ES provided by the municipal forest of Sivry-Rance and their users, four surveys were conducted from 2019 to 2021. Each survey focused on one specific forest user type:

- The inhabitants of the municipality of Sivry-Rance who harvest firewood;
- The hunters of the municipal forest of Sivry-Rance;
- The fishers of the municipal ponds;
- The other recreation users of the municipal forest of Sivry-Rance who do not pay for their recreation activity (e.g. hiker, biker, horse rider, mushroom picker, jogger, naturalist, artist).

We focused on these four forest user types because we had very little or no knowledge on the users of the cultural ES. We differentiated the users that use freely the forest (i.e. other recreation users) from the ones that must pay for their recreation activity to adapt the questions (e.g. how much they pay for their recreation activity?). We further distinguished the users that must pay for their recreation activity depending on the activity they carry out (i.e. wood harvesting, hunting and fishing are the three paid activities[6] in the municipal forest of Sivry-Rance) to account for the particularities of each activity in the survey. By differentiating the different forest user types, we were able to see if the motivations, expectations, and values varied from one forest user type to another.

[6] By paid activities we mean the activities for which there is always a fee to pay to use the corresponding cultural ES (e.g. even if the joggers must pay for some organized activities (e.g. pedestrian race), they can run freely in the forest otherwise while the hunters must always pay for hunting).

4.3.1 Content of the surveys

Most of the questions were shared by the four surveys. The other questions were specific to the forest user type.

The common questions of the four surveys were adapted from two surveys of the Agreta project: (1) survey on the actions and expectations of the visitors regarding the natural areas of the Ardennes region (Breyne et al., 2020a), and (2) survey on the actions and expectations of the residents, the tourists and potential tourists regarding the natural areas of the Ardennes regions (Breyne et al., 2020b). We first selected the relevant questions (i.e. those best suited to understand the cultural ES and the needs and expectations of the forest users while keeping a reasonable length of the survey). Then, we adapted the questions and answers wording. **Table 2-9** synthetizes the common questions of the four surveys by thematic.

Table 2-9. The topic of the questions of the common questions of the four surveys (i.e. inhabitants harvesting firewood, hunters, fishers and recreation users) by thematic group. We indicated which Agreta survey was adapted for each thematic group.

Thematic	**Topic of the questions**	**Survey of the Agreta project**
Introduction	-Presentation of the survey -Protection of personal data	Both surveys
TCM	-Number of visits a year -Composition of the visitor group -Duration of the visit -Home and accommodation (if any) -Distance between the visited place and their home/accommodation -Means of transport	Both surveys
Activities and experiences	-Reason(s) of the visit -Activities in the natural areas -Cultural activities -What they like and dislike -Socio-cultural values -Preferences for tourism infrastructures[7]	Both surveys
DCE	-Features of the forest	Residents, tourists and potential tourists
Contingent valuation	-WTP to improve the cultural ES	Visitors
Respondent profile	-Gender -Marital status -Age -Living environment -Professional situation	Both surveys

[7] The hunters survey was long enough, so this group of questions was removed because it was the least relevant in this survey.

After an introduction of the survey (i.e. presentation of the survey and information on the protection of personal data), the first group of questions focused on the timing and travel of the visit (e.g. frequency of visits, duration of the visit) to gather the information necessary for the TCM. This method is a model of the demand for the services of a recreational site based on the cost a visitor must incur to overcome the distance (Haab and McConnell, 2002). So, the individual price for recreation at the site is her/his trip cost of reaching the site and her/his WTP is the number of trips they make annually to the site multiplied by her/his trip cost (Parsons, 2003).

The second group of questions aimed at understanding the different activities done by the respondents, their experiences of the visit (e.g. reasons of the visit, what they like and dislike) and their preferences (i.e. socio-cultural values (Annex 3) and preferences for tourism infrastructures (Annex 4)).

In the third group of questions, the preferences for the visual forest structural characteristics were elicited thanks to a DCE. Hoyos (2010) defines DCE as “several choice sets, each containing a set of mutually exclusive hypothetical alternatives between which respondents are asked to choose their preferred one”. Alternatives are defined by a set of attributes, each attribute taking one or more levels (Hoyos, 2010). Individuals' choices imply implicit trade-offs between the levels of the attributes in the different alternatives included in the choice set (Hoyos, 2010). In our DCE, five attributes (i.e. forest structural characteristics) were selected:

1. Tree species (i.e. softwood vs hardwood);
2. Age structure (i.e. young tree, middle age tree and old tree);
3. Variation in the tree height (i.e. regular or irregular stand);
4. Presence of deadwood (i.e. lack or presence of deadwood);
5. Forest cover (i.e. continuous forest, forest with clear-felling and forest with natural open areas). (Annex 5)

The choice was limited to five attributes because of the restrictions on the number of variables used within DCE (Breyne, 2021). They represent the five more relevant attributes related to the degree of naturalness of a forest (see Breyne (2021, pp. 92–94) for a more detailed justification of the choice of each attribute). An attribute of distance was also considered to add an economic dimension to the DCE (i.e. if the respondent is willing to go further, he/she is willing to pay more on his/her travel). The distance was defined as a proportion of the distance travelled by the respondent to go to the site. The attribute distance had six levels: 0.5; 0.75; 1; 1.25; 1.75 and 2. The different levels of the six attributes were mixed in twenty-four choice sets. Each respondent had to choose between two alternatives or neither alternative (i.e. three options of choice) of six choice sets, randomly attributed to each respondent.

The fourth group of questions concerned the WTP to improve the corresponding cultural ES used by the respondent (e.g. to improve the hunting infrastructures for the hunter survey) (i.e. contingent valuation). Contingent valuation is an economic assessment method which consists of asking individuals how much they are hypothetically willing to pay for a scenario (e.g. a good, a service or a decision)

(Abildtrup et al., 2021; Johnston et al., 2017). We focused on the cultural ES because we wanted to assess this category of ES for which we had very little or no information and that are more difficult to grasp. In the contingent valuation question, the scenario was first described (e.g. To improve the local economy in line with the natural areas, the municipality of Sivry-Rance wants to develop the hunting offer by diversifying the hunting infrastructures). Then, the way they would pay if the scenario would have happened was explained (e.g. for the hunters, it was an annual municipal taxes charged in addition to the day hunting price). Two price ranges (**Figure 2-12**) were tested to see if the price range influenced the amount given by the respondent. One of the two prices ranges was randomly proposed to each respondent.

Figure 2-12. The two price ranges used in the contingent valuation to test the influence of the price range on the amount given by the respondents.

The final group of questions gathered the socio-economic characteristics of the respondents (e.g. gender, age, profession, marital status) to test the influence of these characteristics on the answers of the other questions.

Because the two Agreta surveys were designed for recreation users, specific questions were added to the surveys of the inhabitants harvesting firewood, the hunters and the fishers to understand their activity (**Table 2-10**).

Table 2-10. Specific questions asked to the inhabitants harvesting firewood, the hunters and the fishers about their activity, in their corresponding survey.

Inhabitant harvesting firewood	**Hunter**	**Fisher**
-Firewood harvesting -Home firewood burning -Organization of the working time -Firewood transport -Firewood resale -Reason(s) of firewood harvesting -Purchasing of other firewood than the one from the municipal forest of Sivry-Rance -Dead wood harvesting -Costs of firewood harvesting	-Hunted species -Hunted species sale -Hunting trophy -Hunting weapons -Hunting dogs -Costs of hunting	-Costs of fishing -Organization of the working time -Fish sale

From the surveys, we gathered information on the specific values (e.g. reason(s) of visit, socio-cultural values) and value indicators (e.g. number of visits, costs), depending on the question.

The four surveys were designed in the limesurvey software (i.e. online survey tool) on the INRAe platform. They were exported on two Windows tablets to administer them in the forest without internet connection.

4.3.2 Administration of the surveys

The inhabitants harvesting firewood were personally contacted from a list of contacts provided by the municipality of Sivry-Rance (i.e. the list of all the inhabitants who bought firewood in 2019) and the DNF (i.e. during the interviews of the stakeholder analysis, the contacts of inhabitants harvesting firewood were asked to the four forest officers). Each person was contacted by phone, in June-July 2019 or in February-March 2020, to ask them if they wanted to answer the survey. If yes, we either sent them the survey by email or we met them to ask the questions face to face.

The hunters were also personally contacted from the list of the lessees of the 16 hunting areas (hunting lease from 2019 to 2028) provided by the municipality of Sivry-Rance. Each person was contacted by phone, in autumn 2019, to ask them if they wanted to answer the survey and if they were willing to distribute the survey to the hunters of their hunting lease(s). If yes, we sent them the survey by email. We also met some of them face to face to conduct the survey.

The fishers and the recreation users were directly interviewed in the municipal forest of Sivry-Rance around the municipal ponds or on the trails, in spring-summer 2019, 2020 and 2021. We also took advantage of several events (e.g. Adeps walk[8]) to conduct the survey. Finally, we contacted fisher and recreation associations to ask them to distribute the survey to their members.

The four surveys were in French, the mother language of a large majority of the respondents. For the few respondents having another mother language, the questions were directly translated into their mother language during their interview if the interviewer knew it or in English otherwise.

The surveys were conducted by Laura Maebe and her team of interns (i.e. Nolwenn Ogor and Luidivine Loizet in 2019; Gwendoline Gérard, Ludovic Pereira and Lucie Gleyze in 2020; Julie Satinet and Benjamin Bettonville in 2021). To limit the bias of having different interviewers, each interviewer got acquainted with the questionnaire, prior to the administration of the survey. Moreover, Laura Maebe administrated the questionnaire in front of each interviewer, for the first time and was present for their first administrations of the survey.

[8] Every Sunday and public holiday, some twenty signposted walks are suggested in Wallonia and Brussels regions. They are co-organized by Adeps (i.e. General Administration of Sport) and local partners.

4.3.3 Analysis of the answers of the surveys

All the analyses were adapted from the Agreta project (see Breyne et al. (2020a) and Breyne et al. (2020b) for the descriptive analysis and see Abildtrup et al. (2021) for the TCM, DCE and contingent valuation). They were performed in the R software (version 3.6.3).

4.3.3.1 Descriptive analysis

First, a descriptive analysis was performed by displaying the percentage of respondents for each answer, of each question except the ones concerning the DCE and the contingent valuation. The number of respondents (i.e. P) and the number of answers (i.e. N) were given on each graph (for some questions, the respondents could choose several answers, N>P). The answers of the closed-ended questions were either represented on a pie chart or on a histogram. For the open qualitative questions (i.e. what they like and dislike in their visit of the municipal forest of Sivry-Rance), the answers were grouped into categories. For the open quantitative questions with a limited number of different answers (e.g. number of persons in the car), a histogram representing the percentage of respondents for each answer was made. For the open quantitative questions with many different answers (e.g. distance, number of visits a year), a histogram with fixed intervals (e.g. 1-5, 6-10, etc.), with a bar giving the mean, was made, except for the costs of hunting and fishing. Indeed, in these two questions, the costs of each category of expenditure was asked. The costs of each category was then represented on a violin plot like the socio-cultural values question.

4.3.3.2 TCM

We pooled the answers of the two following thematic groups: (1) TCM and (2) respondent profile of the four surveys. We added a variable “Type of forest users” to differentiate the four surveys.

First, these data were cleaned. We only considered the respondents who answered all the TCM questions. We looked for inconsistent data for the number of visits a year and the travel distance by representing these two variables on a boxplot. We tested the hypothesis of the TCM being the number of visits is inversely proportional to the travel cost by displaying the number of visits according to the travel distance on a plot for each of the four forest users.

Then, the cleaned data were edited for the TCM analysis. The questions with two possible answers were transformed into binomial data (i.e. first answer=1 and second answer=0). For two closed-ended questions (i.e. the composition of the visitor group and the profession), the different possible answers were grouped into two categories to have binomial data. For the composition of the visitor group, 0 refers to a single visitor and 1 to a group of two or more visitors (e.g. family, friends). For the profession, 1 refers to executive manager, scientific and high-skilled profession or intermediate salaried profession and 0 to any other. The middle of the quantitative class was taken for the age (for the open classes: <18 years old=15 and >70 years old=75) and the wage (for the open classes: <1500€ a month=1200€ >6000 € a month=7500€).

After, we calculated the travel costs. For the **travel cost of cars**, we considered the fuel costs as well as the other costs depending on the travel distance of the car use (Equation 1). We did not consider the fixed costs because we assumed that the decision to have a car is not specifically determined by the decision to go visiting natural areas.

$$T_c = \frac{(C * P + F) * D * 2}{N}$$

Equation 1. Travel cost of the car (T_c).

With:

- C: Fuel consumption (l(liters)/km). We used the following means: 2017: 0.0639; 2018 et 2019[9]:0.0633 (Statista, 2021);
- P: Fuel price (€/l). We used the mean prices in Belgium: 2017: 1.38; 2018: 1.54; 2019: 1.51 (STATBEL, 2021). The price is a weighted mean of diesel and petrol based on the proportion of cars using diesel and petrol in Belgium. Diesel share: 2017: 58%; 2018: 54%; 2019: 51% (FEBIAC, 2021);
- D: One way distance travelled by the visitor in km, either the one between her/his home and the visited site for the one-day trip or the one between his/her accommodation and the visited site for the several days trip. The distance is doubled to have the round-trip distance;
- F: other costs of the car use (tyre, car check, etc.) (€/km) based on the mean costs of the standard types of car and their annual use including the car maintenance: 2017: 0.108; 2018: 0.111; 2019: 0.117 (Automobile Club Association, 2021);
- N: Number of adults in the car.

Because we did not ask the number of adults in the car, we applied the following formulas depending on the case:

1. When there is no child:

Number of adults in the car=number of persons in the car

2. When there is at least one child and the number of persons in the car is the addition of the number of adults with the number of children:

Number of adults in the car=number of adults

3. When there is at least one child and the number of persons in the car is not the addition of the number of adults with the number of children:

Number of adults=number of persons in the car*adult rate

With adult rate=$\frac{number\ of\ adults}{number\ of\ adults + number\ of\ children}$

[9] Three references years were considered to have a mean value less dependent on the selected year. Because the other costs of the car use were only available until 2019 when we calculated the travel cost of the car, we considered 2017, 2018 and 2019.

For the **travel cost of motorcycles**, we also considered the fuel costs and the other annual costs depending on the travel distance of the motorcycle use (Equation 2). We assumed that the respondent was alone on the motorcycle (we did not ask in the survey the number of persons on the motorcycle).

$$T_m = D * 2 * C_m$$

Equation 2. Travel cost of the motorcycle (T_m).

With:

- D: One way distance travelled by the visitor in km (same calculation as the travel cost of the car);
- C_m: All the annual costs (fuel, maintenance, wearing parts except insurance) for a medium-size motorcycle in 2019: 0.16€/km (Motoservices, 2021).

The **travel cost of public transport** is the price of the ticket given by the respondent in the survey. We did not specify in the question if it was the price of the one-way ticket or the round-trip ticket. We assumed they gave the price of the round-trip ticket because the ticket is generally a round-trip ticket, and it is preferable to choose the option that undervalues the cost to have the most conservative estimate.

To include the **other means of transport that do not have a direct cost** (i.e. walking, biking and horse riding), we also calculated the opportunity cost of time. This cost is the time an individual takes to travel. It is called "opportunity cost" because the travel time could be used to other activities. This cost is generally calculated as a fraction of the wages (Equation 3) because the underlying idea is that the time spent in travelling to the site is not spent in working. (Abildtrup et al., 2021)

$$\mathrm{T}_t = \frac{T}{60} * 2 * 0.3 * \left(\frac{I}{168}\right)$$

Equation 3. Opportunity cost of time (T_t).

With:

- T: One-way travelled time either the one between her/his home and the visited site for the one-day trip or the one between his/her accommodation and the visited site for the several days trip. The time is divided in 60 to have it in hour and is doubled to have the round-trip time;
- I: Monthly income (€). We assumed that an individual works 168h a month;

We multiplied by 0.3 to only retain a fraction of the wage as suggested by a majority of scientific papers (Brahic and Terreaux, 2009; He and Poe, 2021; Parsons, 2003).

However, the consideration of this cost and the way to calculate it is questioned in the scientific literature, lot of papers advice not to take it into account (Parsons, 2003). Therefore, we tested two models of TCM: (1) one considering only the travel cost (i.e. car, motorcycle and public transport), and (2) another considering the travel cost and the opportunity cost of time of all the means of transport. (Abildtrup et al., 2021)

In the TCM, the number of visits is estimated depending on the travel cost (i.e. demand curve) based on the following assumption: the farther an individual lives from the natural site, the more it costs to go on the site and the less visits he/she will do (**Figure 2-13**). From this demand curve, the consumer surplus can be assessed as the difference between the maximal cost an individual is willing to pay to go to the natural site (C^0) and the actual travel cost he/she paid to go to the site (C*). (Abildtrup et al., 2021)

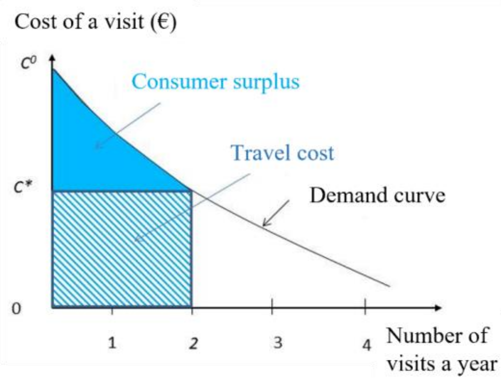

Figure 2-13. Demand curve of the visits in a natural area. The actual travel cost for two visits is represented by the surface area of the blue rectangle: C*x2 and the consumer surplus is the surface area of the blue triangle. Adapted from Abildtrup et al. (2021).

To model this demand curve, several regression models for count data exist: the Poisson model, the Quasi-Poisson model and the negative binomial model. Because they belong to the family of generalized linear model, we used the *glm* function in R. First, we calculated the mean and the variance and compared them to determine if the Poisson model could be used (i.e. the variance is assumed to be equal to the mean in the Poisson model). If not, the Quasi-Poisson model was performed and we calculated the dispersion parameter. If this dispersion parameter was higher than 20, we used the negative binomial model. Finally, because we do not have a number of visits equals to 0 (we only interviewed people who went to the municipal forest of Sivry-Rance), we tested the zero-truncated negative binomial model using the function *vglm* in R to correct this lack of 0 values. (Zeileis et al., 2008; Zuur et al., 2009)

Several datasets were tested to determine which travel cost should be considered to have the best model. We compared the one-day trip visitors to all the visitors knowing that the estimation of the travel cost of the several days trip is less accurate because they travelled in the region of Sivry-Rance not only to go visiting the forest but for other reasons. We also compared the different means of transport: car+motorcycle; car+motorcycle+public transport and all the means of transport including the opportunity cost of time because the estimation of the travel cost of the public transport and the opportunity cost of time are less accurate.

Our regression model also included other explanatory variables regarding the respondent profile to see if some socio-economic characteristics influence the demand curve:

- Type of forest user;
- Inhabitant or not of the municipality of Sivry-Rance;
- If the respondent visited the site alone or not;
- The gender;
- The age;
- The profession;
- The income.

We applied the stepwise method to select the relevant socio-economic variables that could also explained the number of visits along with the travel cost.

Finally, from the final model (the best regression model with the best dataset and the relevant socio-economic variables), we calculated the consumer surplus by dividing -1 by the estimate of the travel cost of the regression model.

4.3.3.3 DCE

We pooled the answers of the three following thematic groups: (1) TCM, (2) DCE, and (3) respondent profile of the four surveys. We added a variable "Type of forest users" to differentiate the four surveys.

These data were cleaned. We only considered the respondents who answered all the DCE questions. First, we looked for inconsistent data in the choice between the two alternatives: (1) a respondent always selected the same alternative (e.g. always the first alternative), and (2) a respondent always selected neither alternative. In the first case, the response time was checked to see if the respondent took or not the necessary time to choose between the two alternatives. In the second case, we asked a follow-up question (i.e. Why did you only select neither alternative in every choice set?). Based on the answers to this question, the protesters (i.e. the ones who do not want to answer this question) were identified and removed from the dataset (**Table 2-11**).

Table 2-11. Reasons proposed in the follow-up question for the respondent who always selected neither alternative to differentiate the protesters from the others.

Reason	**Protester**
The two alternatives were too distinct	No
I have a better option closer where I can go	No
I do not understand the question	Yes
The forests were different from each other according to too many criteria, not choosing was the easiest solution	Yes
The forests are always different from each other. I do not think it makes sense to only use one picture to represent a forest visit	Yes
I prefer other activities than visiting forest	Yes

We also asked all respondents a follow-up question to know if they considered all the six attributes when choosing their preferred alternative. However, even if they said they did not consider some attributes in their choice, Mørkbak et al. (2014) showed that their choice reflected they did consider these attributes. Therefore, we tested two datasets: (1) all the data, and (2) the data without the respondents who said not having considered the distance in their choice. We focused on the distance because it is an essential attribute to consider as the farther is a forest, the more it costs to go there and the least it is preferred, all the other attributes being the same.

Then, we looked for inconsistent data for the number of visits a year and the travel distance by representing these two variables on a boxplot.

After, the cleaned data were edited for the DCE. A line was created for each option of choice for the six choice sets per respondent (i.e. 18 lines a respondent). The different levels of the five forest attributes were transformed into binomial data (e.g. for the age structure, two columns were created one called “Young tree” where 1=young tree and 0=middle age tree or old tree, the other called “Old tree” where 1=old tree and 0=middle age tree or young tree). The qualitative answers were transformed into binomial data and for the interval answers, the middle of the class was taken (see Chapter 2 4.3.3.2 TCM).

DCE is based on the consumer theory of Lancaster (1966) combined with theory of random utility (McFadden, 1974). The central hypothesis of DCE is that the utility of any option depends on the attributes of the goods and an individual will choose the option that maximizes their utility (Abildtrup et al., 2021). Therefore, the resulting choices are analyzed to estimate the contribution that each attribute and their level add to the overall utility of individuals (Hoyos, 2010). Several random utility models (e.g. conditional logit, random parameter logit, latent class model) exist to assess the effect of each attribute on the probability to choose one alternative over another (Bockstaller et al., 2019). These models only analyse the differences of utility between the attributes without measuring the absolute utility (Bockstaller et al., 2019; Hoyos, 2010).

Three random utility models were tested: (1) conditional logit model using the function *clogit* of the *survival* package (Aizaki and Nishimura, 2008), (2) the multinomial logit model using the function *mlogit* of the *mlogit* package (Croissant, 2020), and (3) the latent class model using the function *gmnl* of the *gmnl* package. First, the conditional logit model was applied to the dataset. Because this model considers that all individuals are equals which is not always true especially if the standard deviation is high, this model was compared to the multinomial logit model with a likelihood ratio test (function *lrtest* of the *lmtest* package) to choose the best one (Croissant, n.d.; Mariel et al., 2021). Several parameters of the multinomial logit model were changed and tested with the likelihood ratio test: (1) heteroscedasticity, (2) random attributes, and (3) correlated attributes. Finally, the latent class model was performed. This model makes several classes that differ from each other depending on the preferred levels of attributes. We tested three number of classes: 2, 3 and 4 (Broch and Vedel, 2012).

Then, the willingness-to-travel of each significant attribute (i.e. which additional distance an individual is willing to travel to go to a forest with his/her preferred level of the attribute) was calculated for the best logit model and the different classes of the latent class model. The following functions were used for the three models: (1) *mwtp* (package *support.CEs*) for the conditional logit model, (2) *rpar* (package *mlogit*) in the multinomial model (Croissant n.d.), and (3) *wtp.gmnl* (package *gmnl*) in the latent class model.

Finally, explanatory variables regarding the respondent profile were included in the latent class model to see if some socio-economic characteristics influence the preferred level of the attributes:

- Type of forest user;
- Inhabitant or not of the municipality of Sivry-Rance;
- The number of visits a year;
- The gender;
- The age.

We only tested the socio-economic variables in the latent class model because in the multinomial logit model, each socio-economic variable has to be added through an interaction with another variable (i.e. a forest characteristic), which rapidly increases the number of variables of the model, making it of lower quality. We applied the stepwise method to select the relevant socio-economic variables.

4.3.3.4 Contingent valuation

We pooled the answers of the two following thematic groups: (1) contingent valuation, and (2) respondent profile of the four surveys. We added a variable “Type of forest users” to differentiate the four surveys.

First, these data were cleaned. We only considered the respondents who answered all the contingent valuation questions. We looked for inconsistent data in the contingent valuation. We checked the respondents who decided not to pay or gave a value of 0€ to determine if they were really willing to pay 0€ or if they did not want to participate in this study (i.e. protester). We used the follow-up question about the reasons for which they did not want to pay or gave a value of 0€ to remove the protesters from the dataset (**Table 2-12**).

Table 2-12. Reasons proposed in the follow-up question when the respondent decides not to pay or to pay 0€ to differentiate the protesters from the others.

Reason	Protester
The cultural ES supply (e.g. firewood quantity, tourism infrastructure) is already adequate	No
I do not trust the fact that the money I give will be used for the given purpose	Yes
I will not go in the municipal forest of Sivry-Rance if there is an additional tax	Yes
I will not use the additional infrastructures	No
I think that the tax should be paid by other users	Yes
I do not think the proposed scenario is realistic	Yes
I am already paying enough taxes	Yes
I am already investing enough in the improvement of the infrastructures	Yes

We also looked for inconsistent data for the number of visits a year by representing this variable on a boxplot.

After, the cleaned data were edited for the contingent valuation. The qualitative answers were transformed into binomial data and the middle of the class was taken for the interval answers (see Chapter 2 4.3.3.2 TCM). The two price ranges (**Figure 2-12**) are intervals (e.g. a respondent who selected 4€ is willing to pay between 4€ and 6€ (the next value)). The intervals of the two price ranges were transformed into quantitative data according to two methods: (1) lower-bound estimator (i.e. the lowest value of the class), and (2) mid-point estimator (i.e. middle of the class). For the two open classes of the two price ranges, we considered 15€ for the class >10€ and 35€ for the class >30€.

The mean, median, standard deviation, minimum and maximum of the WTP were calculated for the lower-bound estimator and the mid-point estimator for the two price ranges.

Then, an interval regression (function *survreg* of the *survival* package) was performed to analyse the influence of the socio-economic variables and the price range on the WTP:

- Type of forest user;
- Inhabitant or not of the municipality of Sivry-Rance;
- The home country (Belgium or another country);
- If the respondent visited the site alone or not;
- The number of visits a year;
- The gender;
- The age;
- The income;
- The two price ranges.

We applied the stepwise method to select the relevant explanatory variables. Finally, we estimated the mean WTP and its standard deviation from the selected interval regression model for all the relevant explanatory variables.

4.4 Public information session

To inform the stakeholders on the main conclusions of this study and on the final version of the forest management plan, a public information session was held on Thursday, the 9th of March 2023 from 7 pm to 10 pm, in the room of the cultural center of Sivry-Rance (**Figure 2-14**).

Figure 2-14. Participants to the public information session. © Mélanie Lalmant

The stakeholders invited to the first and second participatory workshops were personally invited. A broader communication was also carried out to reach any person who would be interested in attending this information session by different means of communication (e.g. press release, social networks, website of the municipality of Sivry-Rance). In total, about forty persons were present. They represent different stakeholders (e.g. DNF, local associations, tourism office, hiker, hunter, horse rider, fisher).

After welcoming the participants, the information session started with an introduction by the municipality of Sivry-Rance to introduce the three presenters: Catherine Colson and Eric Declercq from the DNF and myself, and to give the schedule of the evening.

Then, Eric Declercq and Cahterine Colson presented the forest management plan of Sivry-Rance by reminding the context of the municipal forest of Sivry-Rance (area, different managers) and of the forest management plan (procedure, legislation, steps). They showed how the forest management plan of the municipal forest of Sivry-Rance fulfils the economic, ecological and social functions. They concluded with the need to have participatory approaches to assess how the supply of ES influenced by the forest management plan meets the demand of the stakeholders. They insisted on the resources needed to perform such an analysis (time, expertise, tools, etc.). These conclusions introduced the next presentation on this doctoral research.

First, the concept of ecosystem services was explained. Then, after describing how the surveys of the forest users were conducted, their main results were detailed. Next, the forest attendance assessment was discussed. After, the two participatory workshops were presented. The results of the ES assessment and the ranking of the pathways were synthetized. Finally, the main conclusions of this study were reminded.

A conclusion about these two presentations was given by Catherine Colson. She insisted on the complexity of this study and how hard it is to answer the diversity of needs of the stakeholders when managing a forest including when designing its forest management plan. She also showed how this study provides answers to forest management issues (e.g. the forest attendance assessment revealed the most frequented trail of the forest and how the investments in tourism infrastructures were appropriate in this part of the forest). Finally, she discussed how this kind of study should be conducted on other forests, especially the ones having high social stakes but that the resources needed to conduct them are still lacking.

Then, the municipality of Sivry-Rance opened the floor to the questions. Finally, the mayor of the municipality of Sivry-Rance concluded the evening by thanking the presenters, the organizers, the DNF for their daily management of the municipal forest of Sivry-Rance and the participants. He stressed the need for better communication and to protect the forest from some abusive uses. Finally, he gave examples of some investments that are currently made in the forest. The evening was closed by offering a drink to the participants.

5. Pathways definition

Twelve pathways were studied by defining six management scenarios and two climate change scenarios. A scenario is defined as a story about the future that can be told in both words and numbers, offering an internally consistent and plausible explanation of how events unfold over time (Gallopín et al., 1997; Raskin, 2002). Scenarios do not attempt to forecast or predict the future (Kok et al., 2007). They instead envision several plausible pathways along which the future may develop and thereby account for critical uncertainties (Kahn et al., 1967).

5.1 Six management scenarios

From the identification of the individual expectations of the different stakeholders (see Chapter 2 4.2.1 First participatory workshop: the future of the municipal forest of Sivry-Rance), we selected four contrasting expectations where a certain function of the forest is maximized to have four distinct management (**Table 2-13**). From the six ideal future forests of the six groups of participants (i.e. collective expectations), we defined one management scenario that represents a consensus between the different expectations of the stakeholders. The six ideal forests were regrouped into one management scenario because they were very closed to each other in attempt to strike the balance between the different expectations of the stakeholders. To test another multifunctional scenario, we also considered the forest management plan.

Table 2-13. The six management scenarios applied to the municipal forest of Sivry-Rance with a short description.

Management scenario	Short description
Wood production	Intensive silviculture based on the plantation of productive and short-rotation softwood species
Profitability	Maximal profits by cutting trees as they become mature and by promoting hunting
Recreation	Development of the tourism infrastructures and improvement of the appeal of the forest
Biodiversity	Restoration actions and designation of wilderness areas
Users' Forest	Consensus between the different needs of the stakeholders
Multifunctional Forest	Forest management plan that reconciles the different functions of the forests

Each management scenario was described in a storyline detailing: the management goals, the forestry, the nature conservation actions and the development of the recreation activities (see Chapter 3 3 Step 3: Define the pathways).

The management goals were mapped into objective areas (i.e. aggregation of areas having the same management goal) to spatially represent their allocation (**Table 2-14**).

Table 2-14. Description of the different objective areas defined in the six management scenarios.

Objective area	Description
Production	Area suitable for forestry where the main goal is wood production
Multiple ES	Area suitable for forestry where a balance between the different ES is promoted
Multiple ES + biodiversity	Area suitable for forestry with a nature conservation value where a balance between the different ES is promoted while restoring and conserving nature
Nature conservation	Area with a high nature conservation value where nature restoration actions are taken
Wilderness	Area with a high conservation nature value, left on its own
Priority recreation	Priority recreation area easily accessible where recreation activities require little travelling
Recreation	Recreation buffer area where the recreation infrastructures are developed making the transition between the priority recreation areas and the other forest areas
Non-forested area	Non-forested area (e.g. pond, hunting and fishing lodge, tourism infrastructure)

For the management scenario of the forest management plan, the objective areas defined in this plan were considered. For the other management scenarios, to differentiate the areas suitable for forestry (i.e. the productive areas without having a high nature conservation value) from the nature conservation areas, the site directory (i.e. range of typical sites (i.e. a variable surface area characterized by homogenous abiotic and biotic conditions) of a forestry region described in terms of their abiotic characteristics and their vegetation) of the Fagne, Famenne et Calestienne region (i.e. shale topographic low overhung in the South by a limestone bench located in Southwest Belgium) (Legrain, 2022) was used. The similar site types were regrouped to facilitate the analysis (**Table 2-15**).

Table 2-15. Site groups regrouping similar site types from the site directory of Fagne, Famenne et Calestienne with a short description.

Site group	**Description**	**Site type from the site directory of Fagne, Famenne et Calestienne**
Very wet	Shaded site with a high air humidity	Marshes and peatlands
		Low alluvial terrace and very wet small valley
Alluvial	Fertile, well-watered, well-aerated, well-shaded site with a quite high air humidity	High alluvial terrace and wet small valley
		Cool alluvial terrace
		Dry small valley
Cool plateau or slope	Well-drained site with an excess of water in the gleyed loamy plateau that is fertile while the shale is more acidic	Gleyed loamy plateau
		Well-drained shale plateau
		Cool shale slope
Mesic plateau or slope	Well-drained, fertile site with an adequate water supply that allows root development	Acidocline plateau
		Cool acidocline slope
		Deep loamy clay and stony loamy soil
Xeric plateau	Very dry and superficial site with a quite good fertility (except for the acidic forest)	Xeric-thermophilic meso-oligotrophic to acidic forest
		Alternative water regime on shale
Southern slope	Intermediate water supply because the deep soil is subject to a high evapotranspiration. Good fertility, good anchorage and well-aerated site.	Southern acidocline slope
		Southern shale slope

The priority recreation and recreation areas were delignated based on the four different recreation areas defined by Colson et al. (2012):

1. Priority recreation area: the recreation function is a priority, around the forest access points and the main attractive areas. The management is focused on the safety aspects and landscaping;
2. Buffer area: this is an extension of the priority recreation area in the core of the forest to ensure the transition between the areas with a lot of tourism infrastructures and the wild areas. This area has a real recreation function with trails, signposting, and basic tourism infrastructures. The management considers also the recreation function especially around the trails;
3. Circulation area: the recreation function can be present but does not have a direct impact on the management (e.g. a hiking trail that runs through the forest);
4. Exclusion area: the recreation function is not developed in favour of other functions.

We only considered the two first recreation areas of Colson et al. (2012), the other two are included in the other objective areas. The priority recreation objective area was defined in three areas where a high number of tourism infrastructures is already present, easily accessible, and far away from each other to promote the discovery of the different parts of the forest. Around these three areas and the federal forest where the recreation is well developed, the recreation objective area was delimitated.

5.2 Two climate change scenarios

For each of these six management scenarios, we explicitly considered climate uncertainty by means of two climate change scenarios from IPCC (2022):

1. SSP1-2.6: a shift toward sustainability and a rising of the global temperature of 1.8°C by 2100, also called C3 (i.e. Limit peak warming to 2°C throughout the 21st century with a likelihood of >67%);
2. SSP5-8.5: global economy growth fueled by exploiting fossil fuels and energy-intensive lifestyles and a rising of global temperature of 4.4°C by 2100, also called C8 (i.e. Exceed warming of 4°C during the 21st century with a likelihood of ≥50%).

We selected one of the most optimistic scenarios, the one most likely to happen and the most pessimistic one to have highly contrasted climate change scenarios. From these two IPCC scenarios, we only examined the effects of the rising temperature and did not integrate other aspects of these scenarios (e.g. political aspects).

Based on the weather statistics of Sivry-Rance between 1991 and 2020 (IRM, 2020a) and the predictions of the IRM (2020b) of the IPCC climate change scenarios, the two climate change scenarios were translated in **Table 2-16** and **Table 2-17** for the municipality of Sivry-Rance.

Table 2-16. Mean temperature (°C) of the four seasons of the two climate change scenarios in 2085 in Sivry-Rance (IRM, 2020b, 2020a).

Climate change scenario	**Mean temperature (°C)**			
	Spring	**Summer**	**Autumn**	**Winter**
SSP1-2.6	9.8-10.3	17.5-18	10.8-11.3	3.5-4
SPP5-8.5	12.3-12.8	19.5-20	13.8-14.3	6.5-7

Table 2-17. Total rainfall (mm) of the four seasons of the two climate change scenarios in 2085 in Sivry-Rance (IRM, 2020b, 2020a)

Climate change scenario	**Total rainfall (mm)**			
	Spring	**Summer**	**Autumn**	**Winter**
SSP1-2.6	184-194.3	250.9-263.5	222.9-234.6	294-320.5
SPP5-8.5	204.5-214.7	238.4-250.9	258.1-269.8	338.1-352.8

The potential forest species composition of each site group was defined in the two climate change scenarios. The list of potential forest species from the site directory of Fagne, Famenne et Calestienne (Legrain, 2022) was adapted by considering the effects of the two climate change scenarios on the forest species knowing their climate sensitivity and their growth temperature and rainfall range from the "Fichier Ecologique des essences" (i.e. Walloon web tool to select the suitable forest species of an area) (SPW et al., 2018).

5.3 Twelve pathways

The map of the current forest stands of the municipal forest of Sivry-Rance was adapted for the twelve pathways based on the objective areas map of the six management scenarios and the potential forest species composition of the two climate change scenarios (Annex 6 gives the identification keys from each current forest stand detailing which forest stand it becomes depending on the management scenario, the objectives areas, the climate change scenarios and the site conditions). The map of the current forest stands of the municipal forest of Sivry-Rance was built from the map of the forest stands of the municipal forest of Sivry-Rance from the DNF (version 2019) supplemented by the site directory map of Fagne, Famenne et Calestienne (Legrain, 2022) to distinguish the alluvial forests (i.e. the ones on alluvial sites). Another improvement was made to this map by defining the forest edges as a 100m strip of forest (mean width of a natural forest edge according to Colson et Baix (2021)) having a border with an open land cover class.

6. Ecosystem services assessment

In this section, we discuss the methods used to assess the different ES. The ones based on stakeholder engagement were described in-depth in the previous section (see Chapter 2 4 Stakeholder engagement).

6.1 ES selection

The relevant ES were selected by choosing the ES at stake in the municipal forest of Sivry-Rance based on three criteria:

1. The ES provided by forests (e.g. crop production was not considered);
2. Their relevance for the municipal forest of Sivry-Rance and its stakes identified from the literature review and in the first participatory workshop (e.g. the mitigation of visual impacts and noise was removed because there is no real visual impacts or noise in this region and it was not mentioned by any stakeholder during the first participatory workshop);
3. The feasibility of assessing the ES (available methods and data, time and cost, possibility to assess the changes of the indicators in scenarios) (e.g. no feasible and relevant method was found for the ES "Protection against storms").

From the ES typology of Wal-ES (Wal-ES, 2016), we selected 40 ES from the 61 ES of the list. These selected ES were then regrouped into 12 groups (**Table 2-18**) to restrict the number of ES participants of the second participatory workshop had to work on (see Chapter 2 4.2.2 Second participatory workshop: the needs of the stakeholders).

Table 2-18. List of the selected groups of ES assessed with the correspondence with the Wal-ES ES typology (Wal-ES, 2016).

	ES group	Wal-ES
Provisioning ES	Wood	Wood Energy trees and woody residues Exclusive natural area for productive activities
	Hunting	Wild terrestrial animals Ornamental animals Exclusive natural area for productive activities
	Picking	Edible wild terrestrial plants and fungi Edible water plants Ornamental plants Medicinal plants, animals and microorganisms Exclusive natural area for productive activities Non-exclusive natural area for productive activities
	Fishing	Farmed freshwater fish & shellfish Exclusive natural area for productive activities
Regulating ES	Water quality & quantity	Surface water for drinking Ground water for drinking Surface water for non-drinking purposes Ground water for non-drinking purposes Surface water purification and oxygenation Ground water purification and oxygenation Maintenance of the hydrological cycle and water flows
	Control of soil erosion & flooding	Protection against erosion Natural flood protection
	Fauna and flora	Pollination Seed dispersion Maintenance of nursery habitats throughout the life cycle Biological control Regulation of human diseases Natural area and biodiversity source of intrinsic existence values
	Climate regulation and air purification	Capturing dust, chemicals and smells Global climate regulation by reduction of greenhouse gas concentrations Regional climate regulation Microclimate regulation
Cultural ES	Natural surroundings	Natural surroundings around buildings for living, working and studying
	Recreation	Non-exclusive natural area suitable for daily outdoor activities Non-exclusive natural area suitable for outdoor activities
	Nature observation, learning and inspiration	Non-exclusive natural area and biodiversity used for nature experience Non-exclusive natural area and biodiversity source of inspiration and entertainment Non-exclusive natural area and biodiversity source of education Non-exclusive natural area and biodiversity source of scientific research
	Natural heritage	Non-exclusive natural area and biodiversity source of patrimonial & sentimental values Non-exclusive natural area and biodiversity source of symbolic & cultural values Non-exclusive natural area and biodiversity source of sacred & religious values

6.2 Methods selection

First, we compiled the various existing methods to assess ES from different sources of information:

- Review of ES assessment methods from scientific papers (Bagstad et al., 2013; Grêt-Regamey et al., 2017; Harrison et al., 2018; Jacobs et al., 2018);
- National ecosystem services assessment (EFESE, 2022; UK National Ecosystem Assessment, 2012)
- Existing ES assessment tools (TESSA (Peh et al., 2022), NVE (Pairon et al., 2022), InVEST (Natural Capital Project, 2022), EcoServ-GIS (Winn et al., 2015), MIMES (U.S. Climate Resilience Toolkit, 2018), ARIES (ARIES, 2022), LUCI (LUCI, 2018), InForest (Conservation Management Institute, Virginia Tech, 2014), SENCE (Environment Systems, n.d.), SolVES (USGS, 2018) and ESTIMAP (Zulian et al., 2013))
- Scientific papers assessing a specific group of ES (Table 2-19);
- Specific models (Table 2-19).

Table 2-19. Scientific papers and specific models to assess a particular ES.

ES	Papers	Models
Wood	Fédération Wallonie-Bruxelles n.d.	/
Water quality & quantity	Broadmeadow and Nisbet 2004, Fiquepron et al. 2012, Bansept and Fiquepron 2014	WaterWorld (Burke and Mulligan, 2017), OpenNSPECT (NOAA Office for Coastal Management, 2022), BROOK90 (Federer, 2021)
Control of soil erosion & flooding	/	WaterWorld, OpenNSPECT
Climate regulation and air purification	Lettens et al. 2005, 2008, Van Wesemael 2006, Baveye and Massinon 2008, Latte et al. 2013	CO2FIX (Wageningen University et al., 2009)

Then, we selected the most relevant methods based on four criteria:

1. Relevance (first R of the 3R of IPBES (2022)): which elements of the Wal-ES assessment framework (i.e. land cover, ecological context, management, governance and interactions) are considered?; spatial (e.g. is the spatial scale local enough to apply the method to the municipal forest of Sivry-Rance?) and temporal scales (e.g. is it possible to assess the ES in different scenarios?);
2. Scientific validity (i.e. robustness from the 3R of IPBES (2022)): credibility (i.e. recognized method), replicability, holistic approach (i.e. are all the aspects considered in the method? (e.g. the ecological context and the management that need to be taken into account as demonstrated by the improved ES matrix (see Chapter 1 2.3.3 ES matrix)) and uncertainty (level of accuracy and assessment of the errors);
3. Feasibility (i.e. resources efficiency from the 3R of IPBES (2022)): data and expertise needed, time and cost of the method;
4. Legitimacy: Are the stakeholders involved in the method? How?

When possible, several different methods were selected to assess the same ES to perform an integrated assessment. **Table 2-20** provides a synthesis of the different methods used to assess the ES. The methods based on stakeholder engagement were described in the previous section (see Chapter 2 4.2.2 Second participatory workshop: the needs of the stakeholders and Chapter 2 4.3 Surveys of the forest users). The other methods are detailed in the next sections. Most of the methods elicit instrumental values and are based on biophysical indicators. Socio-cultural indicators are also well represented.

Table 2-20. Synthesis of the indicators and methods used to assess the ES and their corresponding type of specific values and of indicators.

ES	Method	Indicator	Type of specific values	Type of indicators
All ES	1.Second participatory workshop 2.Socio-cultural values question of the surveys of the forest users	1.Preferences 2.Socio-cultural values	Instrumental, intrinsic and relational	Socio-cultural
Provisioning and cultural ES	Surveys of the forest users 1.TCM 2.DCE 3.Contingent valuation	1.WTP to go in the forest 2.Preferences for forest characteristics 3.WTP to improve the ES	Instrumental	1.Economic 2.Socio-cultural 3.Economic
Cultural ES	1.Surveys of the forest users 2.Camera traps	1.Preferences for touristic infrastructures 2.Forest attendance	Instrumental	1.Economic 2.Biophysical
Wood	1->3.Data of the forest management plan + IPRFW + expertise 4.Preferences of the forest users based on the surveys	1.Growing stock (m³/ha) 2.Annual volume of harvested timber (m³/ha*year) 3.Annual profit from timber harvesting (€/ha*year) 4.Suitability level of the forest with the preferences of the inhabitants harvesting firewood	Instrumental	1->2.Biophysical 3.Economic 4.Socio-cultural
Hunting	1.Surveys of the forest users 2->4.Literature review	1.Suitability level of the forest with hunters' preferences 2.Habitat quality for game 3.Deer damage mitigation 4.Mean annual profit from hunting leases	Instrumental	1.Socio-cultural 2->3.Biophysical 4.Economic
Picking	1.Surveys of the forest users 2.Literature review	1.Suitability level of the forest with pickers' preferences 2.Fungal potential distribution	1.Instrumental 2.Intrinsic	1.Socio-cultural 2.Biophysical
Fishing	Surveys of the forest users	Suitability level of the forest with fishers' preferences	Instrumental	Socio-cultural
Water quality & quantity	Data from a paper: 1.Broadmeadow and Nisbet, 2004 2.Bansept, 2013 3.EcoServ-GIS	1.% of riparian woodland in the minimal and ideal buffer width for water purification 2.Minimal and maximal % of evapotranspiration 3.Water purification capacity score	Instrumental	Biophysical

Control of soil erosion & flooding	Data from a paper: 1.Broadmeadow and Nisbet, 2004 2.Bansept, 2013	1.% of riparian woodland in the minimal and ideal buffer width for soil erosion and flooding control 2.Minimal and maximal % of precipitation interception and infiltration	Instrumental	Biophysical
Fauna and flora	1->2.Literature review 3.Data from a paper (Broadmeadow and Nisbet, 2004) 4.InVEST Crop pollination	1.Habitat biological quality 2.Forest undesirable species regulation capacity 3.% of riparian woodland in the minimal and ideal buffer width for water habitat quality 4.Mean pollinator abundance	1.Intrinsic 2.Instrumental 3->4.Intrinsic	Biophysical
Climate regulation and air purification	1.Literature review 2.Data from a paper (Latte et al., 2013) 3.Nature Value Explorer	1.Forest temperature buffering capacity 2.Total carbon stock 3.Fine particles capture	Instrumental	Biophysical
Natural surroundings	Surveys of the forest users	% of visible valued forest	Instrumental	Socio-cultural
Recreation	1.Literature review 2.Surveys of the forest users	1.Recreation supply 2.Suitability level of the forest with the preferences of the recreation users	Instrumental	1.Biophysical 2.Socio-cultural
Nature watching, learning and inspiration	1.Literature review 2.Surveys of the forest users	1.Supply of nature watching, learning and inspiration areas 2.Suitability level of the forest with the preferences of the nature watchers or in search of inspiration	Relational	1.Biophysical 2.Socio-cultural
Natural heritage	Literature review	Supply of natural heritage areas	Relational	Biophysical
All ES	PROMETHEE (MCA)	Ranking of the pathways	Instrumental, intrinsic and relational	Biophysical, economic, socio-cultural

6.3 Forest attendance assessment

A monitoring of the forest attendance is essential for the management of the forest and its recreation activities. This monitoring should include the following information as suggested by Muhar et al. (2002): (1) the number of visits, (2) the temporal variability of these visitor frequencies, (3) their spatial variability, and (4) the activity of the visitors. Indeed, the number of visits can be put into relation with the (ecological and social) carrying capacity of the area along with the temporal and spatial variability to understand how the pressures can vary through time and space. From the monitoring of the activity of the visitors, we understand which path is used by which type of visitor (e.g. hiker, biker or horseman) to avoid or ease conflicts between them. All these information can be used to decide if recreation infrastructures should be developed, which kind, for which type of visitor and where. (Breyne, 2021)

Despite the necessity of a visitor monitoring, we did not have any information on the forest attendance of the municipal forest of Sivry-Rance. Therefore, a sound visitor monitoring was performed, taking inspiration from the one developed by the Agreta project. This project selected five relevant methods allowing to assess the four parameters described in the previous paragraph (Breyne, 2021). From these five monitoring methods (i.e. (1) "eco-compteurs"[10], (2) passive Wi-Fi tracking, (3) social media (Flickr), (4) passive mobile phone positioning data, and (5) automatic cameras), only the last one (i.e. automatic cameras) was retained. Indeed, the first three methods were rapidly abandoned by the Agreta project for different practical reasons (i.e. high cost, technical problems, restriction of data access) while the scale of the municipal forest of Sivry-Rance was too small to apply the fourth one. Furthermore, the cameras monitor visitors in a continuous and cost-economic way (Roberts, 2011), revealing small-scale spatial-temporal variations in frequencies (Breyne, 2021). They also provide qualitative data on the visitor profiles (Campbell, 2006), allowing identifying proportions of different types of visitors (Breyne, 2021).

6.3.1 Experimental design

In the spring of 2019, ten camera traps were placed in the municipal forest of Sivry-Rance (**Figure 2-15**). In coordination with the DNF and the municipality of Sivry-Rance, the cameras were set up on the main trails, assumed to be most frequented, and on some trails assumed to have a low attendance to see if it was the case or not. This sampling method allows for obtaining point-specific information on visitor frequencies and profiles, as well as for comparing outcomes between the ten trails. It cannot be used, however, to generalize this data for other hiking trails or for the all forest (Breyne et al., Under review).

[10] Fixed counting devices

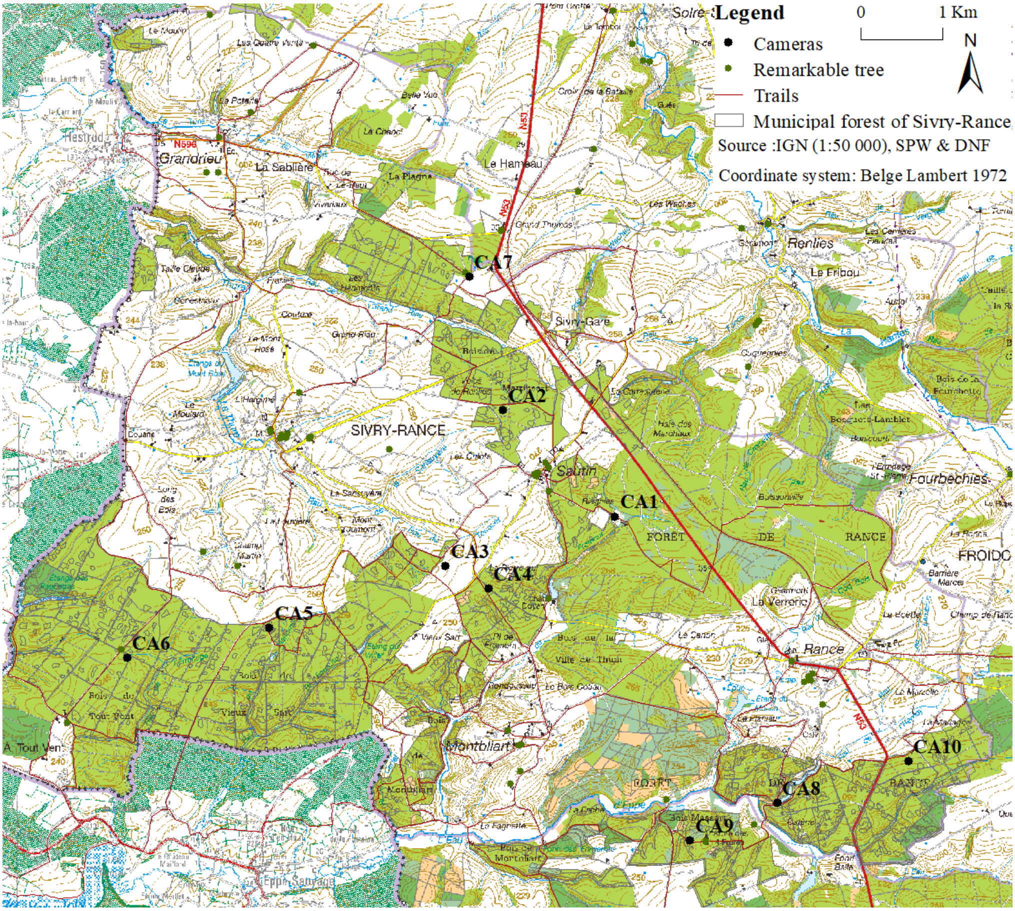

Figure 2-15. Distribution of the ten cameras in the municipal forest of Sivry-Rance with the trails and remarkable trees.

6.3.2 Detection and identification

The camera model is a Dörr Snapshot Limited Black 5.0 S, which costs 89€ and runs on 8 alkaline AA batteries. Each camera was provided with a 16-gigabyte SD card. This model allows to detect objects in movement by infrared detection that works up to 15 to 20 meters of distance. The detection zone of this camera is equal to the field of view, with an angle of 52°. At each detection, the camera was set up to take three images in a row, with an approximate reaction time between the detection and acquisition of the first image of about 0.9 seconds. Concerning the specific settings, three images were preferred over one or two, to allow objects to enter the field of sight after detection. The interval between two detection events was set to a minimum of 5 seconds, to allow the objects to have sufficient time to move out of the capture area of the camera between two movement detection events. Cameras were placed at 3 to 5 meters above ground to discourage theft. The potential areas where people would stagnate (e.g. bank, entrance of the trail) were avoided to limit double counting errors. Vegetation that was obstructing the field of view or potentially triggering a movement detection, was removed on several occasions. The cameras took images for over one whole year starting between the 25th of March 2019 and the 15th of April 2019, depending on the trail, and ending the 3rd of July 2020 (we could not retrieve the camera in spring 2020 due to the covid-19 pandemy). For the analysis, we only considered the images over one year from 23rd of April 2019 (after the easter holidays) to 22nd of April 2020. Images were collected and batteries were controlled once every two to three months. This resulted in a total of 98,221 images for the 10 cameras.

We used artificial intelligence to detect and automatically identify the objects. The team of Marc Van Droogenbroeck (Montefiore Institute of Electrical Engineering and Computer Science, ULiège) ran the seven most used deep learning convolutional neural networks (Faster R-CNN, Retina Net, Mas R-CNN, Point Rend, Yolo, YoloF et YoloX), which were implemented in Python, in the Pytorch deep learning framework, run with Linux (version 3.7). The output of these seven algorithms is a set of predictions which are visualised as a processed image containing bounding boxes around each detected object (**Figure 2-16**), and which are simultaneously saved in one text file per image providing the positions, the classes and the number of detected objects. The seven neural networks have been trained with the Microsoft COCO dataset, which contains over 1.5 million of example objects (Lin et al., 2014) for 80 object classes. For this study, four objects, corresponding to four classes annotated in the COCO dataset, have been selected for detection and identification by the model: persons, bikes, horses and dogs. These objects of interest correspond to the main user profiles of the monitored trails. It should be noted that the models were programmed to detect individual objects and not the ensemble. For example, the model detects a bike and a person, but not a biker. (Breyne et al., Under review)

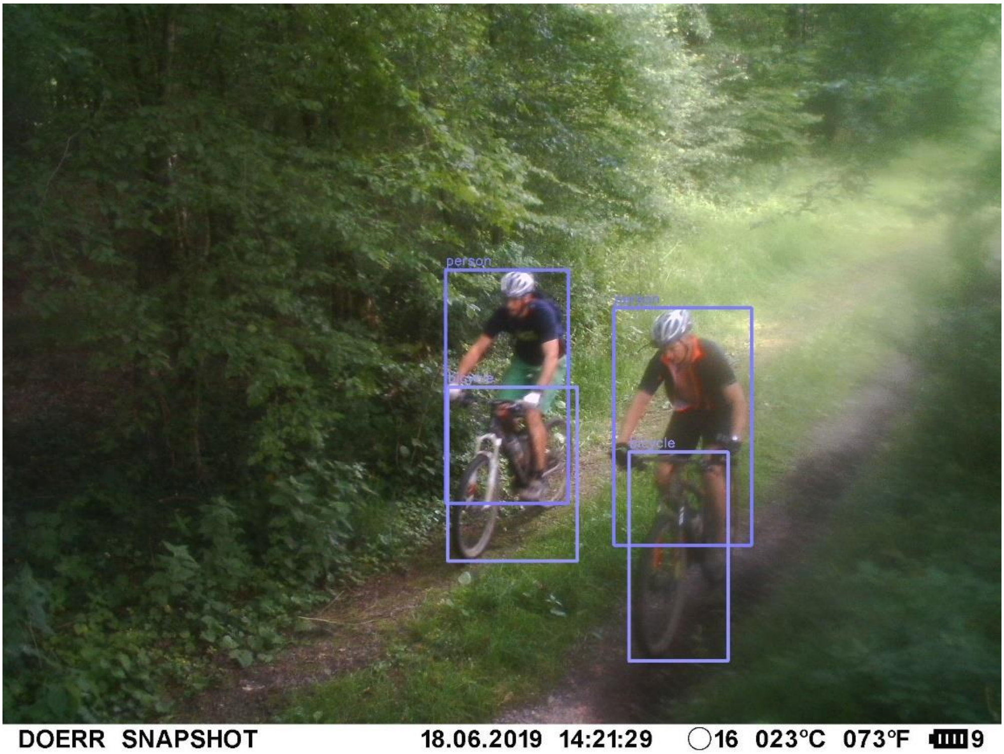

Figure 2-16. Example of a processed image with bounding boxes for each detected and identified object, in this case two persons and two bikes?

6.3.3 Technical and analytical issues

There are some technical inaccuracies that are discussed in Breyne et al. (Under review). We synthetized them in this section and explained how they were addressed.

First, there are some missing data due to the theft of two cameras (cameras 8 and 9). The data of camera 9 were not considered because it was stolen early in the process while the data of camera 8 were included in the analysis as it was stolen at the end.

Secondly, regarding privacy protection, several measurements were taken such to avoid recognizing individuals to comply with the General Data Protection Regulation of the European Union of 2016 (GDPR 2016/679). Automatized data analysis was mobilised based on the contours of objects, hereby avoiding individual recognition. Also, one layer of adhesive tape with fingerprint marks was attached to each camera lens to blur the images at the moment. The position of the cameras at a certain height (>3 meter) and the adjustment of the settings to the lowest resolution possible, contributed to avoid any individual recognition. Furthermore, a description of this study has been hung on the information panels of the trails of the municipal forest of Sivry-Rance to inform the users.

Thirdly, the accuracy of the seven algorithms were tested to select the most accurate model. To account for the potential impact of seasons on the performance of these models due to changes in leaf cover and luminosity, a control sample has been manually checked for each camera during each season. Twenty-five dates and four times of each date were randomly selected all over the studied year to have a minimal sample of 100 detections per camera (for each randomly selected detection, the closed detections in time were also examined to check for redundancy (see the last paragraph of this section)). This resulted in a control sample of over 3% of the total image dataset.

Next, based on these selected images, a confusion matrix was created for each camera, containing four categories: (1) objects detected and correctly categorised (TP), (2) mistakenly detected/identified objects (FP), (3) mistakenly non-detected objects (FN), and (4) correctly non-detected objects (TN). For the detection task in images whose acquisition is triggered by motion, the calculation of TN is problematic as we are unsure about the number of empty images that will be collected in the dataset (Breyne et al., Under review). Therefore, we calculated the sensitivity (Equation 4) and specificity (Equation 5) of the seven models for the four objects (i.e. person, bike, horse and dog). Sensitivity gives the proportion of positives that is correctly identified, so for example a sensitivity of 90% for persons means that out of 100 persons, the model identified 90 persons correctly as persons. Specificity gives the proportion of negatives that is correctly identified, so for example a specificity of 90% for persons means that out of 100 predictions, the model correctly identified 90 as persons, but also wrongly detected 10 other objects as being persons.

$$Sensitivity = TP/(TP+FN)$$

Equation 4. Sensitivity calculation to have an estimation of the proportion of positives which are correctly identified. TP: True Positive, FN: False Negative.

$$Specificity = TP/(TP+FP)$$

Equation 5. Specificity calculation to have an estimation of the proportion of negative which are correctly identified. TP: True Positive, FP: False Positive.

To obtain an estimation that corrects for these errors, Equation 6 was applied to the final visitor numbers:

$$Estimation\ (no.) = N-[(1-Specificity)*\mathrm{N}]+[(1-Sensitivity)*\mathrm{N}]$$

Equation 6. Correction of the estimation of the number of visitors based on the sensitivity and specificity of the model. N: Number of visitors detected by the model.

For the other results (graphs, statistical models), it was not needed to correct the estimations as we only looked at the spatial-temporal variability and the explanatory variables.

Finally, three main issues of redundancy were addressed. First, according to the metadata, a few detection events were triggered at less than 5 seconds after the previous one. This was most likely due to a bug while shooting the image or saving the metadata. These events have been suppressed.

A second issue concerns the series of three images at each detection event. Ideally, every object of interest is photographed a single time. Since cameras have been configured to take three pictures at each movement detection, the maximum number of objects for each class has been used (e.g. if the algorithm detected 2 persons on the first shot, 3 persons on the second one and 2 persons on the last one, it was considered that 3 persons were present).

The third issue was related to the five-second delay between two detection events, intended to allow sufficient time for objects to move out of the field of vision. However, on some occasions, people stagnated under the camera, resulting in multiple detections of the same persons. The time ranges between two detection events were analysed to detect the images taken consecutively. Then, we checked, in the control sample, which detections were redundant or not.

6.3.4 Visitor frequencies and their spatial-temporal variability

Overall visitor frequencies were calculated for each camera and for each type of user profiles using Equation 6 to correct the estimations, in Excel (Windows 10). A specific correction was made to the data of camera 8 to have the annual frequencies. For each user profile, the temporal variability of the camera 8 was compared to the other ones to select the most similar one. Then, a proportion of the number of visitors between the camera 8 and the selected similar camera was calculated based on the data between the 23rd of April 2019 and the 18th of February 2020 (i.e. the theft of the camera 8 was discovered on the 19th of February 2020). To obtain an estimation of the visitor frequency of the camera 8 between the 19th of February 2020 and the 22nd of April 2020, this proportion was multiplied by the number of visitors of the similar camera during this period.

The variability of visitor numbers and of the respective proportions of user profiles was evaluated over time in Excel (Windows 10). This time dimension concerns a potential effect of the seasons, weekends, public holidays and holiday periods, as well as the distribution of visitors over a daily timespan. This information was visualized by means of descriptive graphs. In addition, the DNF and the event organizers (e.g. marche ADEPS, Espace Nature de la Botte du Hainaut) were asked for an inventory of organised activities nearby the concerned camera spots for the time monitored. This information was crossed with the frequency data to potentially serve as an explanation for unusual high frequencies that had been observed.

Three GLM analyses were also performed testing the three regression models for count data (i.e. Poisson, Quasi-Poisson and negative binomial models) with the *glm* function in R (version 3.6.3). The first and second GLM analyses assessed the relative influence of camera positioning, weekends, public holidays, holidays periods and seasons on visitor frequencies for all the visitors (first GLM analysis) and for each user profile (second GLM analysis). The third one focused on the relative influence of the temporal variables on visitor frequencies for each camera.

6.4 *Data of the forest management plan + IPRFW + expertise*

From the data of the IPRFW (Fédération Wallonie-Bruxelles, n.d.) modulated by the expertise of Walloon forest experts and the data of the forest management plan of the municipal forest of Sivry-Rance, we estimated three indicators for the ES Wood:

1. Growing stock;
2. Annual volume of harvested timber;
3. Annual profit from timber harvesting.

All the calculations were performed in Excel (Windows 10).

6.4.1 Growing stock

The average growing stock of each forest stand is given in **Table 2-21**. For the hardwood stands, the growing stock of each site type was considered because there is a match between the forest species and the site type (e.g. an alluvial site is composed of fast-growing best quality wood species compared to a xeric site having stunted oak and hornbeam with a low economic value). We differentiated the mature stand from the young stand (i.e. plantation of less than 33 years old). For the softwood species, the average growing stock was estimated depending on the growing capacity of the different species (**Table 2-21**) because these species are only present on the productive sites. For the stands mixing softwood and hardwood species, a mean of the average growing stock of the hardwood and softwood species was calculated. For the forest edges, the corresponding average growing stock of **Table 2-21** was divided by 2 because their density is lower.

Table 2-21. Average growing stock of the different forest stands of the municipal forest of Sivry-Rance based on the data from IPRFW modulated by expertise.

Hardwood

Site	**Growing stock (m^3/ha)**	
	Mature stand	**Young stand**
Very wet	150	/
Alluvial	200	/
Cool plateau or slope	250	50
Mesic plateau or slope	250	50
Xeric plateau	150	30
Southern slope	200	40

Softwood

Species	**Growing stock (m^3/ha)**
Dense cover (Douglas fir, spruce, fir)	400
Heliophilous productive species (larch, Corsican pine)	300
Scotch pine on southern slope	200

Some adjustments were made in some pathways to account for their particularities.

For the objectives areas where no timber is harvested (i.e. nature conservation and wilderness), the growing stock was increased by adding the annual growth of the forest stand (see **Table 2-22** for the annual growth of each forest stand) multiplied by 65 (i.e. the number of years between the current state (i.e. reference year of 2020) and the pathways (i.e. 2085)).

For the climate change scenario SSP5-8.5, in the sites sensitive to droughts (i.e. cool plateau or slope, xeric plateau and southern slope), a loss of 10% of the annual growth on the growing stock was considered for each year (a tree mortality of 15% of the annual growth was considered but a fraction of the tree mortality (5%) is compensated by an increase growth of the living trees) (Equation 7).

$$Final\ growing\ stock = Average\ growing\ stock - (65 * 0.1 * annual\ growth)$$

Equation 7. Estimation of the growing stock in the sites sensitive to droughts considering a loss of 10% of the annual growth each year.

In the management scenario Profitability, in the objective area where wood is harvested (i.e. production), the growing stock was reduced by 25% of the annual growth each year because more than the annual growth is harvested each year (1.5 times the annual growth knowing that half of this additional harvest is outweighed by an increase in natural regeneration and tree growth).

The average growing stock of each forest stand was multiplied by its corresponding surface and then, summed up to have to the total growing stock of the current state and in each of the twelve pathways. This value was divided by the total surface area of the municipal forest of Sivry-Rance to obtain the growing stock per hectare.

6.4.2 Annual volume of harvested timber

For the current state of the municipal forest of Sivry-Rance, the annual volume of harvested timber comes from the forest management plan (Colson and Baix, 2021). They calculated the mean of the harvested timber between 2009 and 2018. This mean was divided by the total surface area of the municipal forest of Sivry-Rance to obtain the annual volume of harvested timber per hectare.

For the twelve pathways, the annual volume of harvested timber was estimated based on the annual growth of each forest stand (**Table 2-22**). The same method was used to obtain these estimations than the one used to estimate the growing stock (see Chapter 2 6.4.1 Growing stock). We only considered the objective areas where timber is harvested (i.e. production, multiple ES, multiple ES+biodiversity, recreation) in the calculation of the annual volume of harvested timber.

For all the management scenarios in the climate change scenario SSP1-2.6 except the Profitability one, the annual volume of harvested timber is the annual growth of the forest stands. For the Profitability management scenario, because 1.5 times the annual growth is annually harvested, the annual growth of each forest stand was multiplied by 1.5.

Some adjustments were made in some pathways to account for their particularities.

In the management scenario Users' Forest, in the site mesic plateau and slope, because a distinction between the deep loamy clay and stony loamy soil and the two other sites (cfr. **Table 2-15**) was made, the annual growth of the dense cover softwood species in the deep loamy clay and stony loamy soil was revised upwards: 12 m³/ha*year.

In the climate change scenario SSP5-8.5, in the sites sensitive to drought, two corrections were made. First, the annual growth was reduced by 1m³/ha*year to account for the negative impact of increasing droughts on tree growth. Secondly, a tree mortality of 15% of the annual growth was considered. We supposed that these dead trees are harvested. The annual volume of harvested timber was thus calculated by multiplying the annual growth by 1.15.

Table 2-22. Average annual growth of the different forest stands of the municipal forest of Sivry-Rance based on the data from IPRFW modulated by expertise.

Hardwood	
Site	**Annual growth (m³/ha*year)**
Very wet	5
Alluvial	8
Cool plateau or slope	5
Mesic plateau or slope	6
Xeric plateau	2
Southern slope	4
Softwood	
Species	**Annual growth (m³/ha*year)**
Dense cover (Douglas fir, spruce, fir)	10
Heliophilous productive species (larch, Corsican pine)	8
Scotch pine on southern slope	6

Finally, the annual volume of harvested wood of each forest stand was multiplied by its corresponding surface and then, summed up to have to the total annual volume of harvested wood of the current state and in each of the twelve pathways. This value was divided by the total surface area of the municipal forest of Sivry-Rance to obtain the annual volume of harvested timber per hectare.

6.4.3 Annual profit from timber harvesting

For the current state of the municipal forest of Sivry-Rance, the annual profit from timber harvesting comes from the forest management plan (Colson and Baix, 2021). They calculated the mean of the annual profit from timber harvesting between 2009 and 2018. This mean was divided by the total surface area of the municipal forest of Sivry-Rance to obtain the annual profit from timber harvesting per hectare.

For the twelve pathways, the annual profit from timber harvesting was estimated based on the average selling price of timber considering the harvesting costs. This average price accounts for the variable quality of timber (e.g. mature tree, small thinning tree). The average selling price of the different forest species varies between 25 to 50€/m³ (**Table 2-23**).

Table 2-23. Average selling price of timber of the different forest species.

Forest species	**Selling price (€/m³)**
Pine and larch	25
Sciaphilous softwood	40
Hardwood	50

A penalty or a bonus was applied to these selling prices depending on the management and site type (**Table 2-24**).

Table 2-24. Penalty and bonus applied to the average selling prices of the forest species depending on its management and site type.

Management or site type	**Correction (€/m³)**
Steep slope and alluvial site (harvesting constraints)	-10
Xeric or very wet site, forest edge (low quality timber)	-20
Oak stand	+20
Objective tree with a high harvesting size	+5

Several penalties and/or bonuses can be applied to a same forest stand (e.g. a forest stand on a steep slope and xeric site) as long as the income is not lower than 20€/m³ in hardwood stand (i.e. selling price of firewood). For the pine and larch on southern slope and xeric plateau, the penalty of 20€/m³ was not considered as they have still a good selling price on these sites. The bonus Objective tree with a high harvesting size was applied to the management scenario Users' Forest where wood quality is improved.

Finally, the selling price of each forest stand was multiplied by the annual volume of harvested timber and the corresponding surface of the stand to obtain the annual profit from timber harvesting. This value was then divided by the total surface area of the municipal forest of Sivry-Rance to get the annual profit per hectare.

6.5 Preferences of the forest users based on the surveys

From the four surveys of the forest users, several questions were used to understand the preferences for the forest characteristics and infrastructures of the different forest users (see Chapter 2 4.3 Surveys of the forest users):

- What they like and dislike from their visit in the municipal forest of Sivry-Rance (two questions: (1) What are the characteristics of the municipal forest of Sivry-Rance that you like? and (2) What are the characteristics of the municipal forest of Sivry-Rance that bother you?);
- The results of the DCE to elicit preferences for the visual forest structural characteristics (Annex 5);
- Their preferences for tourism infrastructures (Annex 4);

We also considered the management of the corresponding recreation activity and the impacts of climate change on this activity.

From all these information, we defined the ideal forest for each type of users (each type corresponding to one ES) (**Table 2-25**). Then, we assessed, how close is the forest of each pathway and the current state from their ideal forest, on a five-point scale ranging from very high (i.e. the forest is very close to their ideal forest) to very low (i.e. the forest is completely different from their ideal forest), except for the inhabitants.

For the inhabitants, we calculated the proportion of valued visible forest considering only the part of the forest that can be seen by the inhabitants and the forest stands that have the preferred visual structural characteristics. The Viewshed tool in Arcgis (Version 10.4.1) was used to delimitate the visible areas based on the digital surface model of Wallonia (Version 2013-2014) and the points of the houses, in a buffer of 1.5 km around the municipal forest of Sivry-Rance. The points of the houses were obtained by transforming the polygons of artificial areas (Land cover map of the LifeWatch project, version 2015) into points without considering the roads. We used the maps of the current forest stands and of the forest stands in the twelve pathways (see Chapter 2 5.3. Twelve pathways) to select only the forest stands that have the preferred visual structural characteristics.

Table 2-25. ES assessed by the preferences of the different type of forest users with the corresponding indicator and information used.

ES	Type of forest users	Indicator	Source of information
Wood	Inhabitants harvesting firewood	Suitability level of the forest with the preferences of the inhabitants harvesting firewood	Inhabitants harvesting firewood survey
Hunting	Hunters	Suitability level of the forest with the preferences of the hunters	Hunters survey
Picking	Pickers	Suitability level of the forest with the preferences of the pickers	Respondents who indicated that they picked products from the forest in the four surveys
Fishing	Fishers	Suitability level of the forest with the preferences of the fishers	Fishers survey
Natural surroundings	Inhabitants	Proportion of visible valued forest	Preferred visual forest structural characteristics from the DCE for the group of inhabitants + map of the visible forest from houses
Recreation	Recreation users	Suitability level of the forest with the preferences of the recreation users	Recreation users survey
Nature watching, learning and inspiration	Nature watchers or forest users in search of inspiration	Suitability level of the forest with the preferences of the nature watchers or in search of inspiration	Respondents who indicated that they watched nature or recharged their batteries or did a cultural activity in the forest in the four surveys

6.6 Literature review

A literature review was performed for several ES to understand the forest and climate factors that influence the indicator (**Table 2-26**). Then, in the current state and in each pathway, we assessed to what extent each factor contributed positively or negatively to the indicator. Finally, we synthetized all the contributions of the different factors on a five-point scale ranging from very high (i.e. the forest of the pathway contributes positively to the indicator for almost all the factors) to very low (i.e. the forest of the pathways contributes negatively for a majority of the factors to the indicator).

Table 2-26. Indicators used to assess some ES based on a literature review to determine the forest and climate factors that influence the indicator.

ES	Indicator	References
Hunting	Habitat quality for game	Vospernik and Reimoser 2008, Reimoser et al. 2009, Morelle and Lejeune 2015, Colson and Baix 2021
	Deer damage mitigation	Gerhardt et al. 2013, Spake et al. 2020
	Mean annual profit from hunting leases	Colson and Baix 2021, habitat quality for game, choice experiment of the hunters' survey, hunting method
Picking	Fungal potential distribution	Pilz et al. 2002, Tomao et al. 2017, 2020, Olah et al. 2020
Fauna and flora	Habitat biological quality	Lejeune et al. 2007, Dorioz et al. 2018, Colson and Baix 2021, Natural Capital Project n.d.
	Forest undesirable species regulation capacity	Brockerhoff et al. 2017, Staab and Schuldt 2020, Jactel et al. 2021, Marini et al. 2022, Shao et al. 2022
Climate regulation and air purification	Forest temperature buffering capacity	Frey et al. 2016, Zellweger et al. 2019, De Frenne et al. 2019, 2021, Haesen et al. 2021
Recreation	Recreation supply	Colson et al. 2012, Pairon et al. 2022
Nature watching, learning and inspiration	Supply of nature watching, learning and inspiration areas	
Natural heritage	Supply of natural heritage areas	

6.7 Data from a paper

We extracted the data from a specific paper that gives quantitative values useful to assess indicators of some ES (**Table 2-27**). We explained in the three next sub-sections how each of these three papers was used to assess their corresponding indicators.

Table 2-27. ES assessed by the data from a paper with the corresponding indicators and reference.

ES	Indicator	Reference
Water quality & quantity	Proportion of riparian woodland in the minimal buffer width for water purification Proportion of riparian woodland in the ideal buffer width for water purification	Broadmeadow and Nisbet 2004
	Minimal percentage of evapotranspiration Maximal percentage of evapotranspiration	Bansept 2013
Control of soil erosion & flooding	Proportion of riparian woodland in the minimal buffer width for soil erosion & flooding control Proportion of riparian woodland in the ideal buffer width for soil erosion & flooding control	Broadmeadow and Nisbet 2004
	Minimal percentage of precipitation interception Maximal percentage of precipitation interception Minimal percentage of precipitation infiltration Maximal percentage of precipitation infiltration	Bansept 2013
Fauna and flora	Proportion of riparian woodland in the minimal buffer width for water habitat quality Proportion of riparian woodland in the ideal buffer width for water habitat quality	Broadmeadow and Nisbet 2004
Climate regulation and air purification	Total carbon stock	Latte et al. 2013

6.7.1 Forest buffer width

Broadmeadow and Nisbet (2004) defined the minimal and ideal forest buffer width for six indicators characterizing water quality and biological quality, from a literature review. Each of them was related to one or several ES to define the minimal and ideal buffer width of each ES (**Table 2-28**).

Table 2-28. Minimal and ideal forest buffer width of each ES as defined by Broadmeadow and Nisbet (2004) with their corresponding water and biological quality indicators.

ES	**Minimal forest buffer width (m)**	**Ideal forest buffer width (m)**	**Indicators from Broadmeadow and Nisbet (2004)**
Water quality & quantity	15	100	Denitrification Sediment removing Sediment control
Control of soil erosion & flooding	25	100	Sediment removing Sediment control
Fauna and flora	15	70	Water temperature buffering Invertebrates' diversity Woody debris and leaves retention

For each ES, we calculated the percentage of forest buffer (i.e. ideal riparian forest that performs correctly its functions) in the minimal and ideal width, for the current state and in each pathway. In Arcgis (version 10.4.1), four buffers of 15, 25, 70 and 100m were created around each river crossing the municipal forest of Sivry-Rance (map of the hydrological network of Wallonia from 2015). A clip was performed between these four buffers and the maps of the current forest stands and in the twelve pathways to have the surface occupied by each forest stand in the four buffers. Finally, the percentage of the ideal riparian forest stands (i.e. alluvial forest, uneven-aged irregular hardwood forest, forest edge, gap and water body) was calculated in each of the four buffer width in Excel (Windows 10).

6.7.2 Water cycle

Bansept (2013) synthetized the minimal and maximal percentage of evapotranspiration, precipitation interception and infiltration of different land covers, from a literature review. For each forest stand, the corresponding minimal and maximal percentage of these three indicators is given in **Table 2-29**. For the current state and in each pathway, we calculated the weighted mean by area of each forest stand of the minimal and maximal percentage of the three indicators in Excel (Windows 10).

Table 2-29. Minimal and maximal percentage of evapotranspiration, precipitation interception and infiltration for each forest stand based on Bansept (2013).

Forest stand	% of evapo-transpiration	% of precipitation		Land cover in Bansept (2013)
		Interception	Infiltration	
Old hornbeam forest Old oak hornbeam forest Old beech forest Even aged hardwood forest Uneven aged mixed hardwood forest Alluvial forest Forest edge Coppice with standard Young oak forest Young beech forest	48-72	15-45	32-56	Hardwood
Even aged softwood forest	42-72	20-55	17-41	Softwood
Uneven aged softwood hardwood forest	45-72	17.5-50	24.5-48.5	Mean of hardwood softwood
Gap	32-48	5-15	16-28	Grassland
Water body	0	0	100	/
Artificial area	0	0	0	/

6.7.3 Total carbon stock

Latte et al. (2013) developed a methodology to assess carbon stock in four forest pools in Wallonia: (1) living biomass, (2) dead trees, (3) litter, and (4) soil biomass.

To calculate the carbon stock in the aboveground and belowground living biomass of each forest stand, Equation 8 was used.

$$C_{aboveground\ and\ belowground\ biomass} = V_{aboveground} * WD * CC * (1 + BF)$$

Equation 8. Carbon stock in the aboveground and belowground biomass.

With:

- $V_{aboveground}$: Aboveground wood volume estimated by the growing stock (m^3) (see Chapter 2 6.4.1. Growing stock);
- WD: Wood basic density of Wagenführ and Scheiber (1985) (Table 2-30);
- CC: Carbon content (0.5);
- BF: Biomass factor of Vande Walle et al. (2005) given the ratio of belowground biomass to aboveground biomass (Table 2-30).

The WD and BF were calculated for each forest stand by defining their forest species composition as these two factors are defined for each forest species.

Table 2-30. WD (wood basic density) of Wagenführ and Scheiber (1985) and BF (Biomass factor) of Vande Walle et al. (2005) for each forest stand with the correspondence with the forest species for which the WD and BF were given in Latte et al. (2013).

<table>
<tr><th colspan="2">Forest stand</th><th>WD</th><th>BF</th><th>Corresponding forest species</th></tr>
<tr><td colspan="2">Old hornbeam forest</td><td>0.625</td><td>0.21</td><td>70% hornbeam and 30% hardwood</td></tr>
<tr><td colspan="2">Old oak hornbeam forest</td><td rowspan="2">0.568</td><td rowspan="2">0.21</td><td rowspan="2">70% hardwood and 30% hornbeam</td></tr>
<tr><td colspan="2">Coppice with standard</td></tr>
<tr><td colspan="2">Even aged hardwood forest</td><td>0.573</td><td>0.21</td><td>50% indigenous oak and 50% red oak</td></tr>
<tr><td colspan="2">Uneven aged mixed hardwood forest</td><td rowspan="3">0.525</td><td rowspan="3">0.21</td><td rowspan="3">100% hardwood</td></tr>
<tr><td colspan="2">Alluvial forest</td></tr>
<tr><td colspan="2">Forest edge</td></tr>
<tr><td colspan="2">Young oak forest</td><td>0.568</td><td>0.21</td><td>100% indigenous oak</td></tr>
<tr><td colspan="2">Old beech forest</td><td rowspan="2">0.586</td><td rowspan="2">0.24</td><td rowspan="2">100% beech</td></tr>
<tr><td colspan="2">Young beech forest</td></tr>
<tr><td rowspan="4">Even aged softwood forest</td><td>Current state in cool and mesic plateau or slope</td><td>0.419</td><td>0.20</td><td>70% spruce and 30% larch</td></tr>
<tr><td>Southern slope</td><td rowspan="2">0.423</td><td rowspan="2">0.16</td><td rowspan="2">100% pine</td></tr>
<tr><td>Pathways in cool plateau or slope</td></tr>
<tr><td>Pathways in mesic plateau or slope</td><td>0.423</td><td>0.17</td><td>100% Douglas fir</td></tr>
<tr><td rowspan="2">Uneven aged softwood hardwood forest</td><td>Cool plateau or slope and southern slope</td><td>0.474</td><td>0.19</td><td>50% pine and 50% hardwood</td></tr>
<tr><td>Mesic plateau or slope</td><td>0.487</td><td>0.19</td><td>50% Douglas fir, 30% indigenous oak and 20% hardwood</td></tr>
</table>

To calculate the carbon stock of the aboveground and belowground biomass of dead trees, Equation 8 was also used. To estimate the aboveground volume of dead trees, we multiplied the number of dead trees (**Table 2-31**) by the average volume of a dead tree (i.e. 3m^3) and the corresponding surface. In the climate change scenario SSP5-8.5, in the sites sensitive to droughts, in the objective areas where no wood is harvested, 15% of additional number of dead trees was added to account for the additional tree mortality due to drought. As dead trees are mainly hardwood species, we considered the WD and BF values of hardwood (**Table 2-30**).

Table 2-31. Number of dead trees per hectare considered to calculate the carbon stock of dead trees depending on the objective areas with its justification.

Objective areas	**Number of dead tree/ha**	**Justification**
Current state	0.49	Actual number of dead trees (Colson and Baix, 2021)
Multiple ES, multiple ES+biodiversity, recreation	2	Standard of the forestry code (Walloon government, 2008)
Production	0	No dead tree is maintained
Nature conservation, wilderness, priority recreation	10	Ideal number of dead tree (Vallauri et al., 2016)

The carbon stock of the litter was estimated for each site based on the humus type for which the carbon content is given from the data of Latte et al. (2013). All the sites have a mull humus (332g/m²) except the marshes and peatlands site which has a peat humus (1206g/m²). The carbon content of each site was multiplied by its corresponding surface to have the total carbon stock of the litter.

The carbon stock of the soil was calculated from the data of Latte et al. (2013) given the carbon stock at 0.2m deep per hectare for each type of soil (**Table 2-32**). This carbon stock was multiplied by the surface of each type of soil in the municipal forest of Sivry-Rance obtained from the Walloon Soil Map (Version 2015).

Table 2-32. Carbon stock of the soil at 0.2m deep for each soil type given in Latte et al. (2013) with its corresponding surface in the municipal forest of Sivry-Rance.

Soil type	**Surface (ha)**	**Soil carbon stock at 0.2m (Mg/ha)** (Latte et al., 2013)
Quite wet loamy sand soil	1	96
Well-drained loamy soil	132	82
Quite wet loamy soil	433	77
Wet loamy soil	58	102
(Quite wet) clay soil	12	67
Wet clay soil	12	96
Well-drained slightly stony loamy soil	43	105
Quite wet slightly stony loamy soil	118	88
Well-drained shale stony loamy soil	938	79
Well-drained psammite or shale psammite stony loamy soil	389	83

The total carbon stocks of the living biomass, the dead trees, the litter and the soil were summed up and then divided by the total surface area of the municipal forest of Sivry-Rance to have the total carbon stock per hectare for the current state and the twelve pathways.

6.8 Existing models

Three existing ES models were selected to assess three ES (**Table 2-33**).

Table 2-33. Models used to assess the ES with the corresponding indicator and a short description of the model.

ES	Indicator	Model	Description of the model
Water quality & quantity	Water purification score	EcoServ-GIS (version 3.3)	Toolkit for mapping ecosystem services at the county or region scale (Winn et al., 2015)
Fauna and flora	Pollinator abundance	InVEST (version 3.11.0)	Suite of open-source software models used to map and value the goods and services from nature that sustain and fulfil human life (Natural Capital Project, 2022)
Climate regulation and air purification	Fine particules capture	NVE (version 2.2 for Wallonia)	Pragmatic methods that value ES and help9+ planners, land managers and policy makers to map nature’s socio-economic importance (Pairon et al., 2022)

Each model is detailed in the three next sub-sections.

6.8.1 Water purification score (EcoServ-GIS)

We applied the method developed in EcoServ-GIS to assess the water purification capacity score based on the Manning coefficient of each forest stand (i.e. hydraulic roughness of the vegetation) (**Table 2-34**) and the slope (Winn et al., 2015).

Table 2-34. Manning coefficient of each forest stand with the correspondence of the habitat in EcoServ-GIS (Winn et al., 2015)

Land cover	WD	Corresponding habitat EcoServ-GIS
Old hornbeam forest	0.60	Broadleaved woodland
Old oak hornbeam forest		
Coppice with standard		
Even aged hardwood forest		
Uneven aged mixed hardwood forest		
Alluvial forest		
Forest edge		
Young oak forest		
Old beech forest		
Young beech forest		
Even aged softwood forest	0.50	Coniferous woodland
Uneven aged softwood hardwood forest	0.55	Mixed woodland
Gap	0.35	Other mixed habitats
Water body	0.00	Rock &Water
Artificial area	0.00	Manmade surfaces & structures

The slope was calculated in each watershed of the municipal forest of Sivry-Rance with the Slope tool (Spatial Analyst) in Arcgis (Version 10.4.1) from the Digital Elevation Model (map of ERRUISSOL, version 2005). Then, they were grouped into the five classes defined in EcoServ-GIS to convert them into the corresponding pollution interception capacity value (**Table 2-35**) (Winn et al., 2015).

Table 2-35. Pollution interception capacity value for each slope class given in EcoServ-GIS (Winn et al., 2015).

Slope class (°)	Pollution interception capacity value
0-5	100
5-8	85
8-15	70
15-25	60
25-35	30

The Manning coefficient and the pollution interception capacity value were multiplied for each forest stand in each slope class. Then, the weighted mean by area was calculated in Excel (Windows 10) to obtain the water purification score of the current state and the twelve pathways.

6.8.2 Pollinator abundance (InVEST)

The InVEST Crop pollination model (Natural Capital Project, n.d.) assesses the pollinator abundance based on three sources of information:

1. A land cover map;
2. A biophysical table giving for each land cover, its nesting potential and availability of floral resources;
3. A pollinator table giving for each wild bee species, its season flight, its nesting preferences, its flight range, and its relative abundance.

To account for pollinator movement, a buffer of 1.5km (i.e. average maximal wild bee flight range according to Benjamin et al. (2014)) was considered around the municipal forest of Sivry-Rance. A land cover map of the 1.5km radius around the municipal forest of Sivry-Rance was added to the maps of the forest stands of the current state and the twelve pathways (see Chapter 2 5.3 Twelve pathways) to obtain the land cover map on the all studied area. The cover map of the 1.5km radius was derived from several sources of information:

- The land cover map of the LifeWatch project (version 2015);
- The forest stands map of the federal forest from the DNF (version 2019) to differentiate the different forest stands;
- The land cover map of the Parc Natural Régional de l'Avesnois (version 2015) to have the land cover in the French part of the 1.5km buffer;
- The site directory map of Fagne, Famenne et Calestienne (Legrain, 2022) to distinguish the alluvial forests;
- Field data for the undefined forest stands (i.e. the private forests and the French forests that are not enough detailed in their land cover map) for which we manually attributed a forest stand type based on field observation.

The forest edge was added to this final map (see Chapter 2 5.3 Twelve pathways that describes how the forest edge was designed).

Then, the biophysical table was filled with the following indices:

- Cavity and ground nesting availability indices ranging from 0 (no availability) to 1 (maximal availability);
- Relative abundance of floral resources in spring and summer ranging from 0 (null abundance) to 1 (maximal abundance).

The two first indices characterizing the nesting availability were derived from a literature review (Affek, 2018; Brockerhoff et al., 2017; Ekroos et al., 2020; Grafius et al., 2016; Groff et al., 2016; Grundel et al., 2010; Koh et al., 2016). This literature review showed that:

- The cavity nesting availability index increases with the species mix, the coppice and the forest age;
- This index is high in semi-natural habitats and better in forests than open habitats;
- This index decreases in wetlands and softwood stands.

Based on these factors, a ranking of this index in the different forest stands and other land covers was made (Figure 2-17).

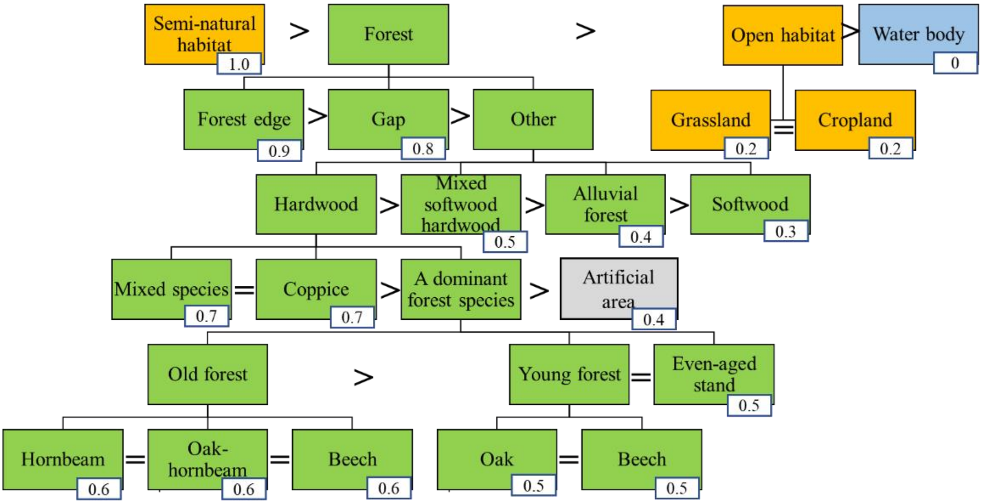

Figure 2-17. Diagram illustrating the ranking of the cavity nesting availability index of the different forest stands, adapted from Monseu (2021).

The ground nesting availability index is influenced by the following factors:

- This index increases slightly in mixed species stands and coppices;
- It increases in forest edges;
- It is better in open habitats than in forest ones;
- It is high in semi-natural habitats;
- It decreases with the forest age, in softwood stands and in wetlands.

Based on these factors, a ranking of this index in the different forest stands and other land covers was made (**Figure 2-18**).

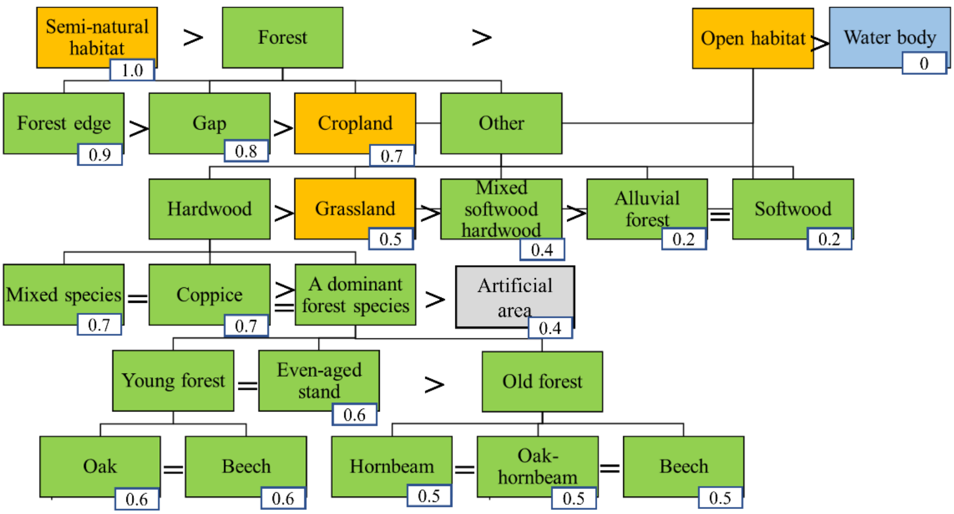

Figure 2-18. Diagram illustrating the ranking of the ground nesting availability index of the different forest stands, adapted from Monseu (2021).

The relative abundance of floral resources in spring and summer was then calculated based on the flowering period of each plant species, being pollinated by wild bees, present in the study area. From the data on Walloon floral resources of 2000 to 2017 (Jacquemin et al., Under review), we obtained the list of plant species in each forest stand and other land cover type. We only selected the ones being pollinated by wild bees thanks to the BDFGM, established under the EU FP7 STEP project (Rasmont and Iserbyt, 2014)). Then, we used the TRY database (Kattge et al., 2020) to have the flowering period of each plant species to calculate its floral index for spring (i.e. March, April, May, June) and summer (July, August, September, October) considering that each month where the plant is flowering is equal to 0.25. For example, *Achillea millefolium* L. has a flowering period between June and October, its spring floral index is 0.25 and its summer floral index is 1. Then, the mean of these two floral indices for all the plant species, being pollinated by wild bees, in each land cover was assessed (**Table 2-36**). With this method, we only got the floral indices of current land covers. For three new land covers only present in the pathways, we considered the floral indices of similar land covers:

- For the mixed softwood hardwood forest, we calculated the mean of the floral indices of the uneven aged mixed hardwood forest and even aged softwood forest;
- For the even aged hardwood forest, the mean of the floral indices of the young oak and beech forests was calculated;
- For the old hornbeam, we took the same floral indices as the old beech forest being similar in terms of cover density.

Table 2-36. Relative abundance of floral resources in spring and in summer for each land cover based on Monseu (2021).

Land cover	Relative abundance of floral resources	
	Spring	Summer
Undefined forest	0.28	0.45
Cropland	0.36	0.61
Grassland	0.36	0.59
Semi-natural habitat	0.31	0.64
Coppice with standards	0.39	0.46
Uneven aged mixed hardwood forest	0.43	0.30
Young oak forest	0.21	0.50
Old oak hornbeam forest	0.36	0.49
Young beech forest	0.13	0.50
Old beech forest	0.13	0.50
Even aged softwood forest	0.25	0.53
Forest edge	0.37	0.55
Gap	0.40	0.60
Alluvial forest	0.43	0.38
Water body	0	0
Artificial area	0.43	0.51
Mixed hardwood softwood forest	0.34	0.42
Even aged hardwood forest	0.17	0.50
Old hornbeam forest	0.13	0.50

The pollinator table has the following indices for each wild bee species present in the municipal forest of Sivry-Rance:

- A preference nesting index ranging from 0 (no use of the nesting site) to 1 (full use of the nesting site) for the cavity and ground nesting;
- A pollination activity index ranging from 0 (no pollination activity) to 1 (the species is active the entire season) for spring and summer;
- The average flight range;
- A relative abundance index ranging from 0 to 1.

First, we identified the wild bee species present in the study area from the BDFGM, between 2000 and 2017. We selected only the ones that have a clear role in pollination. The three species of the *Nomada* genus were thus removed because they do not have a specific hair system dedicated to collect pollen (Monseu, 2021) (**Table 2-37**).

Then, the preference nesting indices for the cavity and ground nesting for each wild bee species were estimated based on their nesting behaviour obtained from the European Bee Traits database (Roberts, 2020).

Table 2-37. Preference nesting indices for the cavity and ground nesting of the wild bee species, having a clear role in pollination, present in the municipal forest of Sivry-Rance within a 1.5km radius (BDFGM) based on their nesting behaviour obtained from European Bee Traits database (Roberts, 2020), adapted from Monseu (2021).

Wild bee species	**Nesting behaviour**	**Preference nesting index**	
		Cavity	**Ground**
Andrena cineraria L.	Digger	0	1
Andrena fulva M.	Digger	0	1
Andrena nitida M.	Digger	0	1
Andrena sabulosa S.	Digger	0	1
Anthophora plumipes P.	Digger	0	1
Bombus hortorum L.	Cavity nester	1	0
Bombus lapidarius L.	Cavity nester	1	0
Bombus pascuorum S.	Carder[11]	1	0.5
Bombus pratorum L.	Cavity nester	1	0
Bombus sylvestris L.	Social parasite[12]	1	0
Bombus terrestris L.	Cavity nester	1	0

The pollination activity indices for spring and summer were estimated based on the flight period of the wild bee species obtained from the European Bee Traits database (Roberts, 2020) (**Table 2-38**). The calculation of these two indices is identical to the one of the two relative abundance of floral resources indices for spring and summer.

Table 2-38. Pollination activity indices for spring and summer calculated from the flight period (European Bee Traits database (Roberts, 2020)) of the wild bee species, having a clear role in pollination, present in the municipal forest of Sivry-Rance within a 1.5km radius, adapted from Monseu (2021)

Species	**Flight period**	**Pollination activity index**	
		Spring	**Summer**
Andrena cineraria L.	April-May	0.5	0
Andrena fulva M.	March-May	0.75	0
Andrena nitida M.	April-June	0.75	0
Andrena sabulosa S.	April-June	0.75	0
Anthophora plumipes P.	March-June	1	0
Bombus hortorum L.	March-October	1	1
Bombus lapidarius L.	June-August	0.25	0.5
Bombus pascuorum S.	April-October	0.75	1
Bombus pratorum L.	March-July	1	0.25
Bombus sylvestris L.	March-July	1	0.25
Bombus terrestris L.	March-October	1	1

[11] A carder is a species that builds its nest with vegetable fibres (Vereecken, 2017).

[12] *Bombus sylvestris* L. is a social parasite of *Bombus pratorum* L. The queen bees of *B. sylvestris* take a nest of *B. pratorum* by removing their queen bee. (Rasmont and Iserbyt, 2014)

The average flight range was estimated from a literature review (Gebhardt and Röhr, 1987; Knight et al., 2005; Osborne et al., 2008; Walther-Hellwig and Frankl, 2000). When the flight range was not found in the literature, the mean of two mathematical models, calculating the flight range from the characteristics of the wild bees, was used. The first model estimates the flight range from the distance between the tegulea (**Figure 2-19**) (Equation 9) (Greenleaf et al., 2007), obtained from the European Bee Traits database (Roberts, 2020).

$$\log(Y)=(1.643\pm0.582)+((3.242\pm1.218)*\log X)$$

Equation 9. Mathematical model estimating the flight range of wild bees from the distance between their tegulae (Greenleaf et al., 2007). Y: flight range (m), X: distance between the tegulae (mm).

Figure 2-19. Illustration of the distance between the tegulea (orange arrow) (Engle and Baum, 2017).

Because this model surestimated the flight range of large wild bees (Benjamin et al., 2014; Greenleaf et al., 2007), a second model was considered. It estimates the flight range from the body length of wild bees (Equation 10) (Gathmann and Tscharntke, 2002), obtained from Rasmont et Iserbyt (2014).

$$Y=-232.28+54.69*L$$

Equation 10. Mathematical model estimating the flight range of wild bees from their body length (Gathmann and Tscharntke, 2002). Y: flight range (m), L: Body length (mm).

When the calculated flight range was over 1500m, a flight range of 1500m was taken because it is the average maximal wild bee flight range that we considered in this study.

Table 2-39 synthetises the flight range of the wild bee species with the method used to estimate it.

Table 2-39. Flight range of the wild bee species, having a clear role in pollination, present in the municipal forest of Sivry-Rance within a 1.5km radius, estimated from a literature review or the mean of two mathematical models of the flight range from the insect characteristics (Gathmann and Tscharntke, 2002; Greenleaf et al., 2007), adapted from Monseu (2021).

Species	**Flight range (m)**	**Method**	**Source**
Andrena cineraria L.	300	Literature review	Gebhardt and Röhr 1987
Andrena fulva M.	575	Mean of two mathematical models estimating the flight range	
Andrena nitida M.	640		
Andrena sabulosa S.	560		
Anthophora plumipes P.	1500		
Bombus hortorum L.	1500	Literature review	Walther-Hellwig and Frankl 2000
Bombus lapidarius L.	1400	Literature review	Walther-Hellwig and Frankl 2000, Knight et al. 2005
Bombus pascuorum S.	1500	Literature review	Knight et al. 2005
Bombus pratorum L.	1500	Literature review	Knight et al. 2005
Bombus sylvestris L.	1487	Mean of two mathematical models estimating the flight range	
Bombus terrestris L.	1500	Literature review	Osborne et al. 2008

The relative abundance index was calculated as the proportion of the number of individuals of one wild bee species on the total number of individuals of all the wild bee species from the data of the BDFGM. This proportion was then translated into the scale of 0 to 1 considering that 1 is the highest proportion (**Table 2-40**).

Table 2-40. Relative abundance index of the wild bee species, having a clear role in pollination, present in the municipal forest of Sivry-Rance within a 1.5km radius, estimated from the proportion of the number of individuals of one wild bee species on the total number of individuals of all the wild bee species from the data of the BDFGM, adapted from Monseu (2021).

Species	**Number of individuals**	**%**	**Relative abundance index**
Andrena cineraria L.	4	7	0.2
Andrena fulva M.	1	2	0.1
Andrena nitida M.	2	3	0.1
Andrena sabulosa S.	1	2	0.1
Anthophora plumipes P.	2	3	0.1
Bombus hortorum L.	1	2	0.1
Bombus lapidarius L.	5	8	0.2
Bombus pascuorum S.	39	66	1
Bombus pratorum L.	1	2	0.1
Bombus sylvestris L.	2	3	0.1
Bombus terrestris L.	1	2	0.1

Finally, we put the land cover map, the biophysical table and the pollinator table in the InVEST Crop pollination model. The model gives us two main results for the current state and the twelve pathways: (1) The pollinator supply of each pollinator species, and (2) the total abundance of pollinators in spring and in summer. These two last maps were summed up to obtain the index of pollinator abundance on each cell. We did a weighted mean by area of each land cover to obtain the mean pollinator abundance of the actual state and in each pathway.

6.8.3 Fine particles capture (NVE)

We used the formula of the amount of fine particles removed from the vegetation of NVE (version 2.2 for Wallonia) (Equation 11) (Pairon et al., 2022).

$$Capture = (D * C_{PM10} * 3.1536 * R)$$

Equation 11. Amount of fine particles removed from the vegetation (Pairon et al., 2022).

With:

- Capture: fine particles removed by the vegetation (kg/ha*an);
- D: deposition rate (mm/s) defined for each land cover (**Table 2-41**);
- C_{PM10}: fine particles concentration (µg.m^{-3}). A value of 22.7 was considered (annual mean in Flanders);
- R: resuspension constant, equal to 0.5 (value used in most of the studies (Pairon et al., 2022)).

Table 2-41. Deposition rate of the land covers of the municipal forest of Sivry-Rance with the correspondence of the land cover of NVE, adapted from Pairon (2022).

Land cover	**Deposition rate (mm/s)**	**Land cover (NVE)**
Old hornbeam forest	0.5	Hardwood forest
Old oak hornbeam forest		
Coppice with standard		
Even aged hardwood forest		
Uneven aged mixed hardwood forest		
Alluvial forest		
Forest edge		
Young oak forest		
Old beech forest		
Young beech forest		
Even aged softwood forest	0.7	Softwood forest
Uneven aged softwood hardwood forest	0.6	Mixed forest
Gap	0.2	Grassland (important for biodiversity)
Water body	0.1	Rivers and standing water
Artificial area	0	Sealed soil

We summed up the quantity of fine particles captured by each land cover to have the total amount of fine particles captured in the current state and in each pathway.

7. Multi-criteria analysis

MCA is a commonly used analytical tool for assessing the impact of different decision alternatives based on a set of evaluation criteria (Lawrence et al., 2019). These criteria capture the key dimensions of the decision-making problem and are scored according to relative performance in achieving the objectives (Belton and Stewart, 2002; Langemeyer et al., 2015; Lawrence et al., 2019). They can be weighted and expressed in different units (e.g. monetary, qualitative, quantitative) without translating them into a single unit (e.g. money), which allows dealing with complex problems (Brander and van Beukering, 2015; Grima et al., 2017).

MCA is thus a means of simplifying complex decision-making situations with multiple and often conflicting objectives, that may involve many stakeholders, a diversity of possible outcomes, and many and sometimes intangible criteria by which to assess the outcomes (Cork and Proctor, 2005; Saarikoski et al., 2016). It formalizes the decision-making process in a transparent and consistent manner, leading to rational, justifiable and explainable decisions (Belton and Stewart, 2002; Langemeyer et al., 2015). It provides a model that can serve as focus for discussion and helps to structure the management problem (Belton and Stewart, 2002). These properties make MCA appealing and practically useful, being more and more used, in the recent years, in the environmental context (Michailidou et al., 2016).

Particularly, MCA is well suited to the integrated assessment of ES because it addresses plural value dimensions, including ecological and economic as well as cultural and moral aspects of a policy or management problem (Saarikoski et al., 2016; Vatn, 2009; Wegner and Pascual, 2011). Furthermore, it facilitates open and transparent public debate on the pros and cons of alternative courses of action, including the distribution of gains and losses across beneficiaries of ES (Saarikoski et al., 2016).

MCA is also used to assess resilience (e.g. Seidl et al. 2011, Jactel et al. 2012, Lawrence et al. 2019) sometimes combined with an ES assessment (e.g. de Chazal et al. 2008, Li et al. 2014, Malekmohammadi and Jahanishakib 2017). MCA acknowledges the complexity underlying interactions of SES by considering multiple criteria and alternatives (Malekmohammadi and Jahanishakib, 2017; Seidl et al., 2011a). Furthermore, it explicitly links the multiple stakeholders values enabling understanding the relationships between people and their environment (de Chazal et al., 2008). Finally, MCA allows combining ES and resilience assessments into one single framework.

Therefore, a MCA was performed to analyse the ES and their interactions as well as the resilience of the current state of the municipal forest of Sivry-Rance and in the twelve pathways.

7.1 Selection of the MCA method

A large number of MCA methods have been developed (see de Montis et al. (2005) for a detailed analysis of the pros and cons of various MCA methods in different appraisal contexts) (Saarikoski et al., 2019). They all at least roughly follow the typical steps but have different principles and procedures for eliciting and structuring information and involve different algorithms for combining it (Keisler and Linkov, 2014). There is no better or worse technique, but each one is suitable to different problems according to their specific characteristics (Michailidou et al., 2016).

Because we want to compare the different values of ES to understand their interactions and to analyze resilience, we did not consider any method based on complete aggregation which needs to convert all the values into one single unit. On the other hand, we need to have a ranking at the end to select the best alternative. Outranking methods are thus a good compromise as they determine pairwise outranking assessments of each pair of alternatives to sort or rank the alternatives (Saarikoski et al., 2016), the best alternative being the one where a majority of criteria are good without having a majority of criteria that are bad. They consider that a true ordering of the alternatives is not always possible (in some cases, we cannot say that an alternative is better or worse than another) (Ananda and Herath, 2009). They are thus more flexible than other methods, in situations where aggregated scores are too close to judge that one alternative is better than another (Martin and Mazzotta, 2018). Furthermore, qualitative indicators can be used in outranking methods.

In outranking methods, stakeholders assign preference measures directly to the criteria, making more transparent the decision making process (Martin and Mazzotta, 2018). The preference measures also include the indifference and the incomparability (Munda, 2012). This allows the stakeholders to incorporate insufficient information to be more nuanced when comparing the alternatives (Martin and Mazzotta, 2018).

Finally, in outranking methods, the stakeholders can closely examine the actual differences between the alternatives. It forces them to focus their judgment on actual measurements and the degree of change, not scores, which can more fully inform choices among alternatives. (Martin and Mazzotta, 2018)

Several outranking methods exist such as PROMETHEE (Brans et al., 1986), ELECTRE (Figueira et al., 2013) or NAIADE (Munda, 2012). Among these methods, we selected PROMETHEE for several reasons. First, this method is considered to provide relevant and reliable results (Brans et al., 1986; Kiker et al., 2005; Zhang et al., 2009). Secondly, this user friendly method requires to specify fewer parameters and therefore less trial and error than other common outranking methods (e.g. ELECTRE) (Jactel et al., 2012; Martin and Mazzotta, 2018). Weights and preference functions can be easily changed and indicator values and alternatives added, allowing sensitivity analyses (Fontana et al., 2013; Hermans et al., 2007). On the contrary, in NAIADE, weights are not explicitly defined whereas it is important for transparent valuation (Saarikoski et al., 2016). Finally, the results easily understandable can be readily discussed with the stakeholders (Martin et al., 2018).

Other MCA methods such as AHP (i.e. pairwise comparison of criteria with regard to an overall goal and of alternatives against individual criteria, developed by Saaty (1980)) and ANP (i.e. generalization of AHP where the elements are interlinked to build a network to consider the feedbacks between the elements, developed by Saaty (2004)) are also based on pairwise comparisons and allow using qualitative indicators (Grima et al., 2017). However, these methods are more difficult to compute and the results are not easily understandable, complicating their uptake by the stakeholders (see Table 1 of Grima et al. (2017) who compare different MCA methods that can be used to assess ES in a participatory process).

7.2 Application of the MCA on the municipal forest of Sivry-Rance

The typical steps of the MCA were followed:

1. Define the objectives (step 2 of the Navigate framework);
2. Specify the alternatives (step 3, see Chapter 2 5. Pathways definition);
3. Assess the criteria (step 4, see Chapter 2 6. Ecosystem services assessment);
4. Assign weights to the criteria that reflect their relative importance (step 4, see Chapter 2 4.2.2. Second participatory workshop: the needs of the stakeholders);
5. Select and apply a mathematical algorithm for ranking alternatives (step 5, PROMETHEE);
6. Choose an alternative (step 6, see Chapter 2 8. Resilience assessment) (Ananda and Herath, 2009).

Most of the typical steps of the MCA were already developed in the previous sections. We will only explain the selection and application of the mathematical algorithm in the next paragraphs.

PROMETHEE, developed by Brans et al. (1986), provides a ranking of the compared alternatives as a function of their performance against several criteria, from the best to the worst, using the net flow (Brans and Vincke, 1985; Macharis et al., 2004). This method requires: (1) a matrix of criteria performance over the different alternatives, (2) for each criterion, whether it should be maximized or minimized, (3) the weights of the criteria, and (4) the specific preference functions for each criterion (Brans et al., 1986; Jactel et al., 2012).

In our case study, the matrix of criteria performance is the values of the different indicators of the twelve ES (i.e. twelve criteria) in the current state and in the twelve pathways (i.e. thirteen alternatives) (see Chapter 2 5. Pathways definition for the definition of the pathways and see Chapter 2 6. Ecosystem services assessment which details the assessment methods of the twelve ES) (Annex 7).

The three other parameters (i.e. maximize/minimize, weight and preference functions) were defined from the results of the second participatory workshop (see Chapter 2 4.2.2. Second participatory workshop: the needs of the stakeholders, for a detailed description of this workshop). As a reminder, from this workshop, the following information were gathered for the four 'homogenous' groups of stakeholders for each criterion: (1) their opinion (i.e. maximize, minimize or indifferent to the ES), (2) their weighting (i.e. the importance they give to the different ES), (3) their acceptable level of the ES (i.e. the minimal level that the ES should have), and (4) the satisfactory level of the ES (i.e. the level at which they feel satisfied by the ES).

The opinion was directly used to define whether each criterion and its corresponding indicators should be maximized (i.e. opinion: maximize or indifferent[13]) or minimized (i.e. opinion: minimize).

The stakeholders gave a weight to each criterion whereas the weight of each indicator needs to be put in PROMETHEE. We tested two ways of translating the weighting of the ES into the weight of the indicators of the ES: (1) the weight of the ES is divided by its number of indicators, and (2) each indicator receives the weight of the ES. Comparable rankings were obtained in PROMETHEE from these two translations of the weights, so the most logical (i.e. the first one so the weight of each ES matches the one defined by the stakeholders) was retained.

To define the preference functions, the opinion, the acceptable and satisfactory levels were used. As the weighting, the preference function in PROMETHEE must be defined for each indicator. The opinion, acceptable and satisfactory levels of each criterion was directly used for each of its corresponding indicator.

In PROMETHEE, the preference function is defined by two parameters: (1) an indifference threshold (Q) (i.e. the acceptable level), and (2) a strict preference threshold (P) (i.e. the satisfactory level) (**Figure 2-20**) (Jactel et al., 2012).

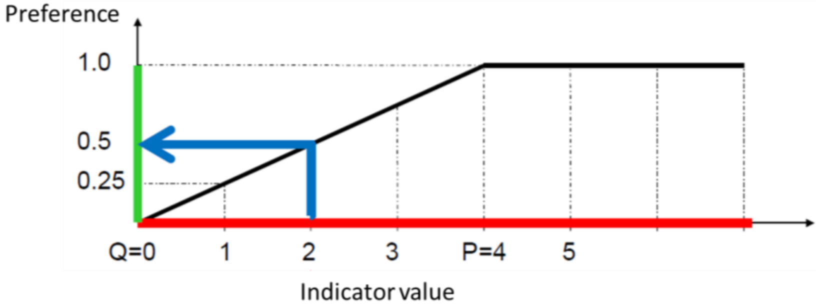

Figure 2-20. Example of a preference function of an indicator in PROMETHEE. In green, it is the preference ranging from 0 (zero preference) to 1 (maximal preference). In red, the values taken by the indicator with the indifference threshold (Q) and the strict preference threshold (P). The blue arrow gives an example of the preference given to the value 2 of the indicator. Adapted from Jactel (2019).

[13] When you are indifferent, it means that your preference is the same whatever the value of the indicator. Thus, whether you choose the maximize or minimize option, we got the same result.

First, the preference function shape was selected among the six possible shapes (**Figure 2-21**) for each indicator using the following rules:

- When the opinion is indifferent, the usual shape function was chosen;
- When the acceptable and satisfactory levels are the same (Q=P), the U-Shape function was selected;
- When the acceptable level was “Very low” (i.e. the lowest value the stakeholders could chosen), the V-Shape function was chosen;
- In the other cases, when the indicator was qualitative, the Level function was selected;
- In the other cases, when the indicator was quantitative, the Linear function was chosen.

We did not consider the Gaussian function as a third parameter (S, standard deviation of the preference function) should have been defined by the stakeholders, this one being too difficult to estimate for them.

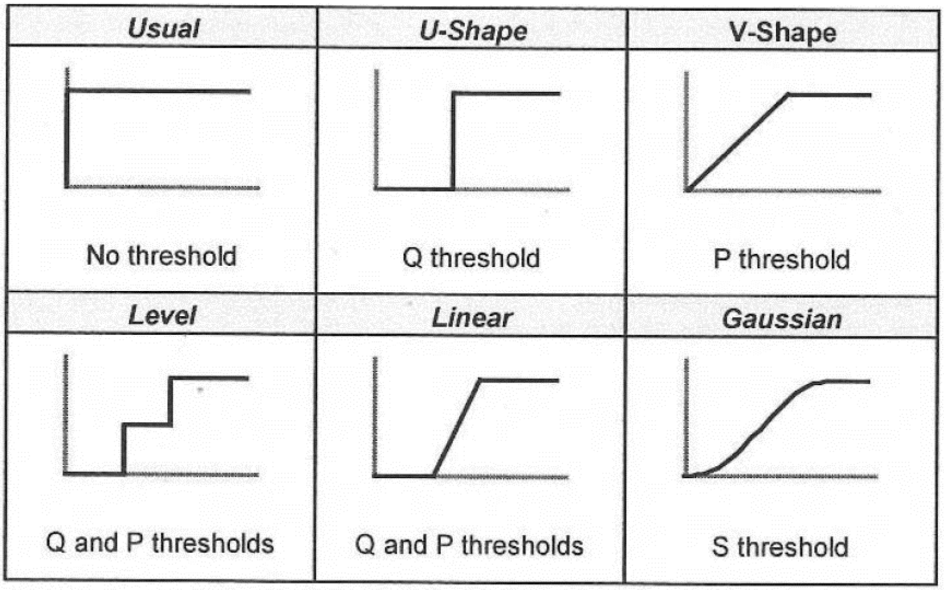

Figure 2-21. Six shapes of the preference functions to be defined in PROMETHEE depending on the indifference threshold (Q) and the strict preference threshold (P). The S threshold is the standard deviation of the Gaussian shape. (Jactel, 2019)

Then, the acceptable and satisfactory levels given by the four groups of stakeholders were transformed for each indicator to obtain the Q and P thresholds, taken inspiration from the methodology developed by Kodikara et al. (2010). For the qualitative indicators, the five-point scale ranging from very low to very high is the same as the one used by the stakeholders to define their acceptable and satisfactory levels. This scale was transformed into quantitative value given an integer ranging from 0 (i.e. very low) to 4 (i.e. very high). For the quantitative indicators, their range of values was divided into five intervals, so it was possible to link their values to the five-point scale used by the stakeholders. We also tested two ways of building the five intervals:

1. The range of values was divided according to the distribution of the values to have intervals that regroup close values with a similar number of values in each of the five intervals (e.g. for the growing stock of wood (m^3/ha), the five following intervals were defined: (1) 186-191 (4 values), 194-198 (2 values), 212-234 (3 values), 326-368 (2 values), and (5) 412-438 (2 values));
2. The range of values was divided in five intervals of the same length.

The mid-point of each interval was then calculated to obtain the Q and P thresholds. Comparable rankings were obtained in PROMETHEE from these two ways of building the intervals, so the most logical (i.e. the first one that considers the distribution of the values) was retained.

One of the four groups did not give the acceptable and satisfactory levels of any ES during the second participatory workshop (see **Table 3-26**). For this group, we used the three following rules to define the two levels:

- When they indicated they wanted to maximize the ES, we considered a medium level for the acceptable level and a high level for the satisfactory level for this ES;
- When they indicated they wanted to keep the ES identical, we considered a medium level for the acceptable and satisfactory levels;
- When they indicated they wanted to minimize the ES, we considered a very low level for the acceptable and satisfactory levels for this ES.

Four scenarios were created in the PROMETHEE software (version 1.9), each one corresponding to the preferences of one of the four groups of stakeholders. For each scenario, the following data were put:

1. The matrix of the ES indicators values X thirteen alternatives (same matrix for the four groups of stakeholders);
2. Whether the indicator is maximized or minimized according to the corresponding group of stakeholders;
3. Its weight;
4. Its preference function shape along with the P and Q thresholds.

From these data, the PROMETHEE software calculated, for each of the four scenarios:

1. The outgoing flow ($\Phi^{+}_{(a)}$) for each alternative to estimate how far it outranks other alternatives;
2. The incoming flow ($\Phi^{-}_{(a)}$) to estimate how far it is outranked by other alternatives;
3. The net flow as the difference between the two unidirectional flows ($\Phi_{(a)}$ = f$\Phi^{+}_{(a)} - \Phi^{+}_{(a)}$). (Jactel et al., 2012)

The four scenarios were also used as a sensitivity analysis to see how the changes in the parameters (i.e. minimize/maximize, weighting and preference function) influenced the ranking of the thirteen alternatives.

8. Resilience assessment

The resilience of the different pathways was assessed in two different ways. First, the resilience of ES was captured by analysing the diversity of ES that answer the needs of the stakeholders (defined in the second participatory workshop) in each pathway. Two results from the PROMETHEE software were used:

1. The ranking of the twelve pathways for each of the four groups of stakeholders (i.e. the best pathway(s) being the ones that provide(s) the ES needed by the stakeholders);
2. The contribution of each ES to the ranking of the pathways (i.e. Does the ES contributes positively or negatively to the ranking of the pathways and to which extent?).

Secondly, the social resilience was studied. The preferences of the stakeholders (defined in the second participatory workshop) were changed four times (i.e. the four scenarios in PROMETHEE) to see how the variation in societal demand modified the preferred pathway(s). We compared the ranking of the twelve pathways of the four groups of stakeholders to see to what extent the preferences influence the ranking. The vulnerability of the stakeholders was also examined by looking at the ES and their respective stakeholders that are negatively impacted by climate change.

Based on the assessment of the resilience of ES and the social resilience, the best pathway(s) is/are the one(s) that provide(s) a diversity of ES answering the needs of the stakeholders whatever their preferences are, being the one(s) that has/have a good ranking in all four scenarios.

Chapter 3

Results

1. Step 1: Define the system

The system (i.e. the municipal forest of Sivry-Rance) is first described. Then, its dynamics are discussed to finally develop the interactions between its components and the scales.

1.1 Define the territory

The municipal forest of Sivry-Rance was analysed based on four sources of information:

1. Review of existing information (see Chapter 2 3. Review of existing information);
2. Stakeholder analysis (see Chapter 2 4.1 Stakeholder analysis);
3. Surveys of the forest users (see Chapter 2 4.3. Surveys of the forest users);
4. Forest attendance assessment (see Chapter 2 6.3. Forest attendance assessment).

First, its ecological context is detailed. Then, its management and the nature conservation and restoration actions are described. Finally, the stakeholders are presented along with the recreation activities. Because little is known about these recreation activities while they are important in the municipal forest of Sivry-Rance, they are more detailed than the other thematises.

1.1.1 Ecological context

The ecological context is already detailed in the presentation of the case study (see Chapter 2 2.2. Ecological context). In addition, the map of the site groups from the site directory of Fagne, Famenne et Calestienne (Legrain, 2022) (see **Table 2-15** for the site groups with a short description) is given (**Figure 3-1**). The cool plateaus and slopes (47% of the forest area) stand the mesic plateaus and slopes (30%). Xeric plateaus are distributed throughout the area (6%). The alluvial sites (7%) and southern slopes (8%) are mainly around the rivers. The very wet sites are poorly represented (2%).

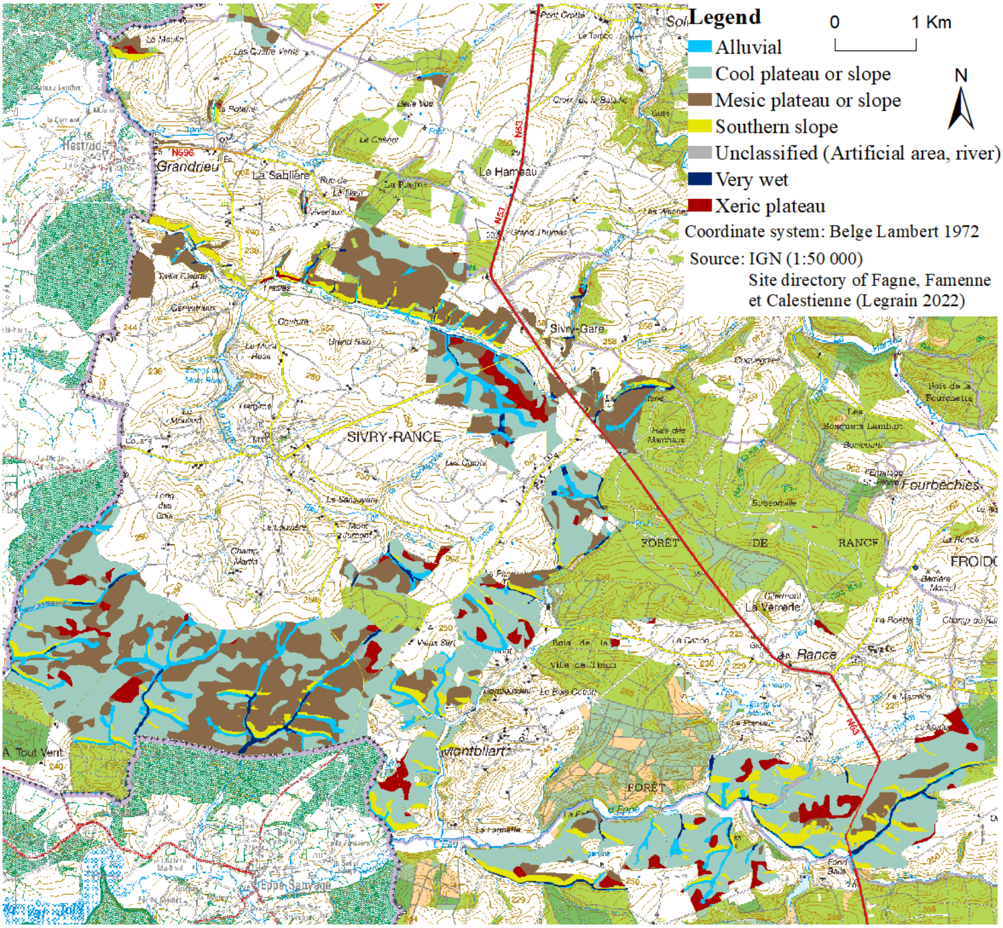

Figure 3-1. Site groups of the site directory of Fagne, Famenne et Calestienne of the municipal forest of Sivry-Rance, adapted from Legrain (2022).

1.1.2 Forest management

The owner and the manager of the municipal forest of Sivry-Rance have been already presented in the description of the case study (see Chapter 2 2.1. Owner and manager) alongside with the different forest stands and their management (see Chapter 2 2.3. Forest stands and their management). The forest management plan is detailed in Chapter 3 3.5. Multifunctional Forest.

1.1.3 Nature conservation and restoration

The nature conservation and restoration actions have been already discussed in the description of the case study (see Chapter 2 2.4. Nature conservation and restoration).

1.1.4 Stakeholders

The stakeholders, their relationships, interests, and influence were studied in the stakeholder analysis. The results are depicted in the ES stakeholder matrix (**Table 3-1**).

This matrix shows the variety of stakeholders interacting with the municipal forest of Sivry-Rance. Some stakeholders interact with multiple ES at different levels (e.g. the municipality of Sivry-Rance is the owner, manages some ES, benefits from some of them and is negatively impacted by others) while others are only linked to a few ES (e.g. fisher, nature associations, recreation users), knowing that one person can wear several hats (e.g. a fisher can also be a recreation user and a member of a nature association) (Pomeroy and Douvere, 2008). This matrix highlights potential conflicts between the municipality/DNF and some users (e.g. recreation users, hunters) and between users (e.g. forest operator and hunter or among recreation users).

Table 3-1. Ecosystem services stakeholder matrix for the municipal forest of Sivry-Rance. In blue, we added the stakeholders not mentioned during the interviews.

Ecosystem services	Owner	Manager	Beneficiary	Negatively impacted	Influencer
Wood	Municipality of Sivry-Rance	DNF Rural development associations Municipality of Sivry-Rance	Merchants Wood sector Inhabitants Municipality of Sivry-Rance CPAS	Hunters Recreation users Inhabitants	Walloon government (forestry code, land use code) DNF (forest management plan) European Union (Natura 2000 legislation)
Hunting		DNF Municipality of Sivry-Rance Hunters	Hunters Municipality of Sivry-Rance	DNF Municipality of Sivry-Rance Recreation users Forest operators Pickers River Contract[14]	Walloon government (Law on hunting) Municipality of Sivry-Rance (leasing contract)
Picking		DNF	Pickers	DNF Municipality of Sivry-Rance Forest operators Hunters	Walloon government (forestry code) Municipality of Sivry-Rance (permit application to pick mushrooms)
Fishing		Public Fishery Service Fishing associations DNF	Fishing associations Fishers	Poachers	Walloon government (forestry code) European Union (Natura 2000 legislation)

[14] Association regrouping the different partners of water management of a watershed.

Ecosystem services	**Owner**	**Manager**	**Beneficiary**	**Negatively impacted**	**Influencer**
Water quality & quantity	Municipality of Sivry-Rance	DNF Farmers River Contract Public Fishery Service	SWDE Local citizens Fishers		Walloon government (forestry code) European Union (Natura 2000 legislation)
Control of soil erosion & flooding		Farmers River Contract Public Fishery Service	Inhabitants		Walloon government (forestry code)
Fauna and flora		DNF River Contract	DNF Bee-keepers Naturalists		Walloon government (forestry code) European Union (Natura 2000 legislation)
Climate regulation and air purification		DNF	Local citizens Users		Walloon government (forestry code)
Natural surroundings		DNF	Local citizens		Walloon government (land use code)
Recreation		DNF Cultural Centers[15] Touristic associations Municipality of Sivry-Rance River Contract	Recreation users Recreation associations Tourism operators	Hunters Recreation users DNF Muncipality of Sivry-Rance	Walloon subsidies European subsidies

[15] Cultural center aims at promoting culture in a local community by organizing shows, exhibitions, conferences, etc.

Ecosystem services	**Owner**	**Manager**	**Beneficiary**	**Negatively impacted**	**Influencer**
Nature observation, learning and inspiration	Municipality of Sivry-Rance	Nature associations Researchers River Contract	Educational organizations Researchers Naturalists Students Artists Cultural Centers Universities Schools Photographers Fishing associations Inhabitants		Walloon subsidies European subsidies
Natural heritage		DNF Municipality of Sivry-Rance River Contract Nature associations	Local citizens Nature associations Museums Historians Researchers Recreation users		Walloon subsidies European subsidies

1.1.5 Recreation activities

A brief description of the recreation activities has already been given in Chapter 2 2.5. Recreation activities. To complete this information, the results of the four surveys of the forest users and the assessment of the forest attendance are presented below.

1.1.5.1 Surveys of the forest users

First, the number of respondents who answer their corresponding survey with their profile are given in **Table 3-2**. The recreation users are more represented than the others having more varied profiles. Still, they all have a common point: they are generally local (i.e. they come from the municipality of Sivry-Rance or the surrounding area).

Table 3-2. Number of respondents who answer their corresponding survey with their profile.

	Inhabitant harvesting firewood	**Hunter**	**Fisher**	**Recreation users**
Number of respondents	30	29	26	83
Living place	Inhabitants of the municipality of Sivry-Rance	Mainly local users (most of them do not live in the municipality of Sivry-Rance but come from the surrounding area)		
Gender	Mainly men			Balance between women and men
Age (years)	25-70	35->70	35-70	25->70

1.1.5.1.1 Descriptive analysis

From the descriptive analysis, we only present the most relevant graphs as it is not possible to present the thirty graphs produced for each of the four types of forest users. First, we discussed the harvesting of firewood by the inhabitants, then the hunting, the fishing, and finally the other recreation activities. After, we compared the activities and experiences of the four types of forest users.

The **inhabitants harvesting firewood** harvest on average fifty cubic meters a year (about three firewood lots), knowing they can buy up to two firewood lots and a third one if it is not sold (**Figure 3-2**). The number of harvested cubic meters varies from one inhabitant to another.

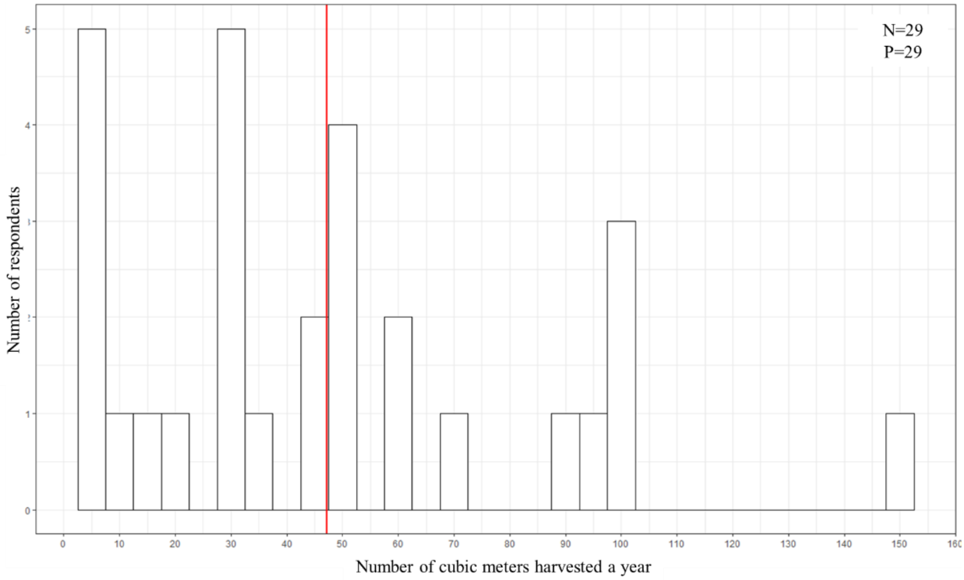

Figure 3-2. Number of cubic meters of firewood harvested a year by the inhabitants harvesting firewood. The mean is given by the red vertical line. N=Number of answers, P=Number of respondents.

In general, they harvest more firewood than the amount they use annually (**Figure 3-3**). They use on average twenty cubic meters a year, some using only a few cubic meters while others use more than fifty cubic meters.

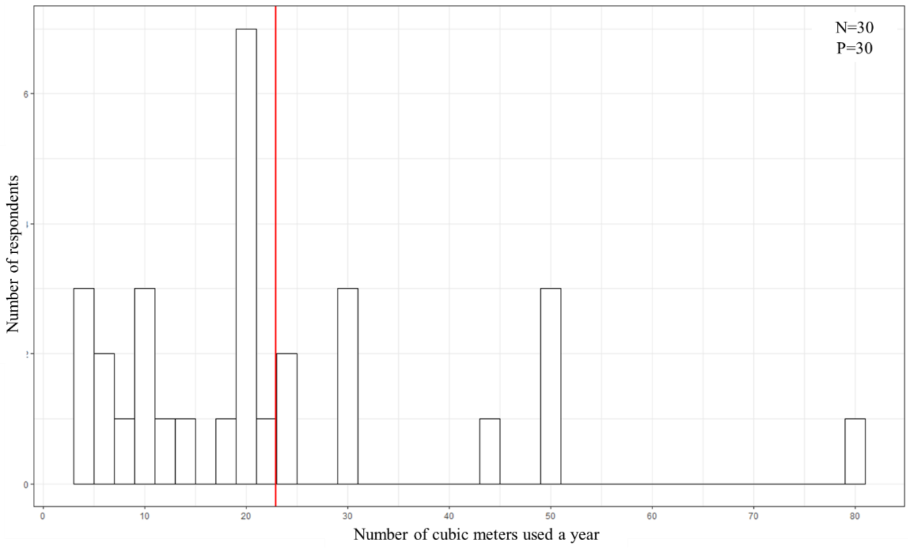

Figure 3-3. Number of cubic meters of firewood used a year by the inhabitants harvesting firewood. The mean is given by the red vertical line. N=Number of answers, P=Number of respondents.

The main reason of buying firewood in the municipal forest of Sivry-Rance is the proximity of this forest to their residence (**Figure 3-4**). They also take pleasure, are attached to the forest and its local heritage, and see this activity as a familial tradition, instead of its rentability.

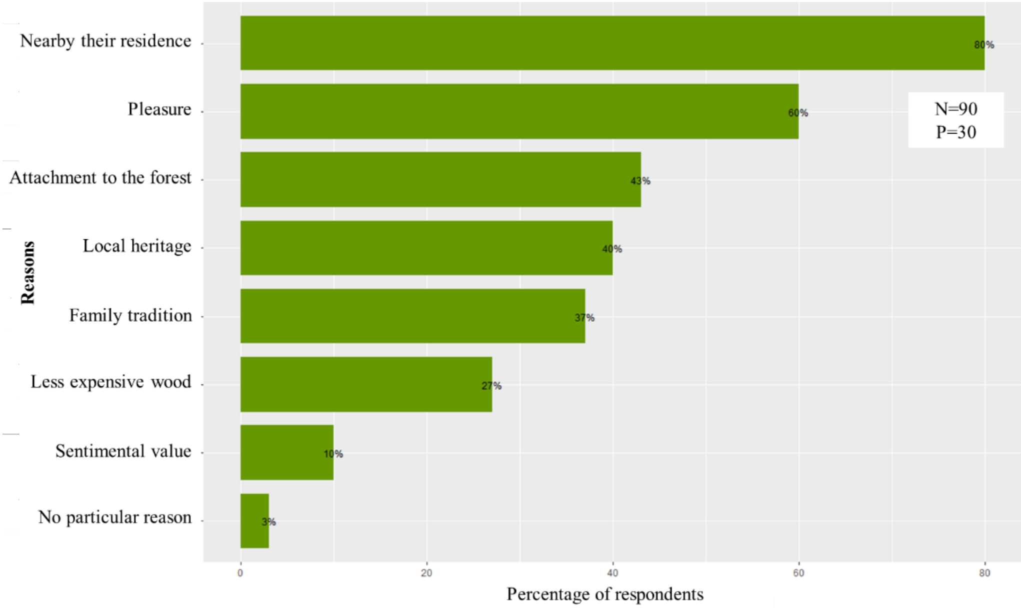

Figure 3-4. Reasons why the inhabitants harvesting firewood buy firewood lots in the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

Firewood harvesting is a familial activity as most of the inhabitants harvest firewood with family members (**Figure 3-5**). Almost half of the respondents harvest firewood alone and a quarter with friends.

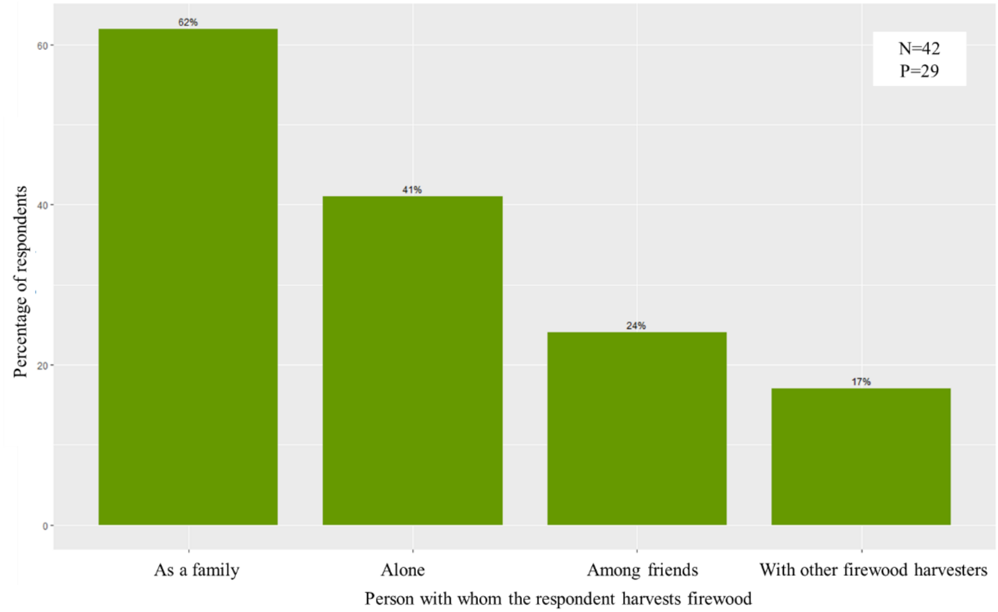

Figure 3-5. Person with whom the respondent harvests firewood in the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

The firewood they harvest is mostly for their personal use (Figure 3-6). The exceedance is given to other family members or friends. The resale is infrequent.

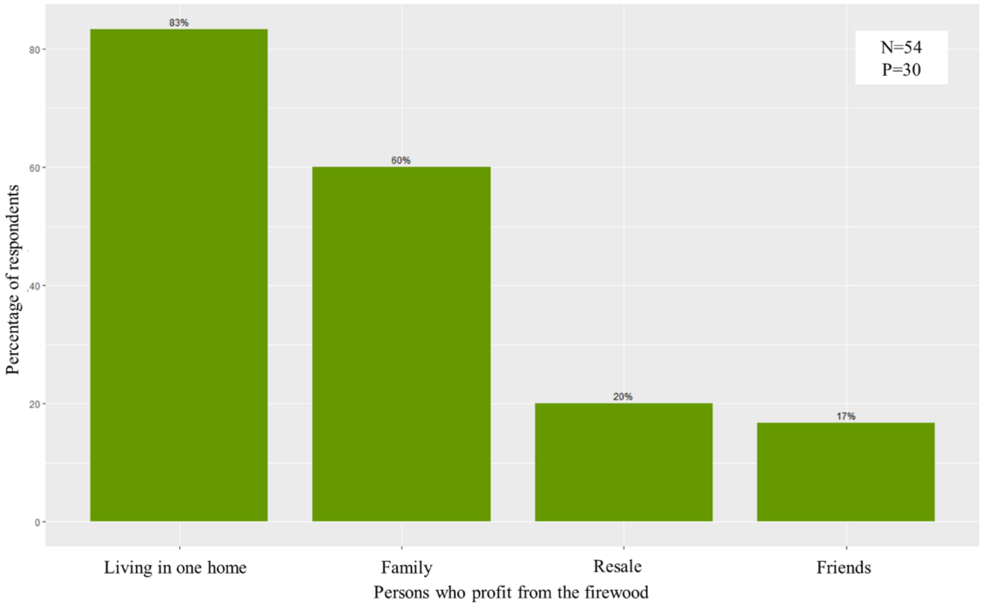

Figure 3-6. Persons who profit from the firewood harvested by the inhabitants of the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

To conclude, firewood harvesting is a local activity performed by inhabitants for pleasure with a strong attachment to the forest and its local heritage, as a family tradition (i.e. high relational value).

The **hunters** mainly hunt in the municipal forest of Sivry-Rance for the social interactions between the hunters (**Figure 3-7**). The next reasons are the proximity to their home and game quality. For some of them, it is also a family tradition.

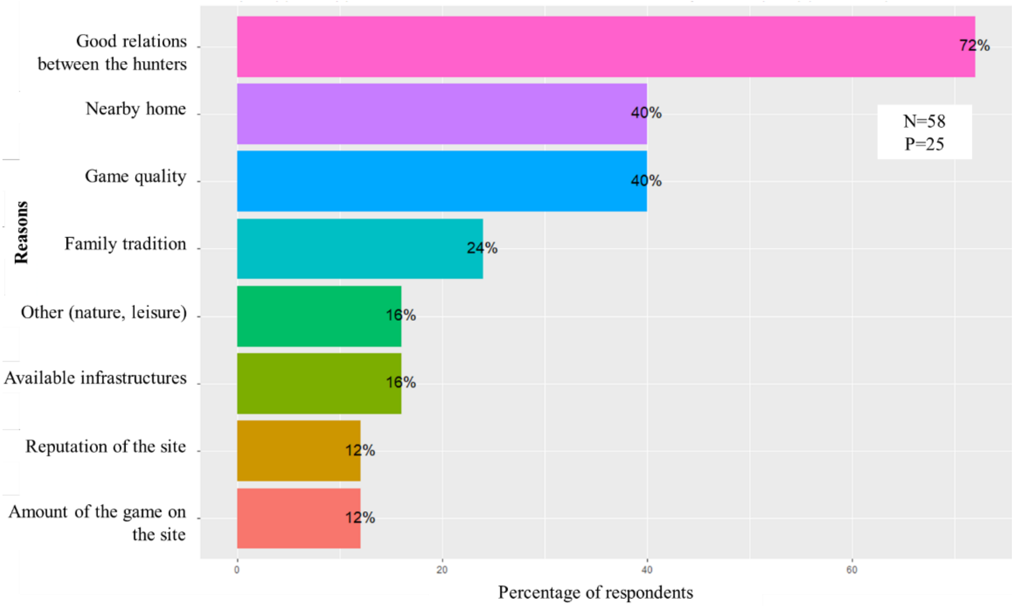

Figure 3-7. Reasons why the hunters hunt in the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

The hunters generally hunt in a group or among friends, showing once more how social interactions are important for them (**Figure 3-8**). Some of them hunt with family members or alone.

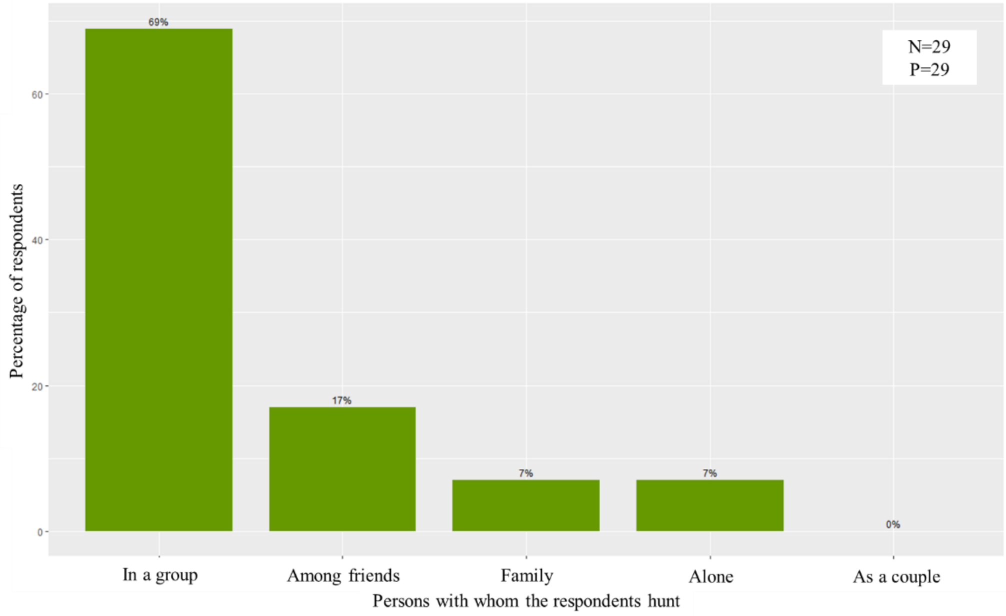

Figure 3-8. Persons with whom the respondents hunt in the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

All the hunters hunt roe deer and wild boar (**Figure 3-9**). Most of them also hunt fox and stray cat.

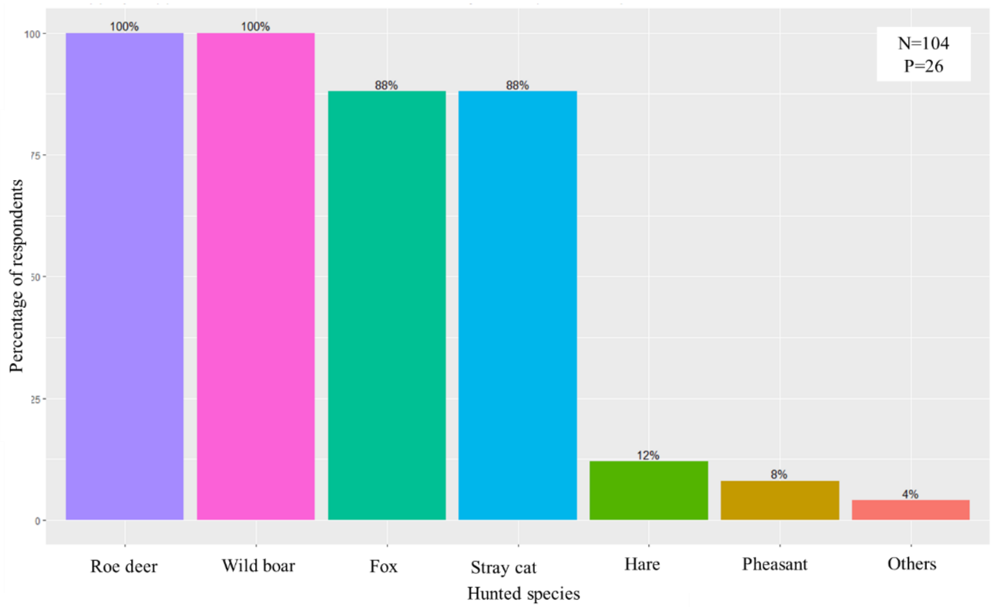

Figure 3-9. Hunted species in the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

To conclude, hunting is mainly a cultural activity that promotes social interactions (i.e. high relational value).

The **fishers** mainly fish for entertainment or pleasure (**Figure 3-10**). The proximity is another reason of fishing as well as the social interactions with friends or family.

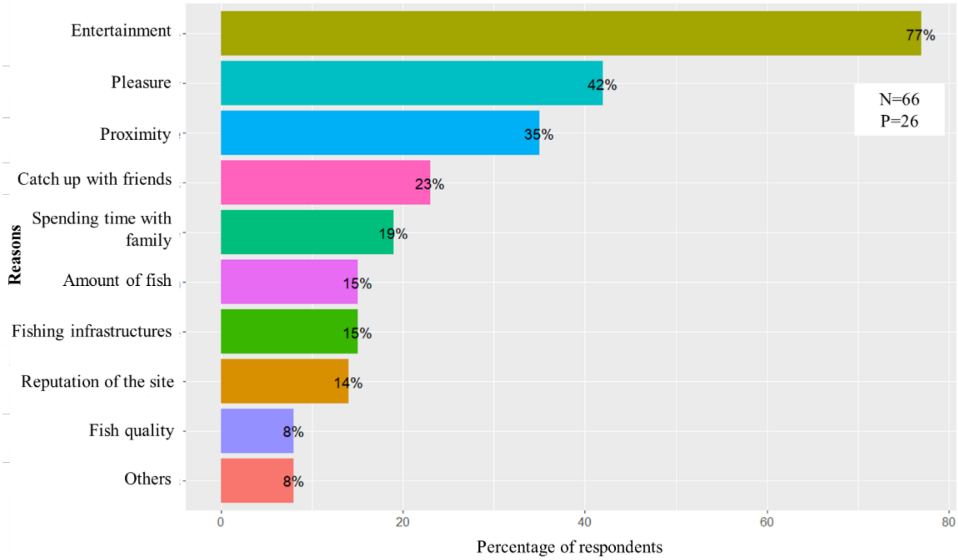

Figure 3-10. Reasons why the fishers fish in the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

The fishers either fish alone, with friends or family members (**Figure 3-11**).

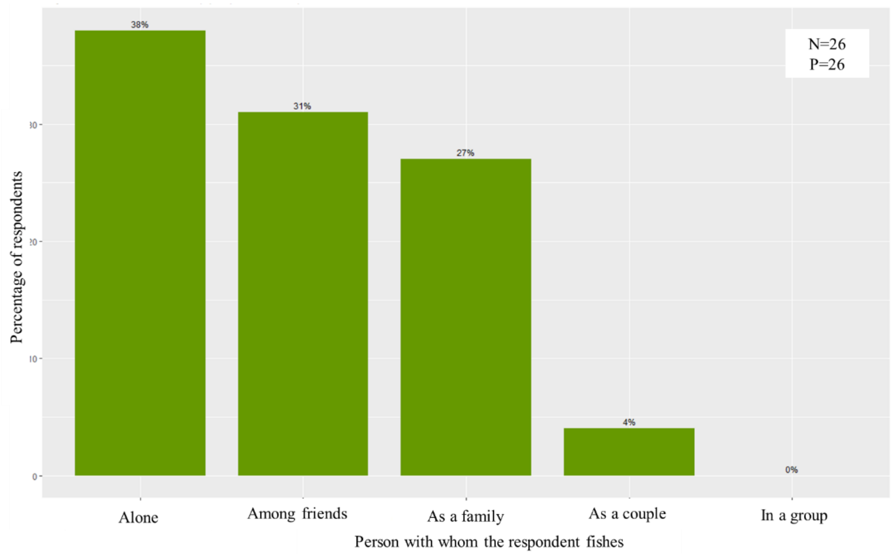

Figure 3-11. Person with whom the fishers of the municipal forest of Sivry-Rance fish. N=Number of answers, P=Number of respondents.

To conclude, fishing is mostly a cultural activity for entertainment and pleasure (i.e. high instrumental value) and for some of the fishers, it also promotes social interactions with friends or family members (i.e. medium relational value).

For the **recreation users**, they mainly come in the municipal forest of Sivry-Rance for a specific activity, its proximity and/or its landscape features (**Figure 3-12**).

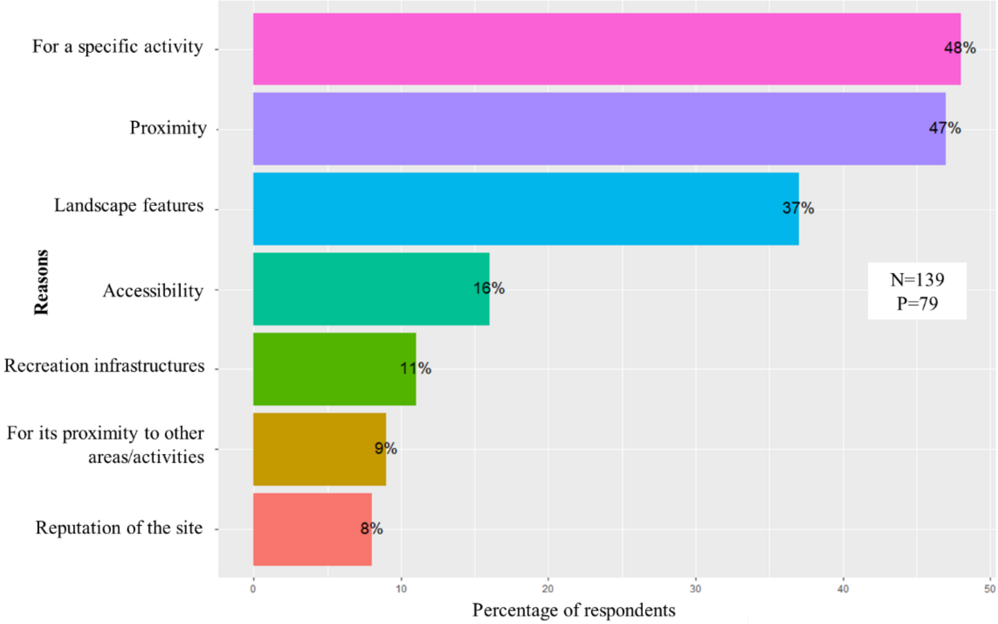

Figure 3-12. Reasons why the respondents come for a recreation activity in the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

They come in the municipal forest of Sivry-Rance for either a sportive or a nature activity (**Figure 3-13**).

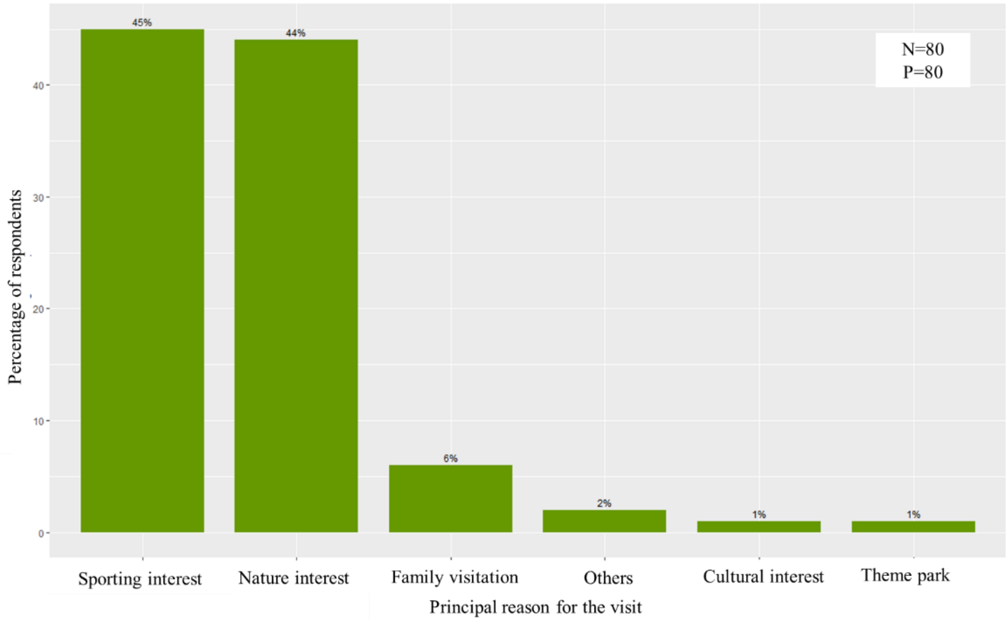

Figure 3-13. Principal reason for the visit of the municipal forest of Sivry-Rance of the recreation users. N=Number of answers, P=Number of respondents.

Indeed, the recreation users mainly undertake sportive activities (e.g. hiking, mountain biking, jogging and cycling) or nature activities (e.g. relaxing walk, nature watching, picking) (**Figure 3-14**). Most of them undertake several activities.

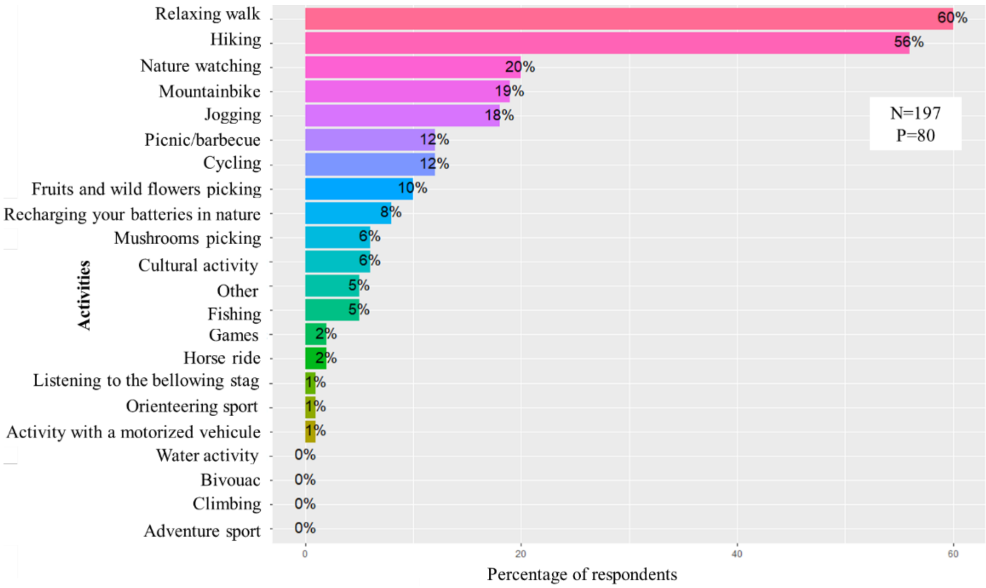

Figure 3-14. Activities undertaken by the recreation users in the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

To conclude, the recreation users mainly come in the municipal forest of Sivry-Rance to play sports (i.e. instrumental value) or enjoy the nature (i.e intrinsic value).

We also asked the inhabitants harvesting firewood, the hunters and fishers if they undertook other recreation activities in the municipal forest of Sivry-Rance. The **inhabitants harvesting firewood** mainly walk (**Figure 3-15**). A third of them do also mountain biking, picnic and barbecue as well as nature watching. A quarter of them fish, pick mushrooms, ride horse or hike.

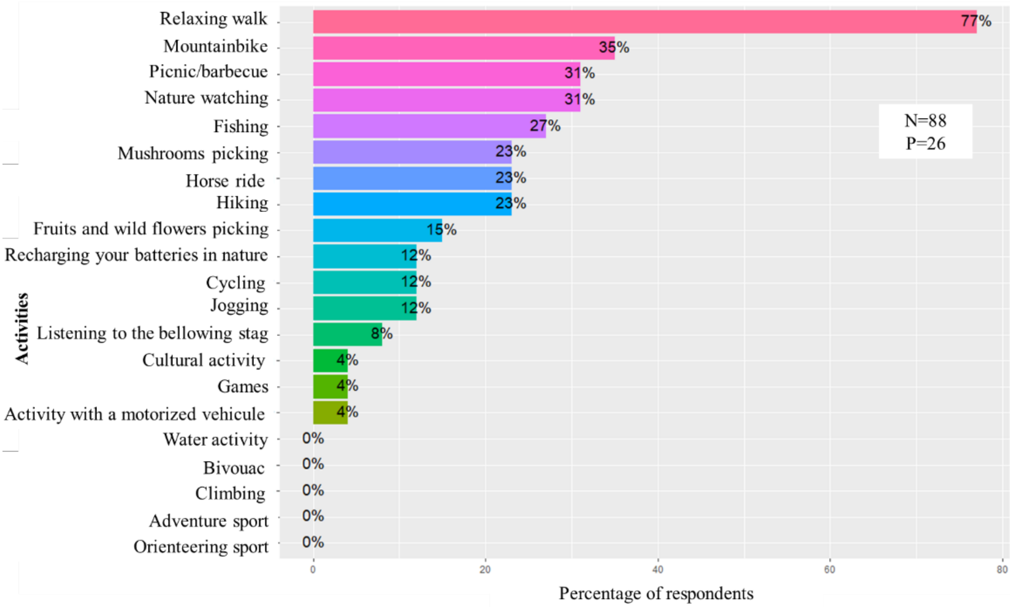

Figure 3-15. Recreation activities undertaken by the inhabitants harvesting firewood in addition to harvesting firewood in the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

Half of the **hunters** also walk in the municipal forest of Sivry-Rance (**Figure 3-16**). A third of them watch nature or pick mushrooms. They also have picnic or barbecue in the forest. A few of them do not undertake other recreation activities in addition to hunting.

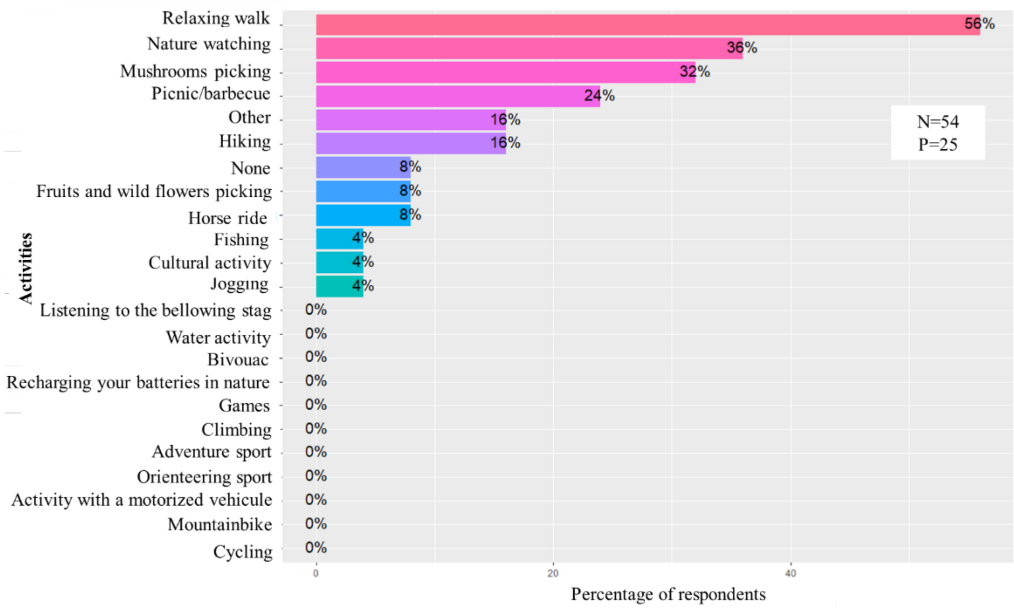

Figure 3-16. Recreation activities undertaken by the hunters in addition to hunting in the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

Half of the **fishers** do not undertake another recreation activity than fishing in the municipal forest of Sivry-Rance (**Figure 3-17**). For the others, they mainly walk. Some of them do also cycling or mountain biking.

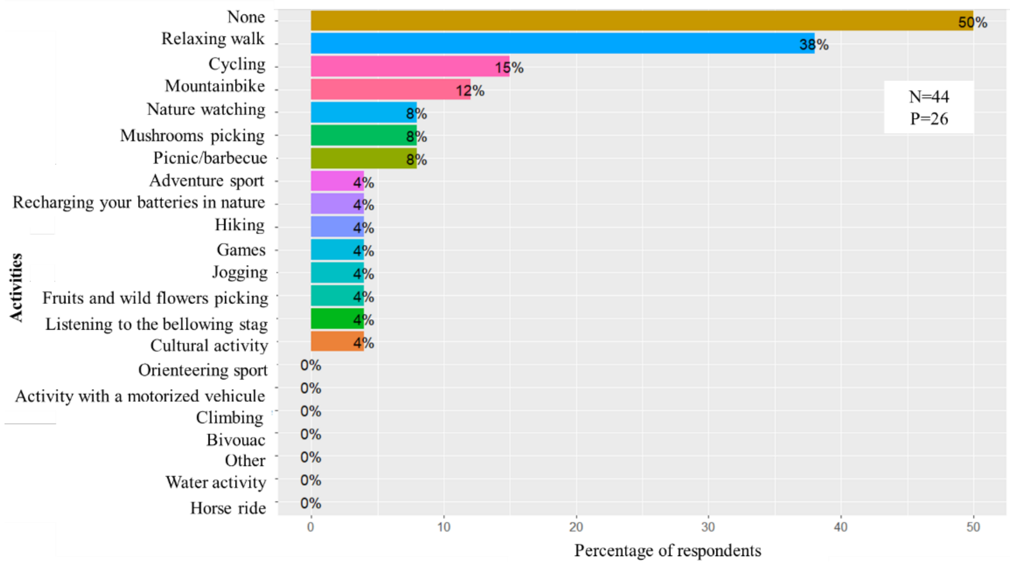

Figure 3-17. Recreation activities undertaken by the fishers in addition to fishing in the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

We also asked **all the forest users** what they like and dislike in the municipal forest of Sivry-Rance. Most of them like the quiet and calm to relax, and nature (**Figure 3-18** to **Figure 3-21**). The accessibility was mentioned by most of them except the fishers. The beauty of the landscape and natural setting was liked by most of them except the inhabitants harvesting firewood. Some hunters also like the social interactions between them and the hunting infrastructures. The relational value (i.e. quiet and calm to relax, heritage, beauty/wild look, social interactions) seems important for most of the forest users and for some of them, the intrinsic value is also important (i.e. nature).

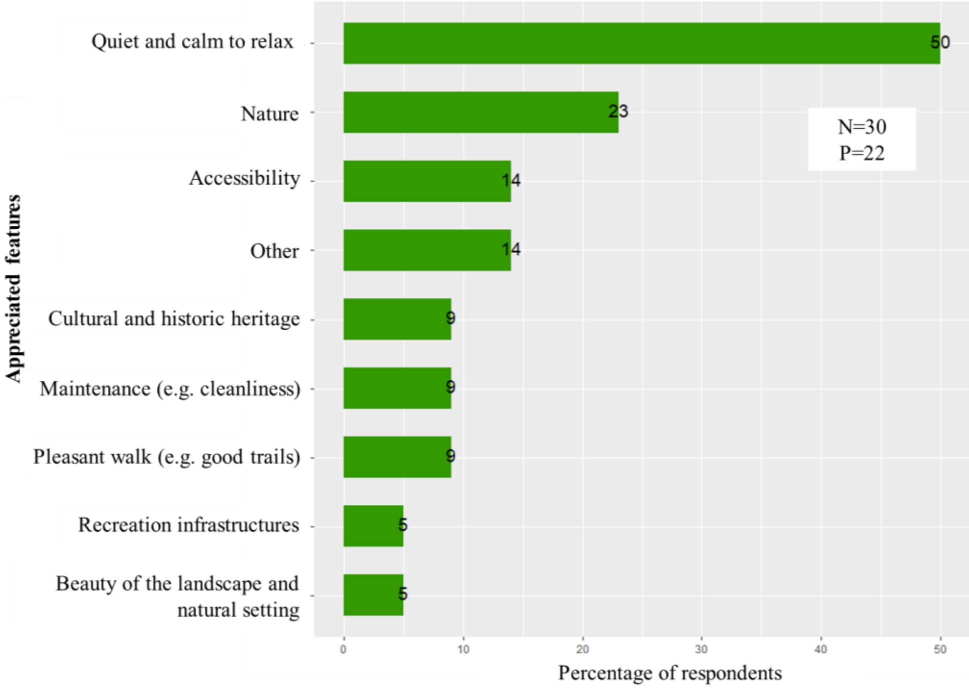

Figure 3-18. Appreciated features of the municipal forest of Sivry-Rance for the inhabitants harvesting firewood. N=Number of answers, P=Number of respondents.

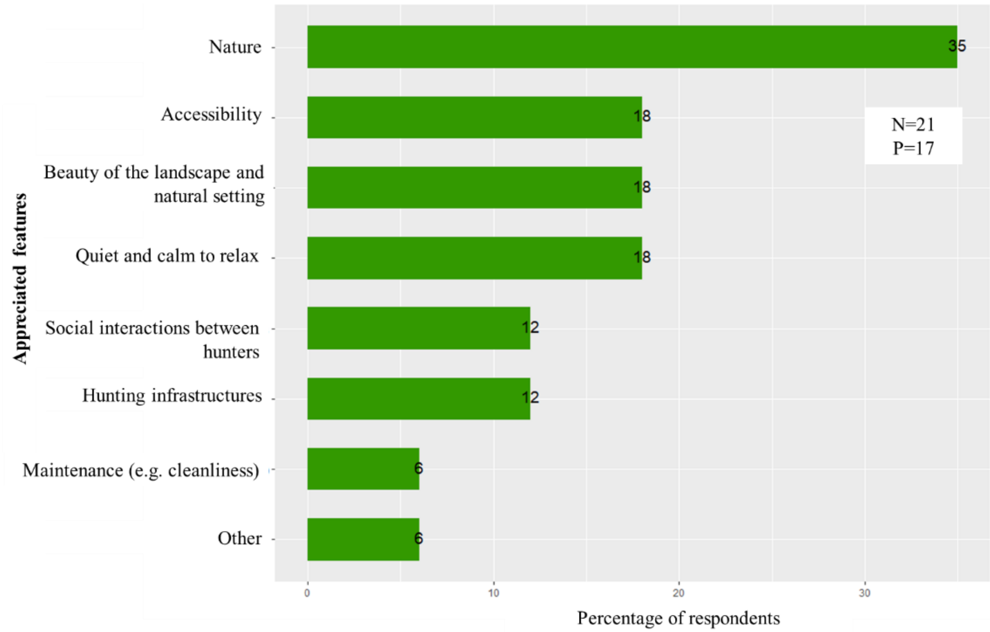

Figure 3-19. Appreciated features of the municipal forest of Sivry-Rance for the hunters. N=Number of answers, P=Number of respondents.

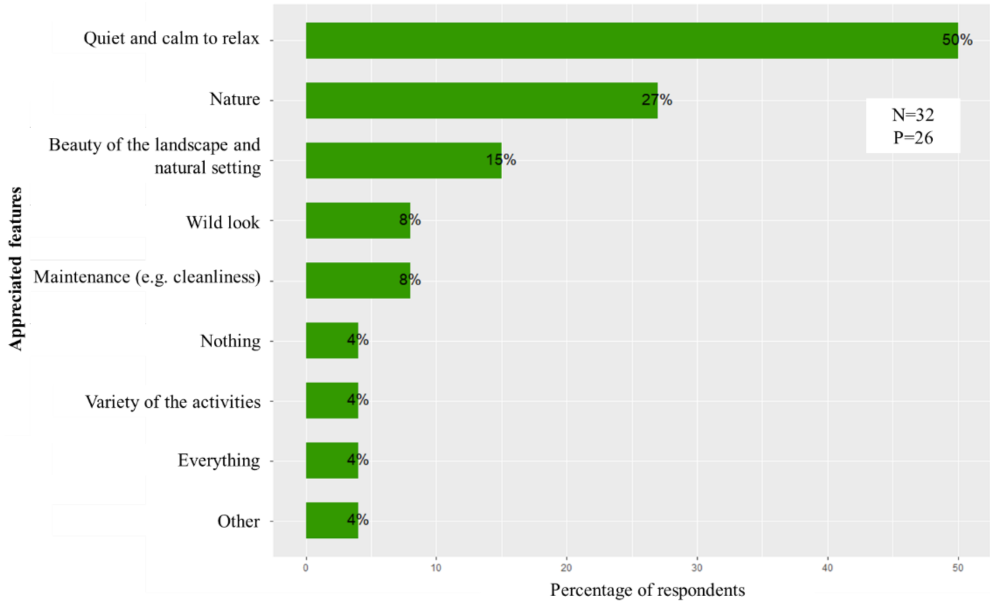

Figure 3-20. Appreciated features of the municipal forest of Sivry-Rance for the fishers. N=Number of answers, P=Number of respondents.

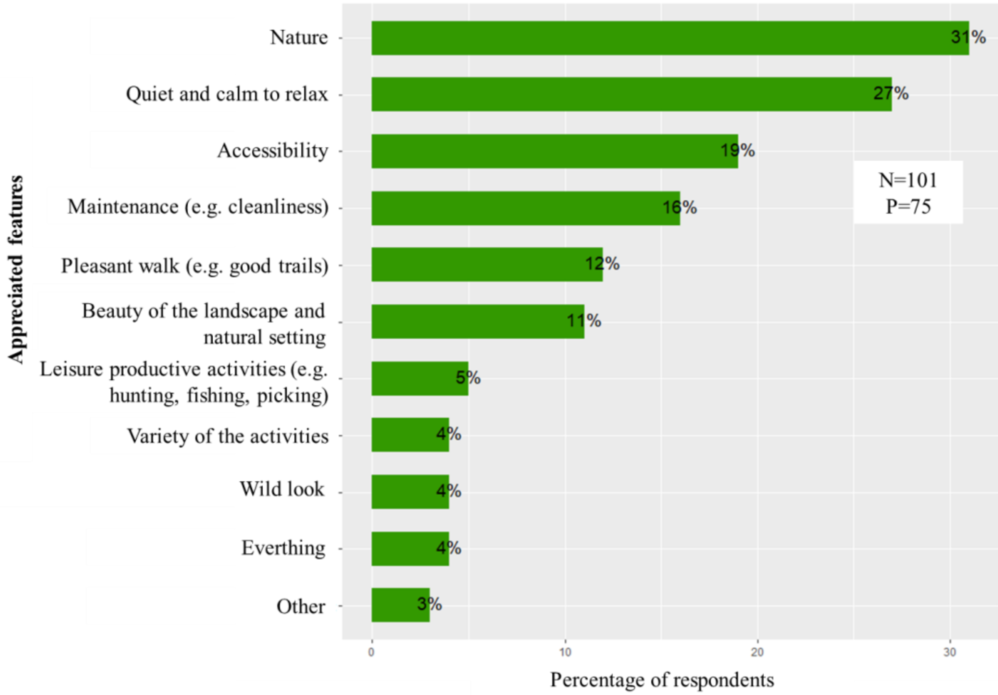

Figure 3-21. Appreciated features of the municipal forest of Sivry-Rance for the recreation users. N=Number of answers, P=Number of respondents.

Most of the forest users are annoyed by the waste, the visual and sound pollution in the municipal forest of Sivry-Rance alongside with the conflicts with other uses and users of the forest (**Figure 3-22** to **Figure 3-25**). The infrastructures conditions including the roads were also mentioned by some of them. For a quarter of the recreation users, nothing bothers them.

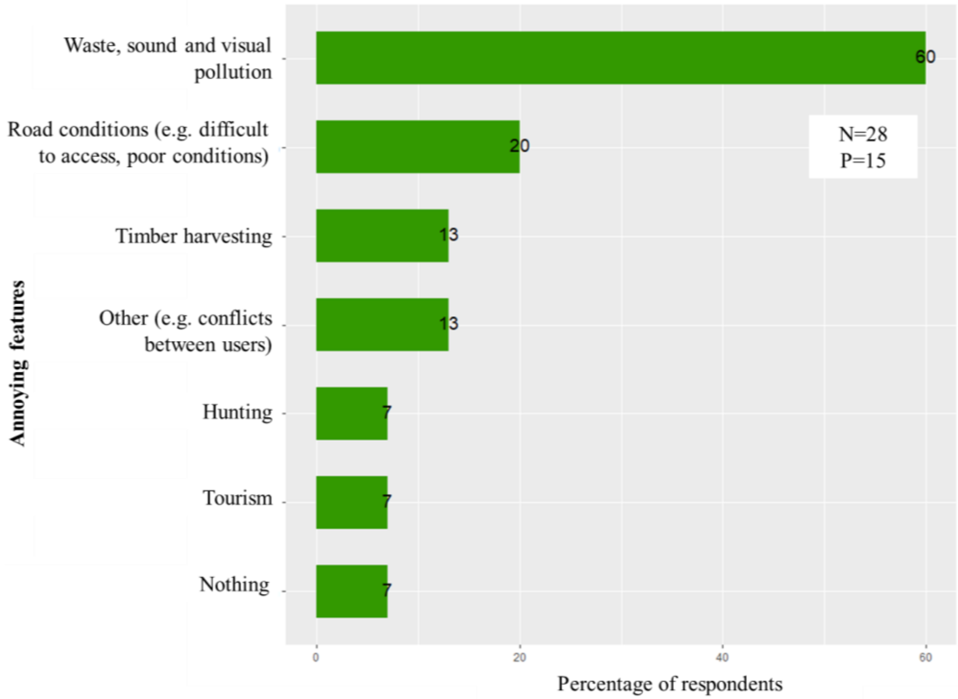

Figure 3-22. Annoying features of the municipal forest of Sivry-Rance for the inhabitants harvesting firewood. N=Number of answers, P=Number of respondents.

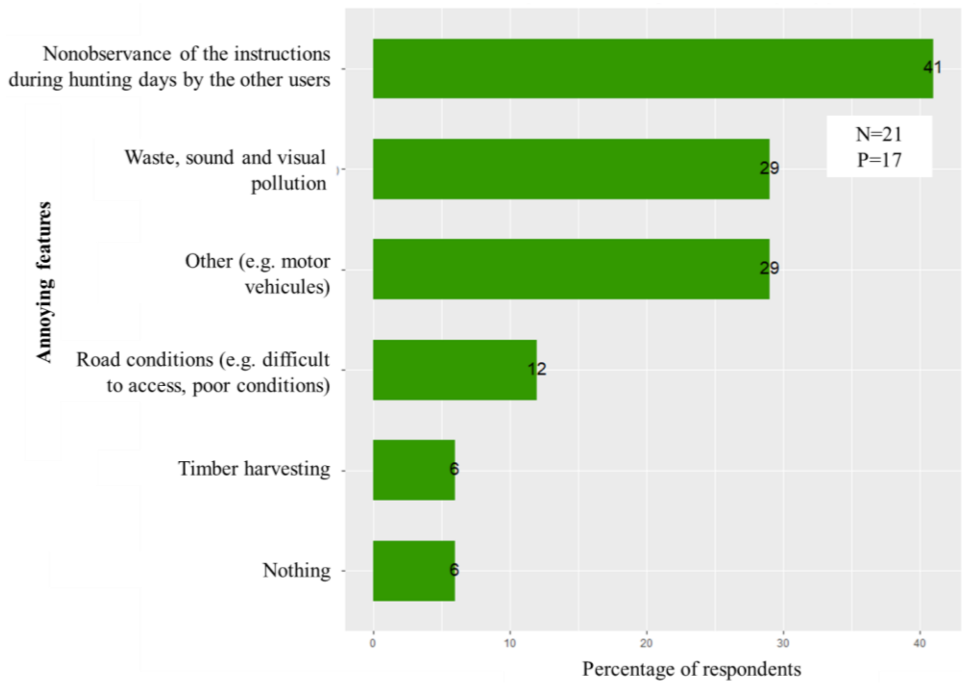

Figure 3-23. Annoying features of the municipal forest of Sivry-Rance for the hunters. N=Number of answers, P=Number of respondents.

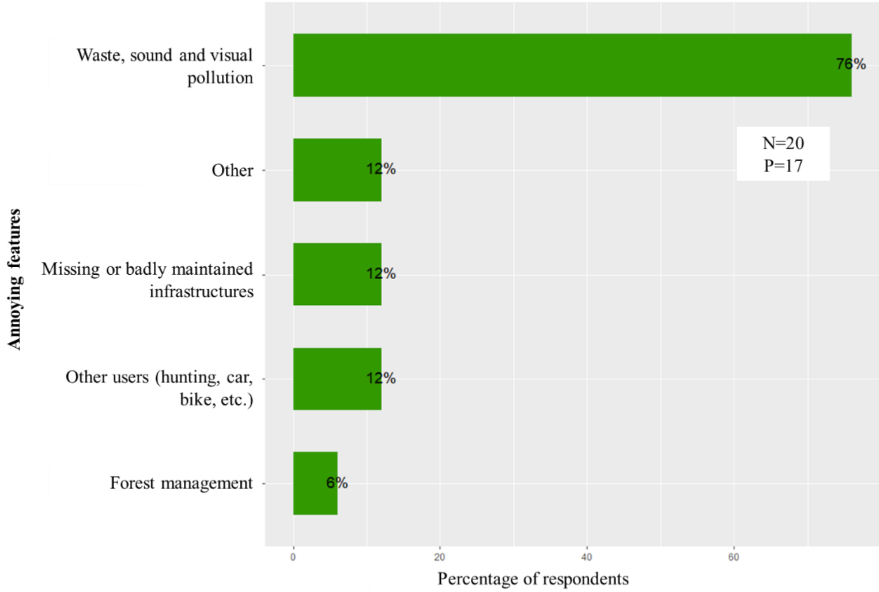

Figure 3-24. Annoying features of the municipal forest of Sivry-Rance for the fishers. N=Number of answers, P=Number of respondents.

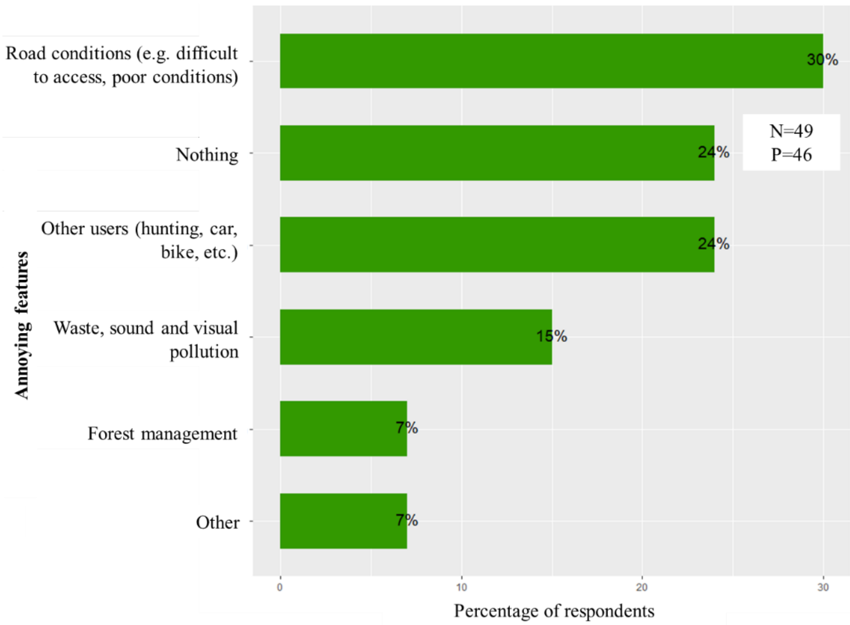

Figure 3-25. Annoying features of the municipal forest of Sivry-Rance for the recreation users. N=Number of answers, P=Number of respondents.

The socio-cultural values given to the municipal forest of Sivry-Rance by the forest users are then discussed. The highest socio-cultural values for the inhabitants harvesting firewood are the direct economic, biodiversity, aesthetic, life support and bequest values, followed by the inspirational/therapeutic, extensive recreation and indirect economic values (Figure 3-26). All these values have variable scores especially the direct and indirect economic ones. For the hunters, the highest socio-cultural value is the biodiversity one followed by the economic one that is more mixed (Figure 3-27). All the other socio-cultural values are less important and quite mixed except the intensive recreation, disservice and mistrust which are very low. The fishers give a high importance to the aesthetic value while all the others are less important but highly variable (Figure 3-28). For the recreation users, the extensive recreation, aesthetic, and inspirational/therapeutic values are on average the highest ones (Figure 3-29). The life support, bequest and biodiversity values are also important for them, followed by the patrimonial one. The other socio-cultural values are less important but mixed except for the intensive recreation, mistrust and disservice which are very low for all the recreation users. The type of specific values associated to the municipal forest of Sivry-Rance varies from one forest user type to another: the inhabitants harvesting firewood and the recreation users attach instrumental, intrinsic and relational values to the forest, while a majority of the hunters hold intrinsic and instrumental values unlike the fishers who hold instrumental values.

Table 3-3. The socio-cultural values presented to the respondents in the four surveys with their corresponding type of specific values (from the IPBES values assessment typology) Respondents could only see the explicative phrase (second column) and had 100 points to divide up between these socio-cultural values, adapted from Breyne et al. (2021).

Socio-cultural value	**Explicative phrase showed to the respondent**	**Type of specific values**
The municipal forest of Sivry-Rance is important to me because …		
Aesthetic value	… I can enjoy the views, sounds, smells, etc.	Instrumental
Biodiversity value	… they provide a habitat for wild animals, plants and microorganisms.	Intrinsic
Direct economic value	… they provide economic products such as timber, mushrooms, game, etc.	Instrumental
Indirect economic value	… they create jobs because of their touristic attractiveness, of which I can make use as a user or operator from the touristic sector.	Instrumental
Extensive recreation value	… they provide a space for my outdoor activities such as hiking, biking, observation of fauna and flora, etc.	Instrumental
Intensive recreation value	… they provide a space for my outdoor activities such as quad, 4x4, MTB circuits, mass events, etc.	Instrumental
Bequest value	… they allow future generations to know and experience these forests.	Relational
Patrimonial value	… they are part of the cultural patrimony in the same way as villages, abbeys, castles, etc., and they are part of the history of the region.	Relational
Relational value	… they provide a place to create or reinforce social relationships (outings with family or friends, working environment, etc.)	Relational
Mistrust value	… one could feel ill at ease in those forests because they create fears (of getting lost, they are dark and gloomy, etc.)	Relational
Life Support value	… in the battle against climate change and the maintenance of a healthy living environment through the renewal of soil, air, water, etc.	Instrumental
Inspirational/ Therapeutic value	… they are inspiring places and make one feel better, physically as well as mentally.	Relational
Disservice value	… they can also have a negative impact on daily life (less room for urbanization or agriculture, pests or damage by wildlife, etc.)	Instrumental

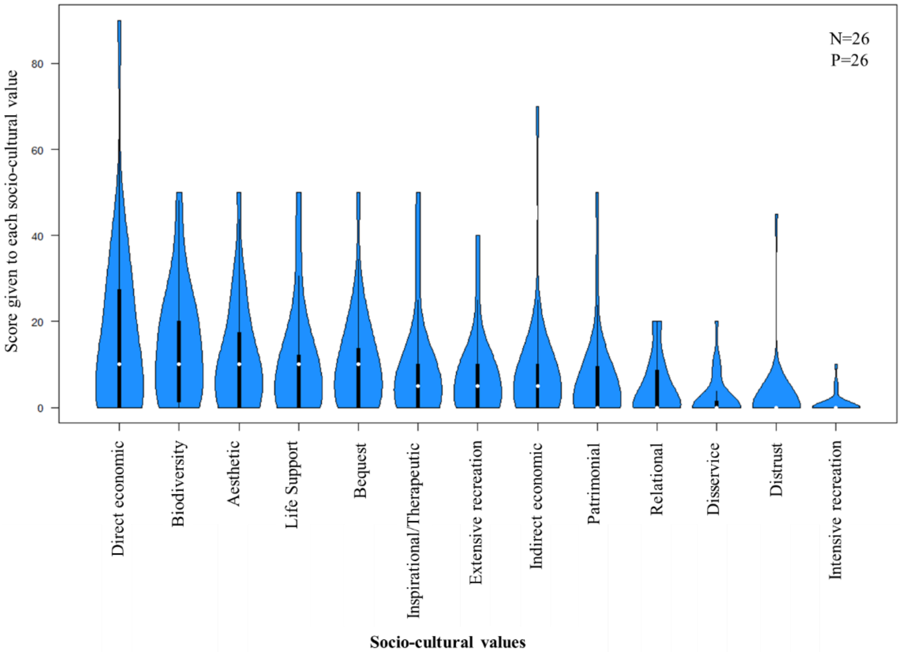

Figure 3-26. Violin plot of the scores given by the inhabitants harvesting firewood to the socio-cultural values of the municipal forest of Sivry-Rance, ordered by mean. N=Number of answers, P=Number of respondents. The socio-cultural values are explained in Table 3-3.

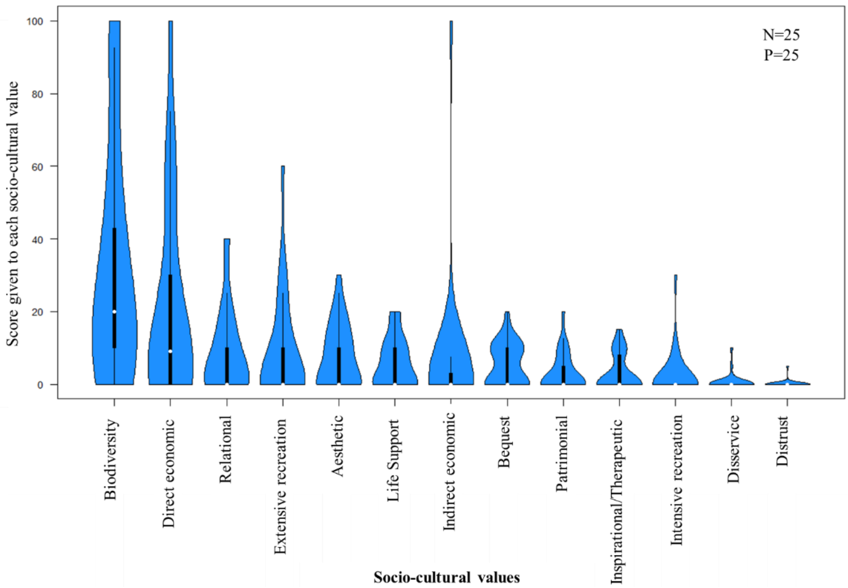

Figure 3-27. Violin plot of the scores given by the hunters to the socio-cultural values of the municipal forest of Sivry-Rance, ordered by mean. N=Number of answers, P=Number of respondents. The socio-cultural values are explained in Table 3-3.

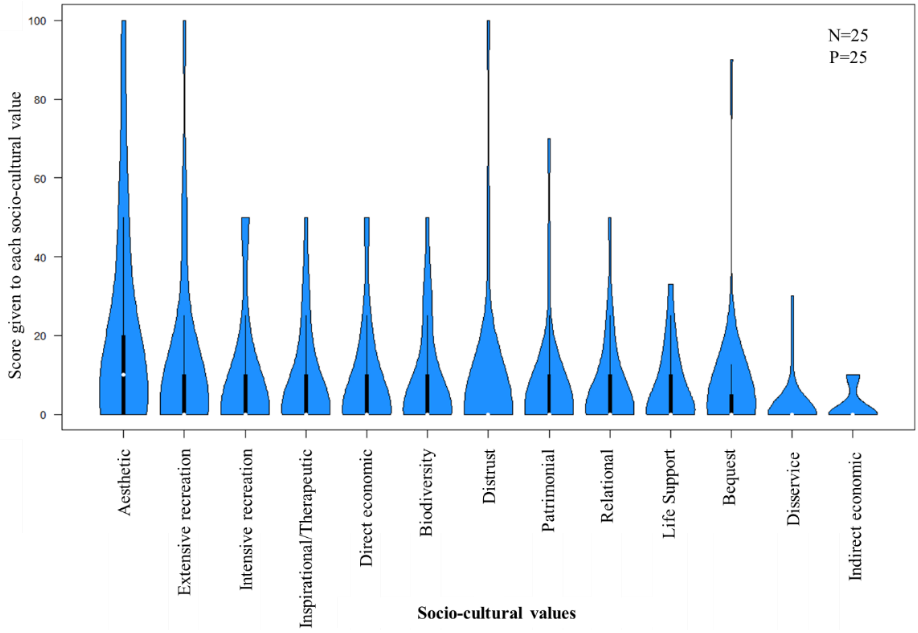

Figure 3-28. Violin plot of the scores given by the fishers to the socio-cultural values of the municipal forest of Sivry-Rance, ordered by mean. N=Number of answers, P=Number of respondents. The socio-cultural values are explained in Table 3-3.

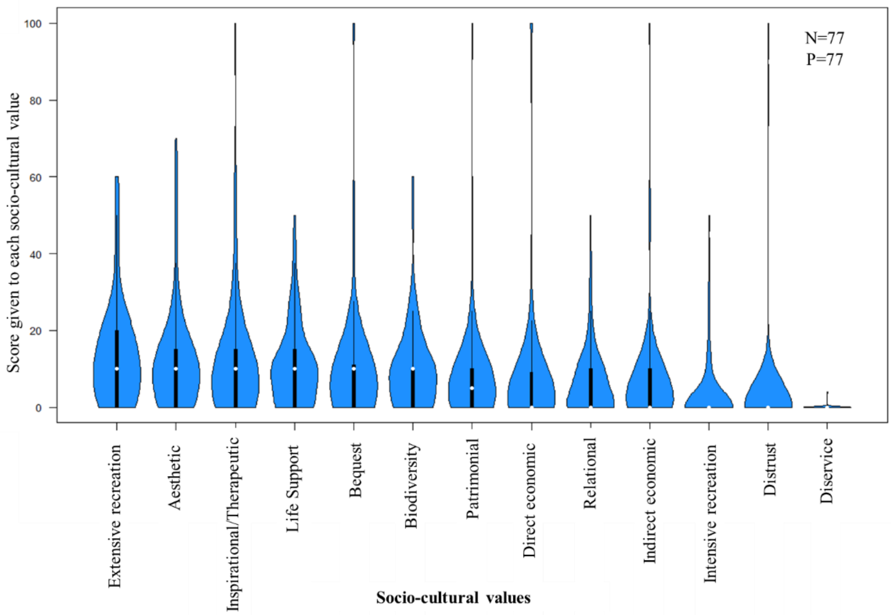

Figure 3-29. Violin plot of the scores given by the recreation users to the socio-cultural values of the municipal forest of Sivry-Rance, ordered by mean. N=Number of answers, P=Number of respondents. The socio-cultural values are explained in Table 3-3.

To conclude, the socio-cultural values vary from one forest user type to another but also among the same forest user type. Still, some values are shared among the same forest user type but also by all of them (i.e. biodiversity value).

Finally, the preferences for the tourism infrastructures are depicted for all the respondents (except the hunters who did not have these questions) regardless of the forest user type because the preferences are quite similar from one forest user to another. When there are some differences, they are discussed.

The respondents mainly prefer to have a standard information system (**Figure 3-30**). Some of them prefer to have a large information system especially the inhabitants harvesting firewood (32% of them) except some fishers who prefer having no information system (19% of them).

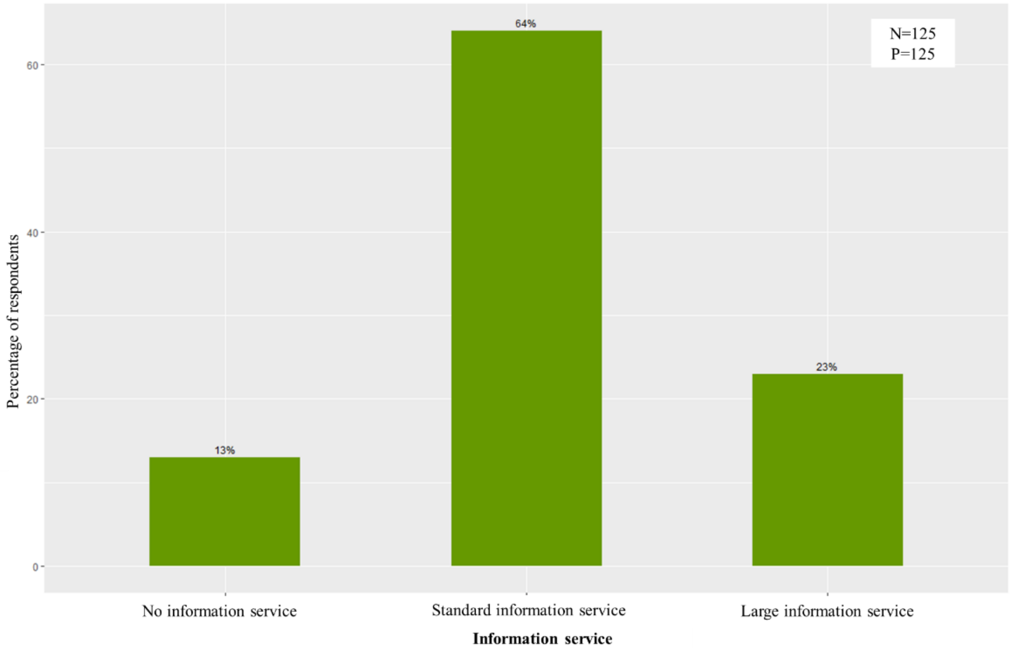

Figure 3-30. Preferences for the information service for all the forest users (except the hunters). N=Number of answers, P=Number of respondents.

The forest users have a large preference for the trails (**Figure 3-31**) even if a significant proportion of the inhabitants harvesting firewood has a preference for the roads (28% of them).

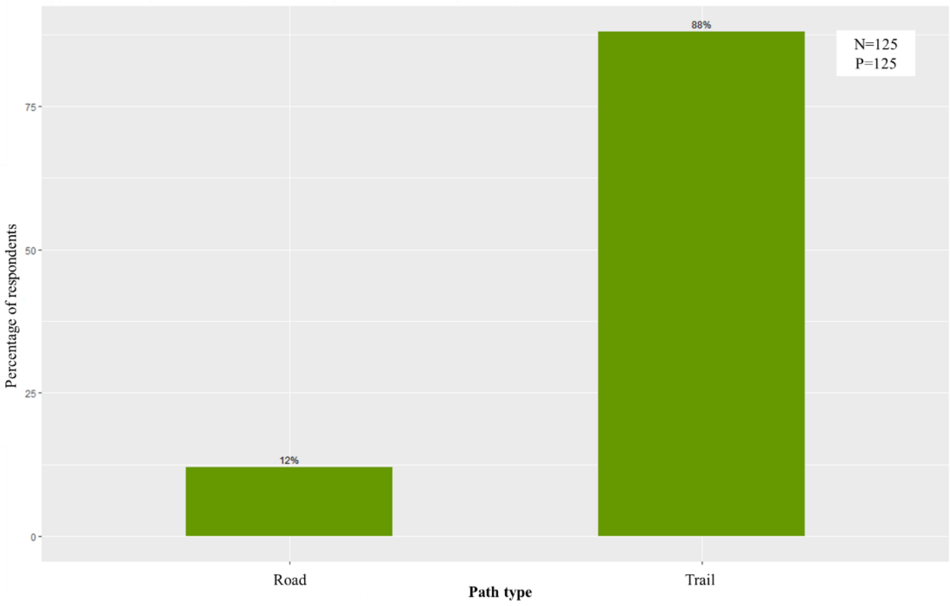

Figure 3-31. Preferences for the path type for all the forest users (except the hunters). N=Number of answers, P=Number of respondents.

Most of the respondents prefer a basic tourism infrastructure while some of them prefer no tourism infrastructure (except hiking paths) (**Figure 3-32**).

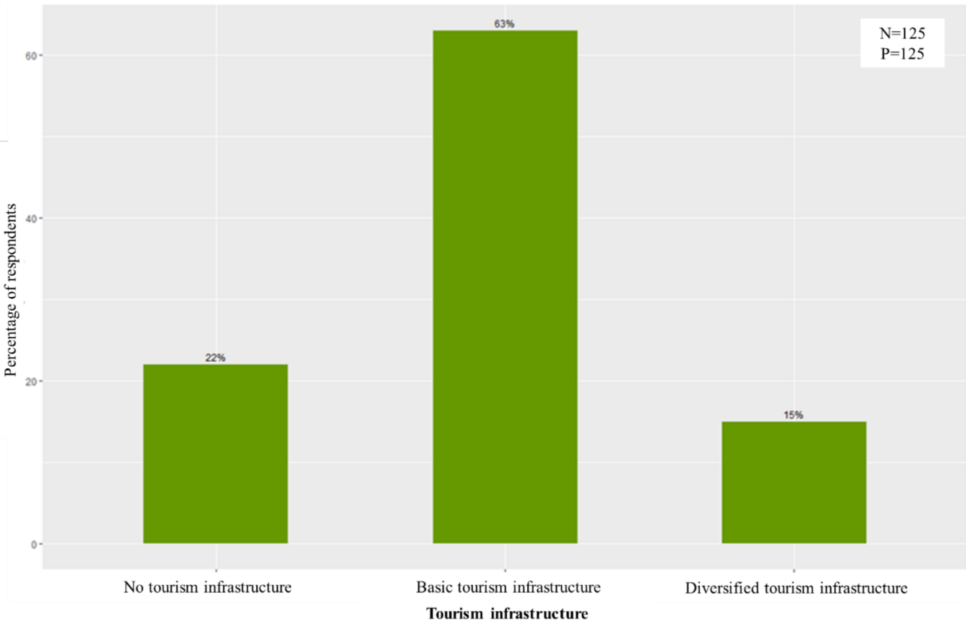

Figure 3-32. Preferences for the tourism infrastructure for all the forest users (except the hunters). N=Number of answers, P=Number of respondents.

Half of the forest users prefer to have local products production or transformation workshop while a third prefer to purchase or to directly pick the local products in the forest (**Figure 3-33**). For the fishers, they either prefer not having local product (35%) or purchasing or picking the local products (35%).

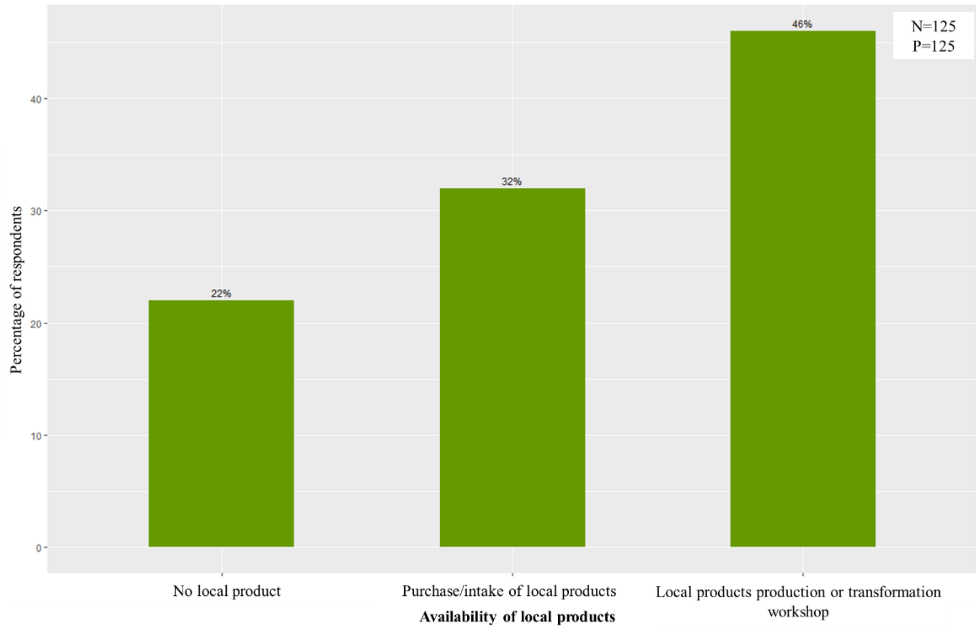

Figure 3-33. Preferences for the availability of local products for all the forest users (except the hunters). N=Number of answers, P=Number of respondents.

The forest users mainly prefer to have well promoted elements of cultural heritage even if some of them prefer not having them promoted especially the fishers (35% of them) (**Figure 3-34**). A significant proportion of fishers prefer to have no element of cultural heritage (23% of them).

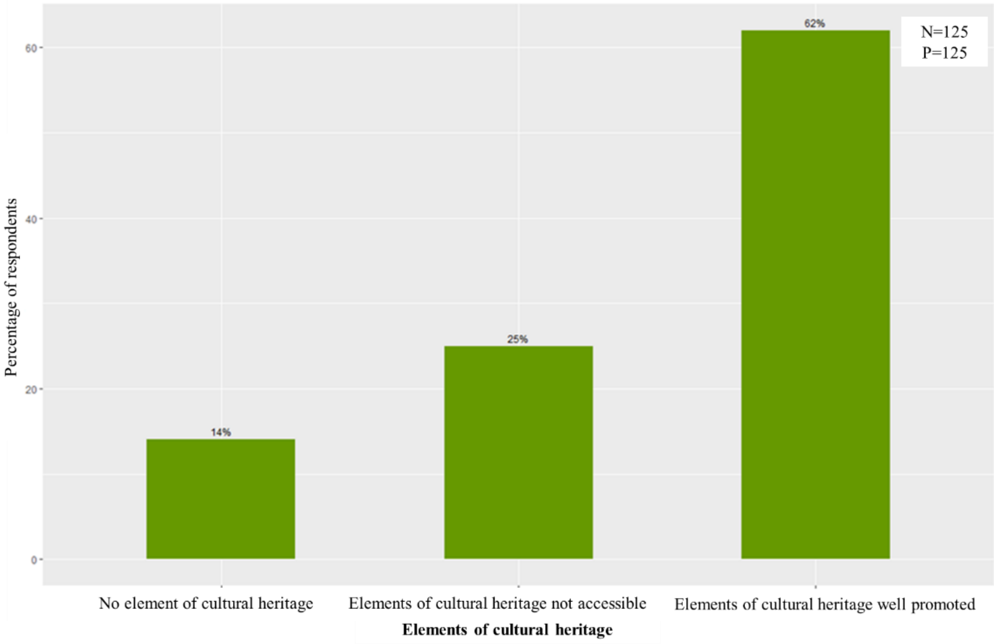

Figure 3-34. Preferences for the elements of cultural heritage for all the forest users (except the hunters). N=Number of answers, P=Number of respondents.

To conclude, the main preferences of the forest users regarding the tourism infrastructure are a standard information system, trails alongside with basic tourism infrastructures, available local products and well promoted elements of cultural heritage.

1.1.5.1.2 TCM

The clean dataset considers 134 respondents after having deleted the inconsistent data (2 respondents who gave a number of annual visits ≥1000, one who gave a one-way distance of 300km for a one-day visit and one who gave a zero distance) and the data of the inhabitants harvesting firewood (30 respondents) because the number of annual visits is not influenced by the travel distance (**Figure 3-35**).

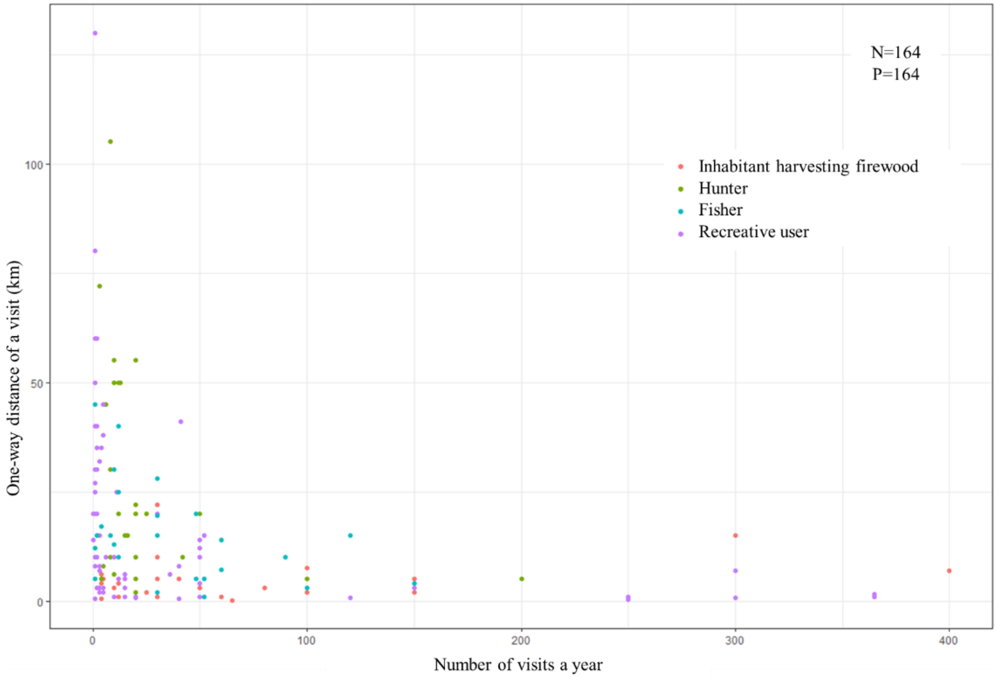

Figure 3-35. One-way distance of a visit depending on the number of visits a year in the municipal forest of Sivry-Rance for the four types of forest users. N=Number of answers, P=Number of respondents.

To visualize the dataset, several graphs depicting the main variables of the TCM are presented below.

The respondents visit around 30 times a year the municipal forest of Sivry-Rance with a high variability (some only do several visits a year while others do more than 100 visits a year) (**Figure 3-36**).

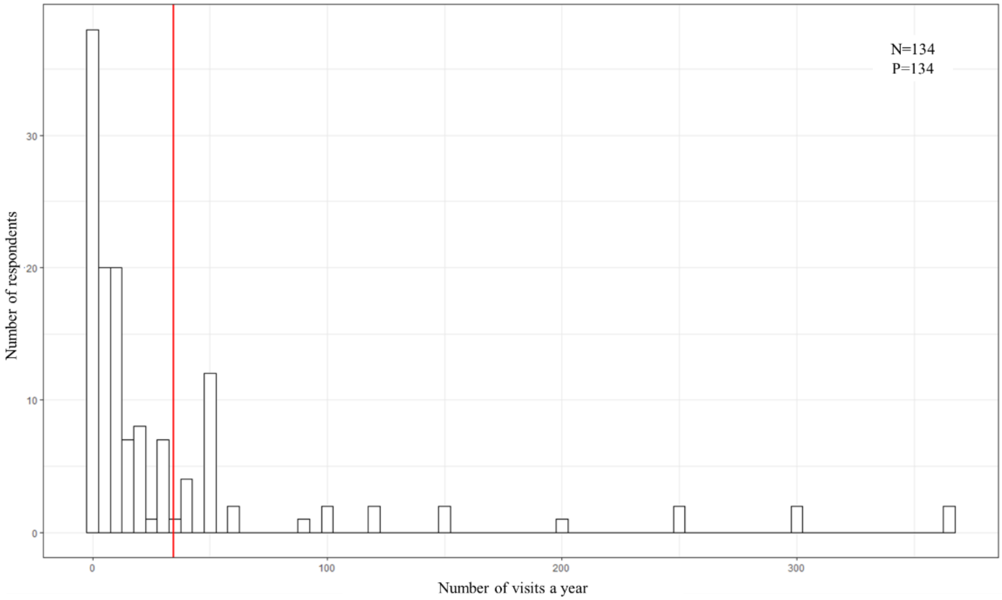

Figure 3-36. Distribution of the number of visits a year in the municipal forest of Sivry-Rance. The red vertical line is the mean. N=Number of answers, P=Number of respondents.

Most of the respondents (90%) do a one-day trip. Most of them use the car to come into the forest (**Figure 3-37**). For half of them, they are two in the car, a quarter are alone, and the others are three or more (**Figure 3-38**). The second mean of transport is walking.

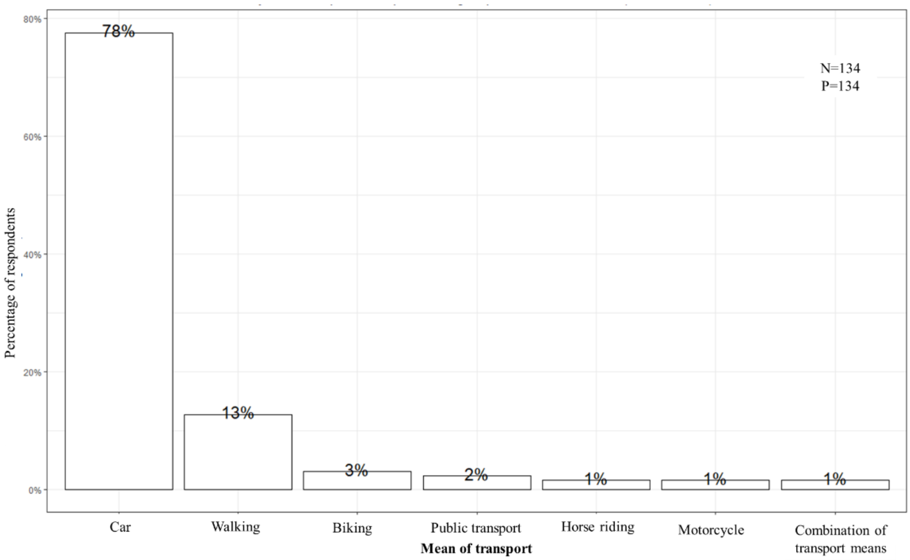

Figure 3-37. Mean of transport used by the respondents to go to the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

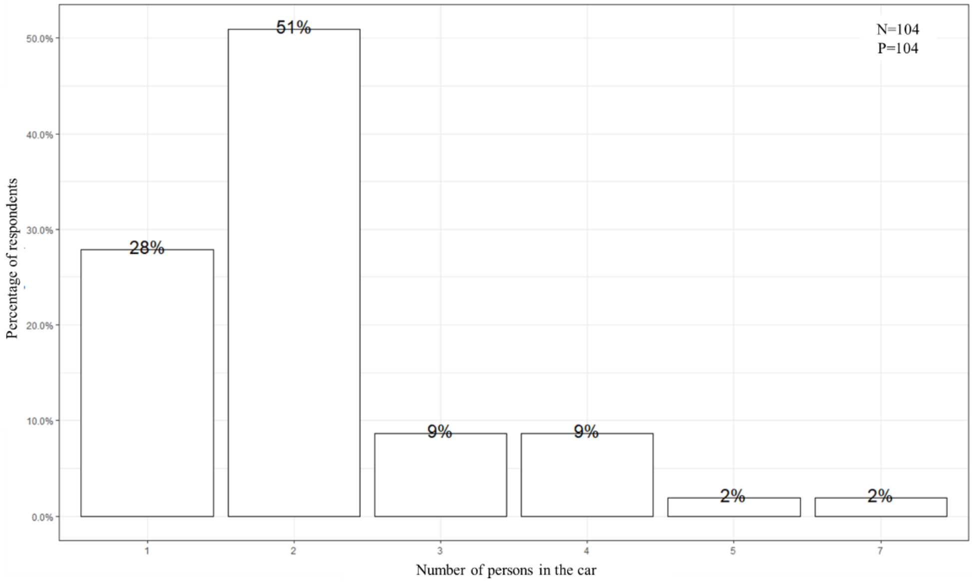

Figure 3-38. Number of persons in the car to go to the municipal forest of Sivry-Rance. N=Number of answers, P=Number of respondents.

On average, the respondents travel around 20km to go to the municipal forest of Sivry-Rance (**Figure 3-39**). Most of them travel less than 50km while some of them travel more than 100km.

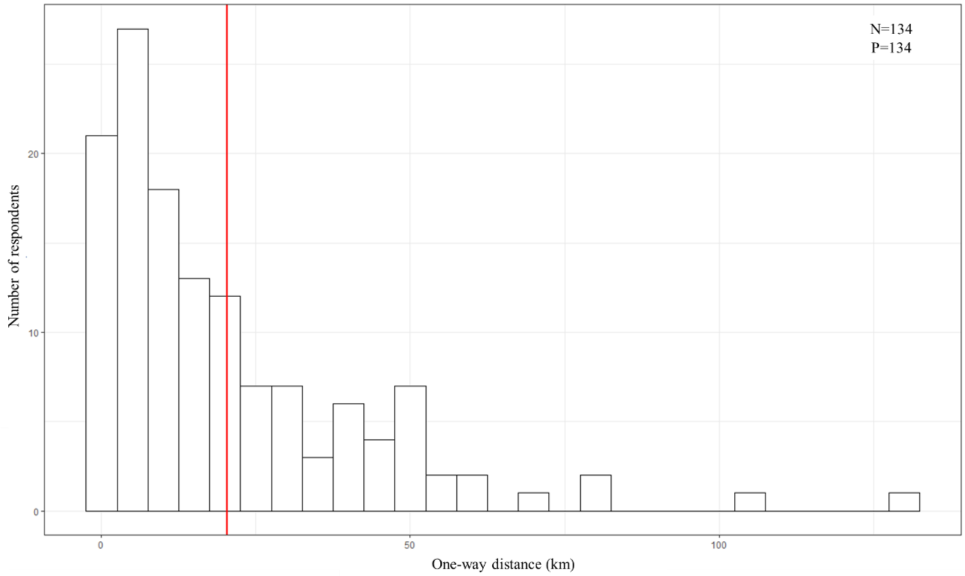

Figure 3-39. One-way distance travelled by the respondents to go to the municipal forest of Sivry-Rance. The red vertical line is the mean. N=Number of answers, P=Number of respondents.

To model the demand curve, the zero-truncated negative binomial model was retained among the three other models (i.e. Poisson, Quasi-Poisson and negative binomial). Indeed, the Poisson model was removed because the variance was much higher than the mean as well as the Quasi-Poisson model which had a dispersion parameter over 20. The quality of the zero-truncated negative binomial model was better than the negative binomial one (i.e. lower AIC and 2 x log-likelihood).

From the test of different datasets (i.e. all means of transport vs car+motorcycle and all the visits vs the one-day trip visit), the dataset of the one-day trip visit by car and motorcycle was retained because it was the best model and the most conservative one. It is also the one used in most of the TCM studies (Parsons, 2003) because overnight trip and multiple-purpose trip modelling need to be improved (Champ et al., 2017). By ignoring the opportunity cost of time, the estimates are conservative and likely lower than the real WTP (Abildtrup et al., 2021).

From the zero-truncated negative binomial of the dataset of the one-day trip visit by car or motorcycle, we found that the recreation users were significantly different from the fishers and hunters. A new dummy variable was thus created where the fishers and hunters=1 and the recreation users=0. The stepwise method was applied to this transformed dataset.

From the stepwise method, two of the seven explanatory variables were removed: (1) if the respondent visited the site alone or not, and (2) the income. For the income, it is consistent with other studies (Abildtrup et al., 2021; Champ et al., 2017; Martínez-Espiñeira and Amoako-Tuffour, 2008).

The final model is presented in **Table 3-4**. The travel cost is highly significant and negative showing that the number of visits decreases when the travel cost increases (central hypothesis of the TCM). The fishers and hunters tend to make more visits a year in the municipal forest of Sivry-Rance than the recreation users, same goes for the inhabitants. Abildtrup et al. (2021) also found that the residents of the Ardenne region made more visits. There is a slight effect of the gender: women tend to make more visits a year. Older people also tend to make more trips a year. This is consistent with other studies (Abildtrup et al., 2021; Englin and Shonkwiler, 1995). The profession is not significant while other studies found that more highly educated people make fewer trips (Abildtrup et al., 2021; Englin and Shonkwiler, 1995).

Table 3-4. Zero-truncated negative binomial model of the number of visits a year depending on the travel cost by car or motorcycle and the other relevant explanatory variables (i.e. socio-economic characteristics) retained by the stepwise method. Number of respondents=86[16]. With . for 0.05<p<0.1; * for 0.01<p<0.05; ** for 0.001<p<0.01 and *** for p<0.001. Log-likelihood: -294 and AIC: 610.

Variable	Estimate	Standard error	z-value	p
Intercept 1	-0.45	0.85	-0.52	0.6025
Intercept 2	-1.43	0.48	-2.97	0.0030**
Travel cost	-0.12	0.04	-2.76	0.0059**
Fisher or hunter	2.31	0.42	5.54	<0.0001***
Inhabitant	2.16	0.52	4.12	<0.0001***
Gender	0.87	0.47	1.84	0.0654.
Age	0.03	0.01	2.10	0.0360*
Profession	-0.66	0.44	-1.51	0.1301

The WTP is 8.4±0.6€ (with a confidence interval of 95%), meaning that on average, the users of the municipal forest of Sivry-Rance are willing to pay 8.4€ for a visit in the forest.

1.1.5.1.3 DCE

The clean dataset considers 137 respondents after having deleted the respondents who did not answer all the DCE questions (19 respondents), the protesters (7 respondents) and the inconsistent data (one respondent who gave a number of annual visits =1000, one who gave a one-way distance of 300km for a one-day visit and three who gave a zero distance).

We tested several datasets considering or not the respondents who travel a distance higher than 200km and the ones who did not consider the distance in their choice. The best model is given by the dataset that includes the respondents that did not consider the distance and that travelled ≤200km (2 respondents indicated a distance>200km). The final dataset has 135 respondents.

From the lrtest, the best random utility model is the multinomial logit model considering homoscedasticity, correlated attributes and some random attributes (all the forest attributes are random, except the distance). This model is of good quality (the McFadden R^2 is around 0.2 which is the standard for DCE (Abildtrup et al., 2021)) (**Table 3-5**).

[16] 86 is the number of respondents who come by car or motorcycle to the municipal forest of Sivry-Rance and who answer all the socio-economic questions.

This model shows no significant difference between the two alternatives of the choice set (i.e. variable 2:(intercept)) demonstrating that one alternative is not systematically preferred than the other one (Table 3-5)). On the contrary, the respondents prefer the alternative 1 compared to neither alternative (i.e. variable 3:(intercept) is very highly significant) showing that they systematically prefer to go to the forest regardless of its characteristics. It means that other elements not considered in the DCE explain why the respondents go to the forest.

From the forest characteristics that are significant and the sign of the coefficient, the following preferences are found: hardwood (i.e. negative coefficient of the very highly significant softwood variable) continuous forests or with natural open areas and with deadwood are preferred. These preferences show that more natural forests are preferred and confirm the importance of the intrinsic values. The further the forest is, the less it is preferred, which is consistent as the travel cost increases with the travel distance.

Some forest characteristics are correlated:

- The respondents who prefer young trees compared to middle age trees, also prefer old trees;
- The respondents who prefer young trees, also prefer having no deadwood;
- The respondents who prefer softwood, also prefer continuous forests;
- The respondents who prefer young trees, also prefer forests with clear-felling;
- The respondents who tend to prefer softwood, tend to prefer forests with open natural areas (correlation near significant).

Table 3-5. Mixed correlated multinomial logit model of the DCE. Only the significant correlations are given. Number of respondents=135. With . for $0.05<p<0.1$; * for $0.01<p<0.05$; ** for $0.001<p<0.01$ and *** for $p<0.001$. Log-Likelihood: -611 and McFadden R^2: 0.209.

Variable	Estimate	Standard error	z-value	p
2:(intercept)	0.20	0.18	1.08	0.2821
3:(intercept)	-2.69	0.32	-8.35	<0.0001***
Softwood	-1.99	0.28	-7.21	<0.0001***
Young tree	-0.33	0.27	-1.22	0.2241
Old tree	0.33	0.29	1.14	0.2533
Regular stand	-0.22	0.21	-1.06	0.2885
No deadwood	-0.58	0.18	-3.16	0.0016**
Continuous forest	0.72	0.24	3.03	0.0025**
Forest with natural open areas	0.84	0.27	3.15	0.0016**
Distance	-0.57	0.28	-2.04	0.0415*
Young tree*Old tree	1.04	0.37	2.84	0.0045**
Young tree*No deadwood	1.28	0.32	4.05	<0.0001***
Softwood*Continuous forest	0.87	0.35	2.53	0.0115*
Young tree*Continuous forest	-1.27	0.43	-2.98	0.0029**
Softwood*Forest with natural open areas	0.64	0.35	1.87	0.0621.

Table 3-6 gives the willingness to travel for the preferred forest features. The standard deviation is quite high for all the significant forest characteristics, showing the heterogeneity in the strength of the preferences of the respondents.

Table 3-6. Willingness-to-travel (mean and standard deviation) for the significant forest characteristics of the mixed correlated multinomial logit model of the DCE (**Table 3-5**).

Forest characteristic	**Willingness-to-travel (km)**	
	Mean	**Standard deviation**
Softwood	-3.48	3.35
No deadwood	-1.02	2.65
Continuous forest	1.26	3.62
Forest with natural open areas	1.48	2.59

For the latent class model, the model with two classes was retained because it was the best one (i.e. the one having a (near) significant distance variable in all the classes). Two relevant socio-economic variables were considered: Recreation users and inhabitants of the municipality of Sivry-Rance.

The two classes are very highly significant different from each other (i.e. variable (class)2) (**Table 3-7**). In the first class, the respondents prefer nearby hardwood forests with young or old trees while in the second class, the respondents prefer the nearby hardwood irregular continuous forests or with natural open areas with deadwood. The probability of belonging to the first class is 13%, showing that more respondents belong to the second class. The class 1 rather includes the inhabitants of the municipality of Sivry-Rance while in the class 2, we rather found the recreation users.

Table 3-7. Latent class model with two classes and the relevant socio-economic variables of the DCE. Number of respondents=134[17]. With . for 0.05<p<0.1; * for 0.01<p<0.05; ** for 0.001<p<0.01 and *** for p<0.001. Log-Likelihood: -596 and AIC: 1238.

Variable	**Estimate**	**Standard error**	**z-value**	**p**
class.1.ASC1	-3.31	0.97	-3.41	0.0007***
class.1.ASC2	-2.09	0.75	-2.79	0.0053**
Class 1 Softwood	-1.68	0.54	-3.09	0.0020**
Class 1 Young tree	1.73	0.71	2.42	0.0154*
Class 1 Old tree	1.94	0.77	2.50	0.0123*
Class 1 Regular stand	-0.37	0.48	-0.77	0.4440
Class 1 No deadwood	0.67	0.48	1.39	0.1633
Class 1 Continuous forest	0.88	0.60	1.46	0.1451
Class 1 Forest with natural open areas	0.94	0.64	1.48	0.1398
Class 1 Distance	-6.21	2.88	-2.15	0.0313*
class.2.ASC1	3.65	0.32	11.34	<0.0001***
class.2.ASC2	3.67	0.31	11.96	<0.0001***
Class 2 Softwood	-1.09	0.10	-10.49	<0.0001***
Class 2 Young tree	-0.16	0.16	-1.01	0.3146
Class 2 Old tree	0.16	0.16	1.01	0.3146
Class 2 Regular stand	-0.19	0.12	-1.67	0.0944
Class 2 No deadwood	-0.43	0.10	-4.22	<0.0001***
Class 2 Continuous forest	0.26	0.13	2.02	0.0433*
Class 2 Forest with natural open areas	0.49	0.14	3.55	0.0004***
Class 2 Distance	-0.67	0.18	-3.67	0.0002***
(class)2	2.24	0.22	10.38	<0.0001***
Recreative user*Class 2	0.40	0.23	1.72	0.0851.
Inhabitant*Class 2	-0.97	0.23	-4.14	<0.0001***

Table 3-8 gives the willingness-to-travel of class 1 and 2 for the preferred forest features. The standard errors of class 1 are quite high, showing a high variability in the strength of the preferences. The standard errors of class 2 are lower, demonstrating a lower heterogeneity in the strength of preferences.

[17] One respondent was removed because he/she did not answer all the socio-economic questions.

Table 3-8. Willingness-to-travel (mean and standard error) for the (near) significant forest characteristics of the latent class model of two classes with the relevant socio-economic variables of the DCE (**Table 3-7**).

	Willingness-to-travel (km)	
	Mean	**Standard error**
Class 1		
Softwood	-0.27	0.15
Young tree	0.28	0.15
Old tree	0.31	0.18
Class 2		
Softwood	-1.62	0.45
Regular stand	-0.29	0.19
No deadwood	-0.64	0.22
Continuous forest	0.39	0.21
Forest with natural open areas	0.74	0.26

1.1.5.1.4 Contingent valuation

The clean dataset considers 93 respondents after having deleted the respondents who did not answer all the contingent valuation questions (22 respondents), the protesters (52 respondents) and the inconsistent data (1 respondent who gave a number of annual visits ≥1000).

The WTP calculated with the **lower-bound estimator** method for the price range 0->10€ is given in **Table 3-9**. The mean WTP is around 3€ with a significant variation in the data as shown by the standard deviation, minimum and maximum. The lack of data especially for the inhabitants harvesting firewood and the hunters makes the comparison between the forest user types quite irrelevant. Nevertheless, the fishers have a lower WTP than the other forest user types.

Table 3-9. Statistics of the WTP estimated by the lower-bound estimator model for the price range 0->10€ for all the forest users and by forest user type. Min=minimum and max=maximum.

Forest user type	**Number of respondents**	**WTP (€)**				
		Mean	**Median**	**Standard deviation**	**Min**	**Max**
All the data	49	3.2	1	3.9	0	10
Inhabitants harvesting firewood	6	4.0	2	3.6	0	10
Hunters	3	3.3	0	5.8	0	10
Recreation users	28	4.3	2	4.0	0	10
Fishers	12	0.3	0	0.4	0	1

The average WTP of the price range 0->30€ is around 10€ with a significant variation in the data as shown by the standard deviation, minimum and maximum

(**Table 3-10**). The lack of data especially for the inhabitants harvesting firewood, the hunters and the fishers makes the comparison between the forest user types quite irrelevant. Nevertheless, the inhabitants harvesting firewood and, to a lesser extent, the fishers have a lower WTP than the other forest user types.

Table 3-10. Statistics of the WTP estimated by the lower-bound estimator model for the price range 0->30€ for all the forest users and by forest user type. Min=minimum and max=maximum.

Forest user type	Number of respondents	WTP (€)				
		Mean	Median	Standard deviation	Min	Max
All the data	44	9.4	5	10.5	0	30
Inhabitants harvesting firewood	6	1.5	1	1.9	0	5
Hunters	4	12.5	7.5	11.9	5	30
Recreation users	30	10.8	7.5	11.0	0	30
Fishers	4	7.5	5	9.6	0	20

The comparison of the two price ranges shows that on average, the respondents tend to give a higher WTP for the price range 0->30€, except for the inhabitants harvesting firewood (knowing that the low number of respondents makes the comparison less relevant).

The average WTP calculated by the **mid-point estimator** method for the price range 0->10€ is around 5€ (**Table 3-11**) and around 12€ for the price range 0->30€ (**Table 3-12**). The same conclusions can be drawn as the ones discussed for the lower-bound estimator method.

Table 3-11. Statistics of the WTP estimated by the mid-point estimator model for the price range 0->10€ for all the forest users and by forest user type. Min=minimum and max=maximum.

Forest user type	Number of respondents	WTP (€)				
		Mean	Median	Standard deviation	Min	Max
All the data	49	4.2	1.5	4.8	0	12.5
Inhabitants harvesting firewood	6	5.3	4	4.4	0.3	12.5
Hunters	3	4.2	0	7.2	0	12.5
Recreation users	28	5.6	3	5.0	0	12.5
Fishers	12	0.6	0.3	0.6	0	1.5

Table 3-12. Statistics of the WTP estimated by the mid-point estimator model for the price range 0->30€ for all the forest users and by forest user type. Min=minimum and max=maximum.

Forest user type	Number of respondents	WTP (€)				
		Mean	Median	Standard deviation	Min	Max
All the data	44	11.9	7.5	11.5	0	32.5
Inhabitants harvesting firewood	6	2.3	1.5	2.8	0	7.5
Hunters	4	15.6	11.3	11.8	7.5	32.5
Recreation users	30	13.5	11.3	11.8	0	32.5
Fishers	4	10.0	7.5	12.2	0	25

The values given by the mid-point estimator method are unsurprisingly higher than the ones given by the lower-bound estimator method which is more conservative.

In the **interval regression**, because the number of respondents is low for some forest user types and that the fishers and inhabitants harvesting firewood tend to have a lower WTP, a binomial variable was created for the forest user type differentiating the inhabitants harvesting firewood and fishers from the two other forest user types. The final interval regression model with the relevant socio-economic variables is given in **Table 3-13**. The following socio-economic variables have an influence on the WTP:

- The inhabitants harvesting firewood and the fishers have a lower WTP than the two other forest user types;
- The respondents who had the price range 0->30€ give a higher WTP;
- The inhabitants tend to give a higher WTP;
- The more the forest users go to the municipal forest of Sivry-Rance, the lowest is their WTP;
- The higher is the income, the higher is the WTP.

The strong influence of the price range stresses the need to interpret the results with caution because no difference between the WTP of the two price ranges should be found if the respondents had answered in a rational way (Abildtrup et al., 2021). The other trends are logical except the one concerning the number of visits a year: it should be expected that the WTP increases with the number of visits as the more they go to the forest, the more they are willing to pay to improve the cultural ES. It seems logical that the inhabitants give a higher WTP as other users coming from farther away have other forests at about the same distance where they can go (i.e. substitute forests). Finally, the inhabitants harvesting firewood are less willing to pay that the other inhabitants, showing that the firewood harvesters are distinct from the other inhabitants. Indeed, they already pay the wood, so they are less willing to pay an additional fee.

Table 3-13. Interval regression model with the relevant socio-economic variables of the contingent valuation. Number of respondents=87[18]. With . for 0.05<p<0.1; * for 0.01<p<0.05; ** for 0.001<p<0.01 and *** for p<0.001. Log-Likelihood: -186.

Variable	Estimate	Standard error	z-value	p
Intercept	9.53	2.33	4.09	<0.0001***
Inhabitants harvesting firewood or fishers	-6.43	2.43	-2.65	0.0081**
Price range	7.70	2.16	-3.57	0.0004***
Inhabitants	4.92	2.60	1.89	0.0584.
Number of visits a year	-2.43	1.42	-1.71	0.0876.
Income²	$5.19*10^{-7}$	$2.19*10^{-7}$	2.37	0.0177*

From the interval regression model, the WTP is on average 7€ with a quite low variability (**Table 3-14**). The inhabitants harvesting firewood and the fishers have on average a negative WTP of 1€ meaning that we will have to pay them to improve the corresponding cultural ES. The variability of their WTP is very high showing a strong heterogeneity between them. The hunters and recreation users have an average WTP of 10€ with a quite low variability. The WTP of the inhabitants of the municipality of Sivry-Rance is quite similar as the one of the non-inhabitants. There is a strong difference between the WTP of the two price ranges.

Table 3-14. Mean WTP with its confidence interval (95%) given by the interval regression model of the contingent valuation depending on the forest user type, if the respondent lives or not in the municipality of Sivry-Rance and the price range.

Forest user type	Mean WTP (€)	Confidence interval (95%) (€)
All the data	7.4	5.8 - 8.9
Inhabitants harvesting firewood and fishers	-0.9	-9.0 - 4.2
Hunters and recreation users	10.3	8.0 - 12.5
Inhabitants	6.8	3.0 - 10.6
Non-inhabitants	7.6	5.6 9.7
Price range 0->10€	3.7	2.9 - 4.6
Price range 0->30€	11.4	8.3 - 14.4

Figure 3-40 shows the increase of the WTP with the monthly income. The hunters and the recreation users with the price range 0->30€ have by far the highest WTP.

[18] Six respondents did not answer all the socio-economic questions and were removed to perform the interval regression.

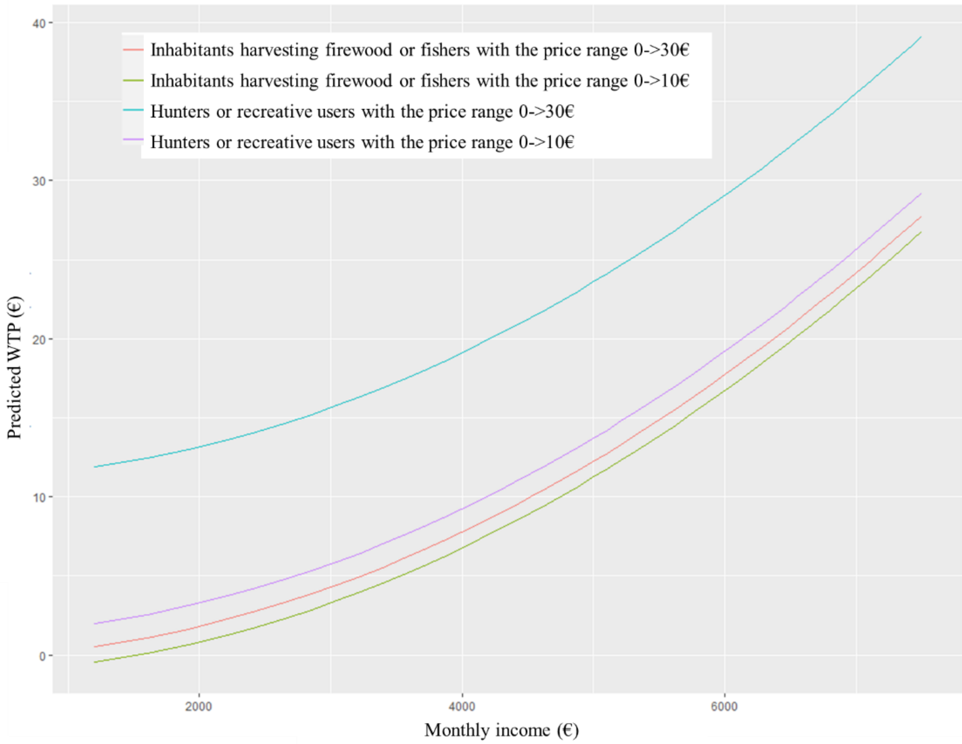

Figure 3-40. Predicted WTP for the interval regression model of the contingent valuation depending on the monthly income, the forest user type, and the price range.

1.1.5.1.5 Conclusion

Three conclusions can be drawn from the surveys of the users of the municipal forest of Sivry-Rance. First, the users are varied while having commonalities. The cultural uses of this forest are diversified (e.g. fishing, hunting, mushrooms and wild plants picking, nature watching, hiking, biking, horse riding) with users wearing several hats (most of the users do several cultural activities). They have different socio-cultural values but most of them find the biodiversity and nature as well as the quiet and calm of the forest important. Most of them are local users with a strong attachment to the forest, the activities it provides and its cultural and social role. To conclude, they hold multiple values (i.e. instrumental, intrinsic and relational values) except the fishers who attach higher importance to the instrumental values.

Secondly, most of the forest users are willing to pay to go to the municipal forest of Sivry-Rance (on average 8€ for a visit) and to improve its cultural ES (on average 7€), especially the hunters. However, their WTP vary from one user to another depending notably on the forest user type, if they live or not in the municipality of Sivry-Rance, their age and income.

Finally, the forest users like the forest as it is now: a hardwood continuous forest or with natural open areas and deadwood with a standard information system, basic tourism infrastructure including trails, available local products and well promoted elements of cultural heritage. These preferences are slightly different from one forest user to another notably depending on the forest user type and if they live or not in the municipality of Sivry-Rance. Some improvements can still be made such as increasing the amount of deadwood or promoting the elements of cultural heritage.

1.1.5.2 Forest attendance

Table 3-15 gives a detailed overview of the overall results for each of the 10 implemented cameras. The numbers in the column "after screening" refer to those images after deleting erroneous images and the triplets, between the 23th of April 2019 and 22th of April 2020 (i.e. the considered time period in the analysis). The total number of visitors (i.e. a person either alone or with a dog or on a bike or an horse), bikes, dogs and horses are the ones from the images after screening from the best algorithm. The relative proportion of visitors refers to the proportion of each camera relative to the total number of visitors in the municipal forest of Sivry-Rance. As a reminder, the images issued from the camera 9, due to its limited number of active days compared to other cameras, have been withdrawn from the analysis.

During a year, for the 9 cameras, almost 25,000 visitors were counted (**Table 3-15**). This number concerns the number of visitors passing on the monitored trails and thus not the number of unique visitors (Breyne et al., Under review). On average, one visitor was detected per image. There is on average 8 visitors a day with a variability between the camera ranging from 33 visitors a day for the camera 3 to 2 visitors a day for the cameras 2, 6 and 7 (**Table 3-15**). The number of bikes, dogs and horses also varies between the cameras and represents only a small proportion of the visitors of the municipal forest of Sivry-Rance.

Table 3-15. Overview of the results of the 10 cameras of the municipal forest of Sivry-Rance. Nbr: number and Avg: average.

Camera code	Start Date	End Date	Nbr of active days	Total nbr of images	Nbr of images /camera /day	Total nbr of images after screening	Total nbr of visitors	Relative % of visitors	Avg nbr of visitors /image	Avg nbr of visitors/ day	Total nbr of bicycle	Total nbr of dogs	Total nbr of horses
CA1	25-03-19	03-07-20	466	8724	19	2175	2062	8	0.95	6	325	71	16
CA2	25-03-19	03-07-20	466	5076	11	1128	718	3	0.64	2	87	82	53
CA3	25-03-19	03-07-20	466	21243	46	5312	12029	49	2.26	33	415	401	24
CA4	25-03-19	03-07-20	466	8025	17	1896	2386	10	1.26	7	428	66	140
CA5	25-03-19	03-07-20	466	14805	32	3290	2366	10	0.72	6	509	49	509
CA6	25-03-19	03-07-20	466	12087	26	2222	567	2	0.26	2	109	9	84
CA7	25-03-19	03-07-20	466	7018	15	1890	858	3	0.45	2	172	20	84
CA8	10-04-19	19-02-20	315	4665	15	1458	2393	10	1.64	8	273	135	665
CA9	10-04-19	26-07-19	107	1338	13	/	/	/	/	/	/	/	/
CA10	15-04-19	03-07-20	445	15240	34	785	1382	6	1.76	4	306	11	33
Total				**98221**		**20156**	**24761**				**2624**	**844**	**1608**

1.1.5.2.1 Data formatting

From the analysis of the performance of the seven algorithms in COCO and their accuracy, the best model is Yolox (**Table 3-16**). It has the highest mAP and overall, the best sensitivity and specificity for the four detected objects (i.e. person, bicycle, dog and horse).

The specificity is generally high while sensitivity is lower, showing that overall, the seven algorithms detect better the negatives than the positives. The sensitivity and specificity are better for the persons than for the three other objects, the horses being better detected than the bicycles. These two metrics are particularly low for the dogs. For this reason, in the rest of the analysis, this object was not considered.

Table 3-16. Analysis of the performance and the accuracy of the seven algorithms for the four detected objects (i.e. person, bicycle, dog and horse).

	Algoritm						
	Fastercnn	Maskrcnn	Pointrend	Retinanet	Yolo	Yolof	Yolox
mAP (%)	41.6	40.8	40.8	38.0	33.7	37.5	50.9
Person							
TP	1830	1819	1827	1675	1415	1155	1831
FP	21	19	22	11	1	0	11
FN	321	334	324	508	778	1043	359
TN	1144	1146	1143	1154	1164	1165	1154
Sensitivity	0.85	0.84	0.85	0.77	0.65	0.53	0.84
Specificity	0.99	0.99	0.99	0.99	1.00	1.00	0.99
Bicycle							
TP	213	211	226	150	114	28	203
FP	0	1	1	0	0	0	0
FN	233	236	222	303	340	426	251
TN	2909	2908	2908	2909	2909	2909	2909
Sensitivity	0.48	0.47	0.50	0.33	0.25	0.06	0.45
Specificity	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Dog							
TP	58	37	36	44	47	6	78
FP	14	5	2	4	10	0	12
FN	191	212	213	205	200	243	171
TN	3100	3109	3112	3112	3104	3114	3102
Sensitivity	0.23	0.15	0.14	0.18	0.19	0.02	0.31
Specificity	0.81	0.88	0.95	0.92	0.82	1.00	0.87
Horse							
TP	130	136	129	106	102	45	150
FP	6	13	14	4	1	2	6
FN	103	100	103	128	135	192	82
TN	3120	3113	3112	3122	3125	3124	3120
Sensitivity	0.56	0.58	0.56	0.45	0.43	0.19	0.65
Specificity	0.96	0.91	0.90	0.96	0.99	0.96	0.96

From the analysis of the time range between the detection events, only nine images were triggered before the 5 seconds delay and were deleted (**Table 3-17**). Only a small fraction of the images are very close in time (6-10 seconds) and this fraction is even smaller when the time interval between one triplet and the second consecutive one is considered. The possibility of redundancy is thus low. When the control sample was checked to see if the close events (6-10 seconds of the time interval between two consecutive triplets) were redundant, only half of them were truly redundant. Because the possibility of redundancy is low and that close events are not always redundant, no adjustment has been made.

Table 3-17. Distribution of the number of images of each camera in two-time intervals: the one between two consecutive triplets and the one between one triplet and the second consecutive one.

	Time interval between two consecutive triplets (seconds)										
Camera code	**0-5**	**6-10**	**11-20**	**21-30**	**31-40**	**41-50**	**51-60**	**60-120**	**120-300**	**300-900**	**>900**
CA1	0	119	1334	361	205	139	123	404	636	975	3270
CA2	0	56	723	144	70	39	36	171	206	331	2142
CA3	0	184	5774	913	501	280	195	825	1171	2396	7618
CA4	0	65	1088	288	158	123	151	356	483	615	3501
CA5	9	97	1607	431	259	170	174	704	1368	2498	6213
CA6	0	32	983	341	337	281	272	1171	1937	2542	3315
CA7	0	45	1231	437	239	145	129	479	568	673	2001
CA8	0	58	975	130	40	80	46	153	210	381	1740
CA10	0	25	5379	1773	978	736	504	1619	1331	945	1200
Total	**9**	**690**	**19279**	**4860**	**2818**	**2014**	**1636**	**5903**	**7970**	**11506**	**31549**
	Time interval between a triplet and the second consecutive one (seconds)										
CA1	0	0	0	300	198	138	83	353	506	981	4059
CA2	0	0	0	167	68	45	31	102	174	222	2216
CA3	0	0	0	1852	974	523	333	829	1171	1943	10414
CA4	0	0	0	226	135	102	59	276	501	537	4023
CA5	0	0	6	343	149	105	103	506	807	1749	8625
CA6	0	0	0	216	88	127	84	566	1590	2907	4959
CA7	0	0	0	381	272	195	148	622	745	681	2155
CA8	0	0	0	243	90	39	45	144	225	318	1953
CA10	0	0	0	1977	1789	1065	839	2690	2533	1461	1607
Total	**0**	**0**	**6**	**5733**	**3784**	**2367**	**1748**	**6109**	**8270**	**10910**	**40626**

1.1.5.2.2 Visitor frequencies and their spatial-temporal variability

The corrected estimation gives a total of almost 29,500 visitors a year. Detected and identified hikers, bikers and horse riders respectively represent 79%, 14% and 7% (**Table 3-18**). This number of visitors represents the number of persons who passed in front of a camera knowing that a same person can pass several times in front of a camera (two different cameras on one day or in front of the same camera several days) and that a person could be missed if she/he did not pass a camera when going in the municipal forest of Sivry-Rance. This number is thus a number of visits rather than the number of visitors.

Frequency results show a high spatial variation (**Table 3-18** and **Figure 3-41**). The camera 3 (Bois des Bruyères) is by far the most frequented area, especially by the hikers. It alone represents more than half of the visitors of the municipal forest of Sivry-Rance. Bois des Bruyères is the most developed area of this forest in terms of tourism infrastructures (e.g. parking, picnic tables, eco-pedological trail, didactic panels, gazebo, sculptures, arboretum, etc.) and several trails cross this forest area. The least frequented areas are the ones covered by cameras 2 (Bois de Blagnies), 6 (Bois de Tout Vent) and 7 (Bois de Martinsart) where only one trail goes through and that are a bit remote from the rest of the forest.

Table 3-18. Number of hikers, bikers and horse riders counted by the Yolox algorithm and corrected by their sensibility and specificity.

Camera code	Nbr of hikers	Nbr of bikers	Nbr of horse riders
CA1	1862	505	21
CA2	627	135	70
CA3	13253	644	32
CA4	1914	665	184
CA5	1280	790	671
CA6	377	169	110
CA7	616	267	110
CA8	1850	602	874
CA10	1082	475	43
Total	**22861**	**4075**	**2116**

Frequency numbers also show a high temporal variation (Figure 3-41). High peaks in frequency were most often related to special events (trail running, educational activities, organized walk, etc.). Indeed, there is no high peak in spring 2020 due to the covid-19 pandemy where no organized activity was allowed. The effect of seasons, weekends, public holidays and holiday periods are less clear on **Figure 3-41** but are demonstrated by the GLM analysis (**Table 3-19**).

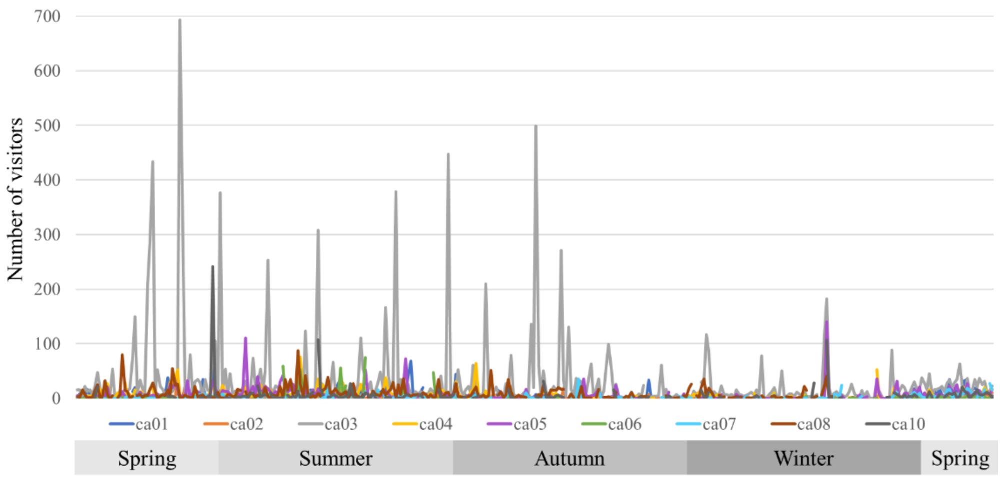

Figure 3-41. Spatial-temporal variation of the number of visitors in the municipal forest of Sivry-Rance over a yearly timespan.

The negative binomial model was selected because the variance was much higher than the mean (Poisson model not suited) and the dispersion parameter was over 20 (Quasi Poisson model not suited). The interaction between public holiday and other temporal variable was not tested because of the low number of such holidays. The four seasons were transformed into a binomial variable "Season type" where the summer and spring were regrouped because they were not different from each other but significantly different from the autumn and winter which were not different from each other (Season type=1 if the season is spring or summer).

The negative binomial model for all the visitors and all the cameras shows that the weekends, public holiday, holidays and the spring and summer are more frequented than the rest of the year (**Table 3-19**). However, during the holidays or the spring and summer, the weekends are less frequented while the visitor frequency is higher during the weekends of the holidays in spring and summer. Almost all the cameras are significantly different from each other, confirming the high spatial variation.

Table 3-19. Negative binomial model for all the visitors with the spatial-temporal variables. With . for 0.05<p<0.1; * for 0.01<p<0.05; ** for 0.001<p<0.01 and *** for p<0.001. AIC: 16151 and 2 X Log-Likelihood: -16115.

Variable	Estimate	Standard error	z-value	p
Intercept	0.45	0.08	5.37	<0.0001***
Weekend	1.51	0.09	16.83	<0.0001***
Public holiday	0.58	0.14	4.22	<0.0001***
Holidays	0.45	0.12	3.66	0.0002***
Season type	1.10	0.07	14.98	<0.0001***
Weekend*Holidays	-0.84	0.19	-4.36	<0.0001***
Weekend*Season type	-0.88	0.14	-6.38	<0.0001***
Holidays*Season type	0.03	0.15	0.22	0.8282
Weekend*Holidays*Season type	0.72	0.24	2.94	0.0033**
CA2	-0.94	0.11	-8.69	<0.0001***
CA3	2.13	0.10	21.42	<0.0001***
CA4	0.12	0.10	1.13	0.2573
CA5	0.07	0.10	0.68	0.4942
CA6	1.41	0.11	-12.52	<0.0001***
CA7	-0.77	0.11	-7.18	<0.0001***
CA8	0.44	0.11	4.17	<0.0001***
CA10	-0.40	0.10	-3.86	0.0001***

A negative binomial model was also performed for each camera to see if the temporal variation depends on the camera (**Table 3-20**). Weekends and the season type are on almost all occasions the main explanatory factors for visitor frequencies. Public holidays, holidays and the interactions between the temporal variables are only significant for a few cameras. If they are significant, they follow the same direction as the previous model except the interaction between holidays and season type. This interaction is significant for some cameras but not always in the same direction: for some cameras, the holidays in spring and summer are more frequented while for others, it is the contrary.

Table 3-20. An overview of the estimates with their significance of the negative binomial model for each of the explanatory variables per camera. With NS: Non-significant; . for 0.05<p<0.1; * for 0.01<p<0.05; ** for 0.001<p<0.01 and *** for p<0.001.

Variable	**CA1**	**CA2**	**CA3**	**CA4**	**CA5**	**CA6**	**CA7**	**CA8**	**CA10**
Weekend	2.03***	1.37***	NS	2.24***	2.10***	1.03*	1.38***	1.59***	1.62***
Public holiday	NS	NS	-0.61.	1.08***	1.37***	NS	NS	0.88*	NS
Holidays	NS	NS	NS	1.27***	NS	NS	NS	1.25***	NS
Season type	1.80***	1.11***	0.97***	1.46***	1.40***	1.37***	0.76***	0.92***	NS
Weekend*Holidays	-1.50**	NS	NS	-2.38***	-0.99.	NS	NS	-1.23*	NS
Weekend*Season type	-1.50***	NS	-0.94**	-1.41***	-1.44***	NS	-1.15**	-0.75.	NS
Holidays*Season type	NS	NS	NS	-0.84*	1.00*	1.51.	0.84.	-0.69.	NS
Weekend*Holidays*Season type	1.52*	NS	NS	2.26***	NS	NS	NS	NS	NS
AIC	1879	1296	3232	1958	1916	870	1418	2021	1505
2 x log-likelihood	-1859	-1276	-3212	-1938	-1896	-850	-1398	-2001	-1485

For all the users, the trails are more frequented during the weekends (**Table 3-21**). The effects of the other temporal variables vary from one user type to another. The biker frequencies are not influenced by the public holidays and the holidays. Their attendance is lower in autumn (this is why the seasons were not transformed into the binomial variable “Season type”), the weekends in holidays, the weekends in spring and during the holidays of summer and winter while it is higher during the weekends in winter and the weekends of the holidays in spring. **Figure 3-42** shows indeed a high attendance of bikers in February demonstrating that they preferred the winter over the autumn.

For the hikers, the trends are the same as the negative binomial model of all the visitors (**Table 3-21**). The most frequented months range from May to August (**Figure 3-42**). Bois des Bruyères (i.e. CA3) has also a high attendance in October.

For the horse riders, some trends are different: the holidays tend to be less frequented, there is no influence of the holidays on the attendance of the weekends, but the weekends are more frequented during spring and summer (**Table 3-21**). Indeed, the most frequented months range from May to September (**Figure 3-42**).

This shows that even if they are some similarities between the user types (the weekends and the spring and summer are more frequented), the temporal variation depends on the user type. For example, the winter is preferred by the bikers while the holidays have little influence on the attendance of the horse riders.

Every camera is significantly different from the others for at least one user type (**Table 3-21**), showing the high spatial variation. **Figure 3-42** also confirms that some trails are more used by some users than others. For example, Bois des Bruyères is more frequented by the hikers but not especially by the bikers and the horse riders. The most frequented trails by the bikers and the horse riders are the ones having a dedicated circuit for these users (1000 bornes à vélo[19] for the bikers (e.g. CA4 and CA5) and equestrian trails for the horse riders (e.g. CA8)) (**Table 3-18**).

[19] Bicycle network composed of road segments between two numbered crossroads.

Table 3-21. An overview of the estimates with their significance of the negative binomial model for each user type. With NS: Non-significant; . for 0.05<p<0.1; * for 0.01<p<0.05; ** for 0.001<p<0.01 and *** for p<0.001.

Variable	Hiker	Biker	Horse rider
Intercept	0.38***	-2.37***	-4.64***
Weekend	1.26***	1.81***	1.80***
Public holiday	0.62***	NS	1.76***
Holidays	0.46***	NS	-0.81.
Season type	1.02***	/	1.43***
Summer	/	1.65***	/
Winter	/	0.51*	/
Spring	/	1.73***	/
Weekend*Holidays	-0.56**	-1.76**	NS
Weekend*Season type	-0.56***	/	-1.50***
Weekend*Summer	/	NS	/
Weekend*Winter	/	1.49***	/
Weekend*Spring	/	-1.22***	/
Holidays*Season type	NS	/	1.22*
Holidays*Summer	/	-0.96*	/
Holidays*Winter	/	-1.35**	/
Holidays*Spring	/	NS	/
Weekend*Holidays*Season type	NS	/	1.16.
Weekend*Holidays*Summer	/	NS	
Weekend*Holidays*Winter	/	NS	
Weekend*Holidays*Spring	/	1.83**	
CA2	-0.96***	-1.11***	0.94**
CA3	2.24***	NS	NS
CA4	NS	0.43**	2.02***
CA5	-0.30**	0.36*	3.48***
CA6	-1.63***	-0.91***	1.64***
CA7	-0.89***	-0.50**	1.46***
CA8	NS	0.31.	3.89***
CA10	-0.52***	NS	NS
AIC	14511	6046.1	3663
2 x log-likelihood	-14475	-5994.0630	-3627

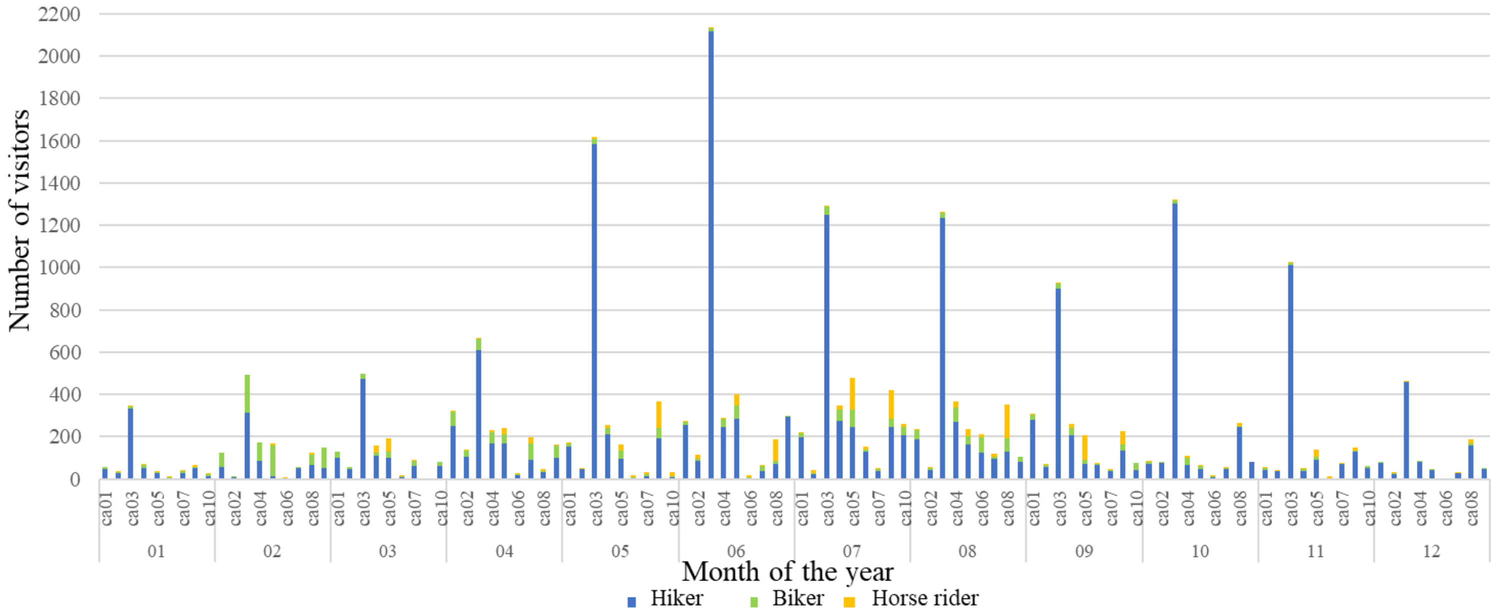

Figure 3-42. The number of hikers, bikers and horse riders per camera for each month over a yearly timespan.

When detailing the frequentation of visitors over the hours of the day (**Figure 3-43**), there are on average two peaks a day for the hikers: a smaller one around 9-10 am (in wintertime), and a larger one between 1 and 4 pm. This pattern is different for the two other types of users. There is a small peak for the bikers between 9 and 11 am while there is no peak for the horse riders. The moment of the peaks varies along the season: the two peaks of the hikers, especially the afternoon one, are larger in spring and summer while the morning peak of the bikers is mostly present in winter. The peaks also vary with the cameras: the cameras 5, 6 and 8 only have the morning peak.

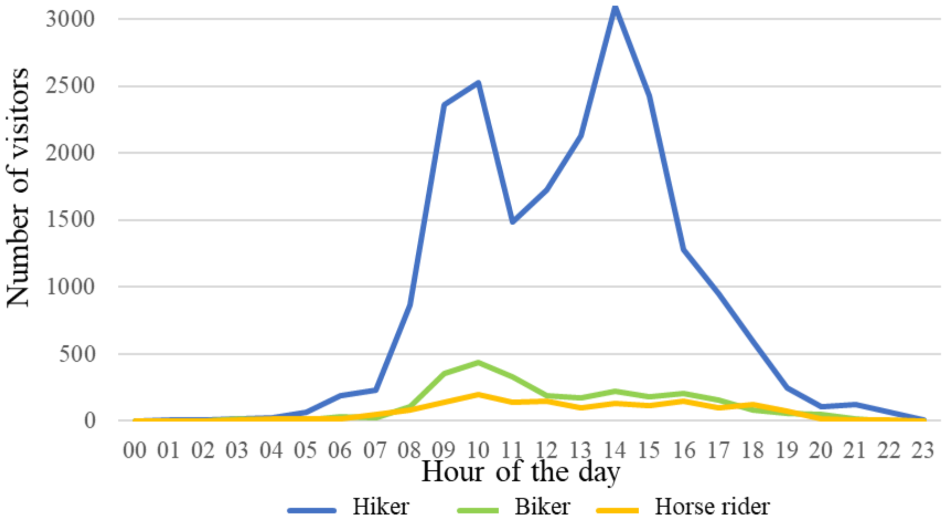

Figure 3-43. Number of hikers, bikers and horse riders over a daily timespan.

1.1.5.2.3 Conclusion

The municipal forest of Sivry-Rance is well attended. This attendance varies spatially and temporarily. The well-laid out trails are more frequented. More persons visit the forest during the weekends, the holidays and the spring and summer months. Most of the visitors are hikers.

1.2 Define the system dynamics

The dynamics of the municipal forest of Sivry-Rance are described by adapting the dynamics of the forests detailed in the scientific literature to the context of the municipal forest of Sivry-Rance.

The municipal forest of Sivry-Rance, as any other forest in the world, is facing myriad threats from both intentional and inadvertent human impacts including invasive species, pests and diseases and perhaps above all, global climate change (Messier et al., 2013; Swanson and Chapin, 2009). Although disturbances contribute to natural dynamics of forest health, their frequency, extent and severity have increased in the last decades (Millar and Stephenson, 2015). Furthermore, their effects are heightened by the interactions between the different disturbances (e.g. between an increasing temperature, drought, native insects and pathogens) (Millar and Stephenson, 2015). This combined with the presence of novel anthropogenic stressors and the burgeoning global human population that imposes escalating demands on forests, alter forest ecosystems beyond the levels of 20th-century experience with potentially far-reaching impacts on their biological diversity and capacity to provide ES to society (Millar and Stephenson, 2015; Thom and Seidl, 2016). This trend is likely to continue in the future as a result of the climate changes expected for the coming decades (Seidl et al., 2011b; Temperli et al., 2013).

The most predominant drivers impacting the municipal forest of Sivry-Rance are: (a) **pests and diseases including non-native species,** (b) **climate change along with the increasing droughts and storms, and** (c) **the growing multiple societal demands**.

The pests and diseases including the non-native species (e.g. ash dieback caused by a fungal pathogen) interacting with heat and drought impair the health of the municipal forest of Sivry-Rance, leading to tree mortality or even to the local extinction of key forest species (e.g. ash), with impacts that ripple through the forest (Ellison et al., 2005; Millar and Stephenson, 2015).

Climate change has numerous impacts: migrations of species across the landscape, reshaping forest communities or even shifting the forest to other ecosystems (Folke et al., 2004), making them vulnerable to pests, pathogens and other disturbances at unprecedented scales (Millar and Stephenson, 2015). The droughts were particularly important in the municipal forest of Sivry-Rance, in the last years, causing extensive tree mortalities. Indeed, rising global temperatures have contributed to droughts of a severity that is unprecedented (Lindner et al., 2014; Park Williams et al., 2013). These hotter droughts are a powerful driver of forest mortality affecting the forest both directly and indirectly (Allen et al., 2015). Directly, higher temperatures increase tree water stress by increasing the atmosphere’s evaporative demand for water (Breshears et al., 2013) and can have detrimental physiological effects (Teskey et al., 2015). Indirectly, hotter droughts make the forest more vulnerable to attacks by insects or pathogens (Millar and Stephenson, 2015). Storms have also increased in the last years in the municipal forest of Sivry-Rance and all over Europe (Schelhaas et al., 2003; Seidl et al., 2014), causing tree mortalities.

The range and demand for societally relevant ES has been growing steadily in the recent decades (Puettmann et al., 2009b; Thom and Seidl, 2016) as it has been observed in the municipal forest of Sivry-Rance (e.g. multiple demands for recreation, hunting, biodiversity conservation, wood). This a complex web of forces operating at local to global scales that may shift the emphasis of management objectives for example from wood production to protection of species, with various intended and unintended consequences for society (Swanson and Chapin, 2009). Thus, social factors can trigger abrupt and profound changes in forest policy and management that can ripple across scales and can be as important as the other disturbances (Swanson and Chapin, 2009).

Changing societal and environmental factors are colliding and interacting and much of the drivers affecting the municipal forest of Sivry-Rance are human-driven (e.g. climate change, species invasions). These changes are particularly challenging in forestry because the trees live longer than the professional lifetimes of people who manage them making it difficult to develop and sustain management strategies with time horizons that extend beyond the short-term motivations of individual decision makers. Furthermore, the municipal forest of Sivry-Rance is likely to encounter novel environmental and socioeconomic conditions during the life of its trees. In addition, the legacies of the past still have an influence on the current and future management of the forest (Puettmann et al., 2009b). (Swanson and Chapin, 2009)

In face of all these changes, the municipal forest of Sivry-Rance will likely, in the short term, continues to absorb or rebound from disturbances and sustain a diversity of ecological functions and their corresponding ES (Millar and Stephenson, 2015). But, over the longer term, this forest is likely to change in condition (Gonzalez et al., 2010), ranging from minor shifts in forest structure (e.g. tree density and ages) and species compositions to major transformations of vegetation types, some resulting in novel ecosystems (Millar and Stephenson, 2015). Drought-hardy species, species with physiological plasticity capable of coping with compound stresses and species with shorter stature might outcompete current species (McDowell and Allen, 2015). Native insects and pathogens may effectively act as invasive exotics as they move beyond their historic ranges (Woods, 2014).

All these changes can impair the ES (e.g. extensive forest mortality can impair water quantity and quality, forest products, cultural and spiritual values and recreation) (I. L. Boyd et al., 2013; Thom and Seidl, 2016). But Thom and Seidl (2016) also found that disturbances affect positively biodiversity. Thus, disturbances can be expected to have both positive and negative impacts on the multiple objectives of forest management (Thom and Seidl, 2016).

Given that these changes are inevitable especially on the long-term horizon of the forest, multiple alternatives states and their relative social and ecological benefits need to be considered to take actions that will diminish the negative effects on forest and human society (Blanco et al., 2017; Millar and Stephenson, 2015; Swanson and Chapin, 2009). This is why twelve pathways of the municipal forest of Sivry-Rance were studied to analyse their impacts on this forest to better understand its dynamics and take relevant actions. So, the system dynamics are also discussed in the next steps.

1.3 Identify the interactions and scales

The scales of the case study and their cross-scale interactions are discussed first detailing the spatial scales, then the temporal ones and finally the social ones.

The central spatial scale is the municipal forest of Sivry-Rance. This scale is influenced by processes occurring at larger and smaller scales (**Figure 3-44**). The largest scale is the world considering for instance the wood market (e.g. part of the timber from the municipal forest of Sivry-Rance is sold to China) or climate change or the invasion by non-native species. Then, the European scale influences this forest through regulation on forestry and nature conservation (European Union is an influencer of several ES in the ES stakeholder matrix (**Table 3-1**)). Same goes for the Belgian and Walloon scales from which tourists also come. Then, there is the scale of the surroundings of the municipal forest with different levels depending on the ES considered. For instance, the scale of the watershed is related to the ES Water quality & quantity and Control of soil erosion & flooding while a buffer of 1.5km around the forest was used for pollination to consider the movement of the wild bees. Another example is recreation considering the trails and the recreation users that come from the surrounding areas to the forest. The municipality of Sivry-Rance as it is the owner of the forest and considering its inhabitants interacting with the forest and the local associations is another relevant scale. There are also the different scales of the DNF from Wallonia to the Direction of Mons (in charge of the management plan), the *Cantonnement* of Thuin to the four management units crossing this forest. The smaller scales for the management are the objective areas, the forest stands and the trees. The scale of the forest stand is also crucial for most of the ES. Regarding biodiversity, the scales ranges from the landscape and even the connectivity between landscapes to the natural habitat.

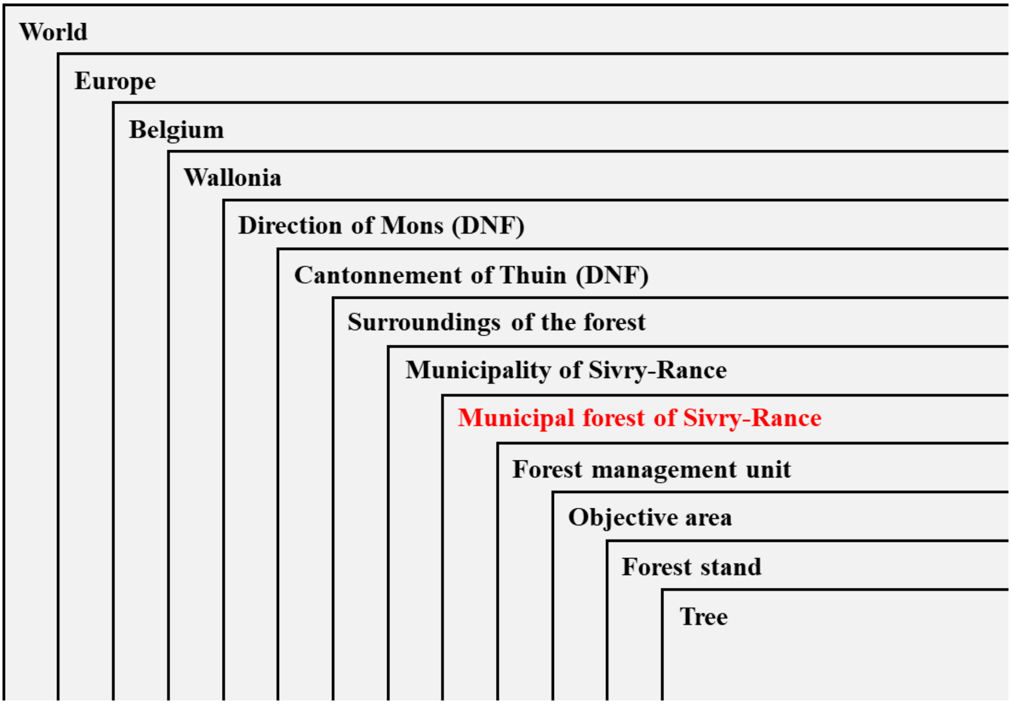

Figure 3-44. Schematic representation of the different spatial scales that influence the municipal forest of Sivry-Rance written in red.

The two main temporal scales considered in this research are the actual state of the municipal forest of Sivry-Rance (reference year: 2020) and its future (reference year: 2085). Even if the forest, the ES its provides and the resilience evolve between these two reference years, it was not considered in this analysis (this point is discussed in Chapter 4 2.4.1.3 Temporal scale). The future beyond 2085 is also considered through the continuous monitoring of this forest. The past is also another important temporal scale to understand the legacies from its past management (the management plan of the municipal forest of Sivry-Rance provides a detailed description of the history of this forest (Colson and Baix, 2021)). The stakeholders interact with the forest in different time horizons. For instance, some recreation users are only in the forest for a few hours in their life while others come daily in the forest. The public institutions and local associations can interact with the forest for only a few years (e.g. a specific project related to the forest) to decades or even centuries.

The social scales are visible in the ES stakeholder matrix (**Table 3-1**). They include the individuals, the associations, the public institutions, and the private sector, operating at various temporal and spatial scales. They also have different levels of influence on the forest: some only using the forest for a few hours (e.g. a touristic that comes once in his/her life to visit the municipal forest of Sivry-Rance) while others shape the forest (e.g. the municipality of Sivry-Rance who decides how to manage the forest in accordance with the DNF).

All these scales are interacting with each other among one type of scale and between them. For the spatial scales, the processes happening at larger scales influence the smaller ones and vice versa. For instance, climate change operating at the world scale impacts the trees and their mortality. Another example is the restoration of a particular habitat (e.g. a pond digging) which has consequences at the landscape level (e.g. connectivity with other ponds so populations of certain species can travel). We have seen how the temporal scales interact with each other especially in forestry (e.g. how the past management still influences the current forest). The same goes for the social scales. For example, the individuals can be part of an association or a public institution. Concerning the interactions between the scale types, we have seen how a certain process/stakeholder operates at specific spatial and temporal scales but has consequences on other scales. For instance, climate change occurs all around the world over long periods of time but at the same time can be responsible of an insect outbreak that happens on a regional scale over a few years (e.g. *Ips typographus* L. which decimated spruce stands from 2018 to 2020 due to successive dry summers in western Europe). Another example is the municipality of Sivry-Rance through its decisions concerning the tourism infrastructures of the municipal forest of Sivry-Rance that influences the tourism in the surrounding areas.

In addition to the interactions between the scales, multiple interactions occur between the different elements of the municipal forest of Sivry-Rance. The interactions between the stakeholders and with the forest and its ES are depicted in the ES stakeholder matrix (**Table 3-1**). The interactions between the ES are discussed in Chapter 3 4.4.13. Interactions between the ES. The interactions between the drivers and the disturbances are discussed in Chapter 3 1.2. Define the system dynamics.

2. Step 2: Define the problem, the stakes and the goals

From the definition of the system, a first synthesis of the stakes can be drawn.

The definition of the system reveals the following stakes:

- The multiple and growing demands from the various stakeholders;
- Climate change and its related droughts and storms;
- The pests and diseases affecting the forest;
- Nature conservation and restoration.

The concerns and wishes concerning the future of the municipal forest of Sivry-Rance reveal the broad values of the stakeholders (**Table 3-22**). They want to have harmonious relationships between the functions of the forests and the users. They feel responsible for protecting the forest and they want to sustain it. They also want to enjoy and experience the forest. The stakeholders hold a variety of specific values (i.e. instrumental, relational and intrinsic) depending on their broad values.

The stakes identified from the system definition were also raised by the stakeholders. They raised a few other stakes such as communication, pollution or the continuity in forest management.

From all these stakes, the following problem was identified**: how to ensure that the municipal forest of Sivry-Rance provides the ES needed by the different stakeholders in the face of the current and future disturbances**.

Therefore, the main goal of this case study is **to have a resilient and sustainable forest that provides multiple ES answering the various needs of the stakeholders in a balance way with a good communication**.

Table 3-22. Synthesis of the concerns and wishes of the stakeholders concerning the future of the municipal forest of Sivry-Rance with their corresponding broad values and type of specific values according to the values assessment typology of IPBES (2022).

Broad values	**Concern**	**Wish**	**Type of specific values**
Desire for harmonious relationships (unity)	Conflicts between the different uses and users (e.g. the closure of certain parts of the forest because of hunting or pollution, too much travelling in the forest that could destroy some habitats or affect the calm and quiet) Balance between the forest functions (e.g. the economic/social function overriding the ecological one) Communication (e.g. not enough information on the available trails, difficulty in involving all the stakeholders of the social and economic sectors)	Respect for the other users Balance between the users (e.g. mutual understanding among the different users, each user respects her/his position and the forestry code, sharing the costs of the recreation activities in the forest) Balance between the functions (e.g. conciliating the social, economic and ecological functions of the forest)	Relational
Duty to protect nature	Forest degradation (e.g. biodiversity loss, diseases) Climate change (e.g. dieback due to climate change) Soil compaction Pollution (e.g. waste, forest degradation due to pollution)	Respect for nature, for the forest Nature (e.g. biodiversity conservation, close to nature forestry)	Intrinsic
Sustaining the forest		Resilience (e.g. adaptive management) Sustainable forestry (e.g. a balanced age distribution, increasing the rotation period) Heritage (e.g. the forest as a heritage for the future generations) Continuity in forest management	Instrumental, relational and intrinsic
Enjoying, benefiting from nature		Recreation (e.g. travelling freely on all the trails, a map of all the authorized trails) Economy (e.g. promoting the incomes from wood production, diversification of economic development)	Instrumental
Experiencing and understanding nature		Experiencing the forest to better understand it	Relational

3. Step 3: Define the pathways

Twelve pathways were defined by combining six management scenarios with two climate change scenarios. Each pathway is described in terms of its management goals, its forestry, its nature conservation actions and its recreation activities. The maps of the objective areas and the forest stands are presented as well.

3.1 Wood production

The focus of this management scenario is to maximize the supply of timber and firewood.

3.1.1 Management goals

Two goals are followed:

- To maximize the profitability from wood production by efficiently harvesting (i.e. optimum mechanization);
- To promote the productive forest species in the short term by planting them (i.e. softwood species).

3.1.2 Forestry

On the productive sites, the hardwood stands are transformed into softwood plantations by clear-cutting them. The resulting harvesting hardwood trees are sold as lumber for the best quality and as wood industry and firewood for the lower quality. So, on the rotation of the softwood species (i.e. on average 80 years), all the hardwood stands in the productive sites are progressively transformed into softwood plantations (i.e. 1/80 of the hardwood stands on the productive sites is transformed each year). If the softwood species are not suitable in some sites in one of the two climate change scenarios, productive hardwood species are used instead. The actual softwood plantations are maintained.

The softwood plantations are managed in regular stands with the following forestry operations:

- One or two cleanings after planting;
- One first thinning to be able to move easily in the plantation;
- Regular thinnings every 6 years to progressively decrease the stand density;
- Final harvesting by clear-cutting.

3.1.3 Nature conservation

On the restrictive sites (i.e. unproductive sites or difficult to harvest (e.g. steep slopes)), the hardwood stands are left free (i.e. no management intervention).

No nature restoration action is undertaken.

3.1.4 Recreation activities

The existing tourism infrastructures are only maintained in the unmanaged hardwood stands.

The fishing activities are maintained.

The firewood harvested by the inhabitants disappears and instead is sold to the wood industries.

The hunting activities are maintained to ensure the balance between forestry and game populations and to limit the game damage on the plantations. The individual protection of the tree plants must still be met by the hunters.

3.1.5 Objectives areas

The objective area Production covers 70% of the municipal forest of Sivry-Rance while the wilderness area covers 30% along the streams, on the xeric plateau and southern slopes (**Figure 3-45**).

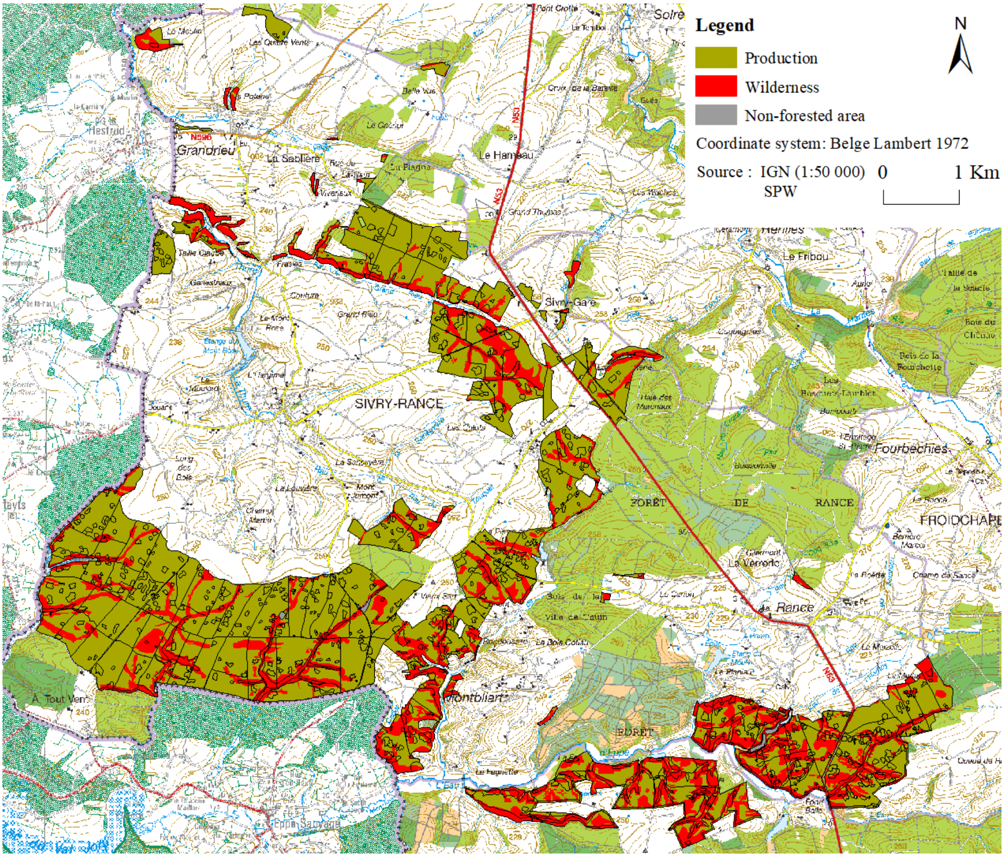

Figure 3-45. Objective areas of the management scenario Wood production for the municipal forest of Sivry-Rance.

3.1.6 Forest stands in the SSP1-2.6

Two third of the forest is composed of even aged softwood stands (67%) (**Figure 3-46**). The hardwood stands are divided between uneven aged hardwood stands (11%), forest edge (10%), alluvial forest (9%), old oak hornbeam forest (2%) and old beech forest (1%). The uneven aged softwood hardwood stands are anecdotal (0.2%).

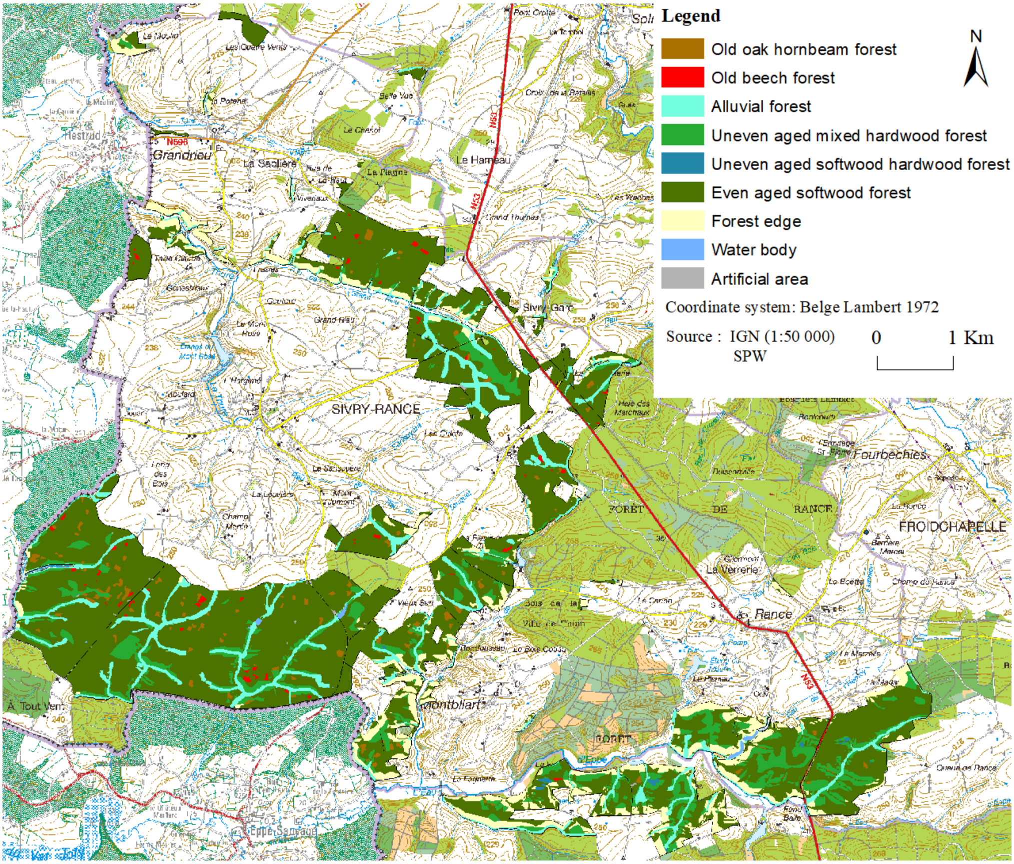

Figure 3-46. Forest stands of the municipal forest of Sivry-Rance in the pathway Wood production SSP1-2.6.

3.1.7 Forest stands in the SSP5-8.5

The even aged hardwood stands cover 40% of the municipal forest of Sivry-Rance (**Figure 3-47**). The even aged softwood stands represents 28% of this forest. The other hardwood stands are divided into uneven aged hardwood forest (11%), forest edge (10%), alluvial forest (9%) and old oak hornbeam forest (2%). The uneven aged softwood hardwood stands are anecdotal (0.1%).

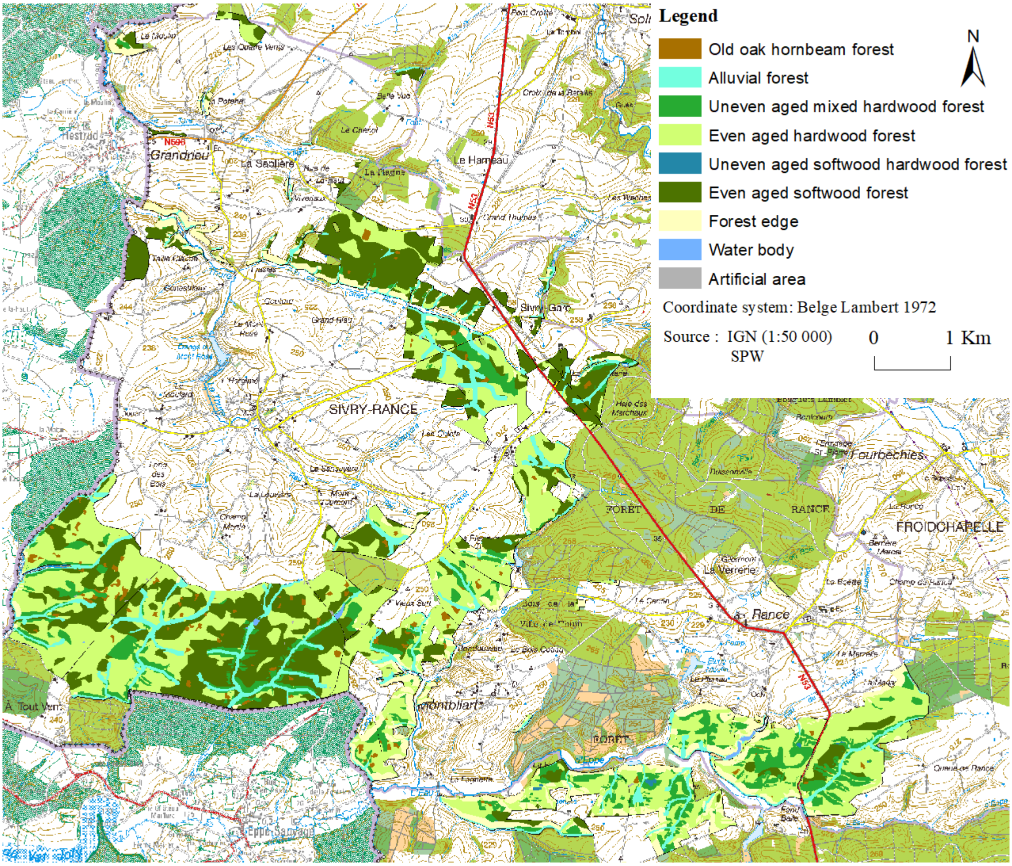

Figure 3-47. Forest stands of the municipal forest of Sivry-Rance in the pathway Wood production SSP5-8.5.

3.2 *Profitability*

This management scenario aims at maximizing the annual income from the municipal forest of Sivry-Rance.

3.2.1 Management goals

The management goals are the following:

- To harvest wood for a maximum income even if it means decapitalizing the forest;
- To promote hunting to maximize profit even if the forestry and game are no longer balanced;
- No investment in the long term.

3.2.2 Forestry

The forest stands are harvested in each cutting cycle by harvesting the valuable trees that reach their exploitable size. Natural regeneration will then take place. No management intervention will be done except the harvesting.

3.2.3 Nature conservation

In the forest stands which are difficult to harvest (e.g. steep slope), no harvesting is done. These stands are left free.

The nature conservation actions (e.g. ponds digging, creation of forest edges, maintenance of natural open areas) are maintained to improve the game habitat quality (see Chapter 3 3.5.3. Nature conservation).

3.2.4 Recreation activities

Outside the hunting period, the circulation in the forest is only authorized on the municipal trails to ensure the quiet of the game. During the hunting period, the circulation is only allowed from Tuesday to Thursday.

The fishing activities are maintained.

The firewood harvested by the inhabitants disappears and instead is sold to the wood industries.

The hunting activities are promoted by extending the hunting period (from August to January), feeding is allowed all over the year and game can be introduced.

3.2.5 Objectives areas

The objective area Production covers 82% of the municipal forest of Sivry-Rance while the other 18% is covered mainly by the Wilderness objective area (17%) and by the Nature conservation one (1%) (**Figure 3-48**).

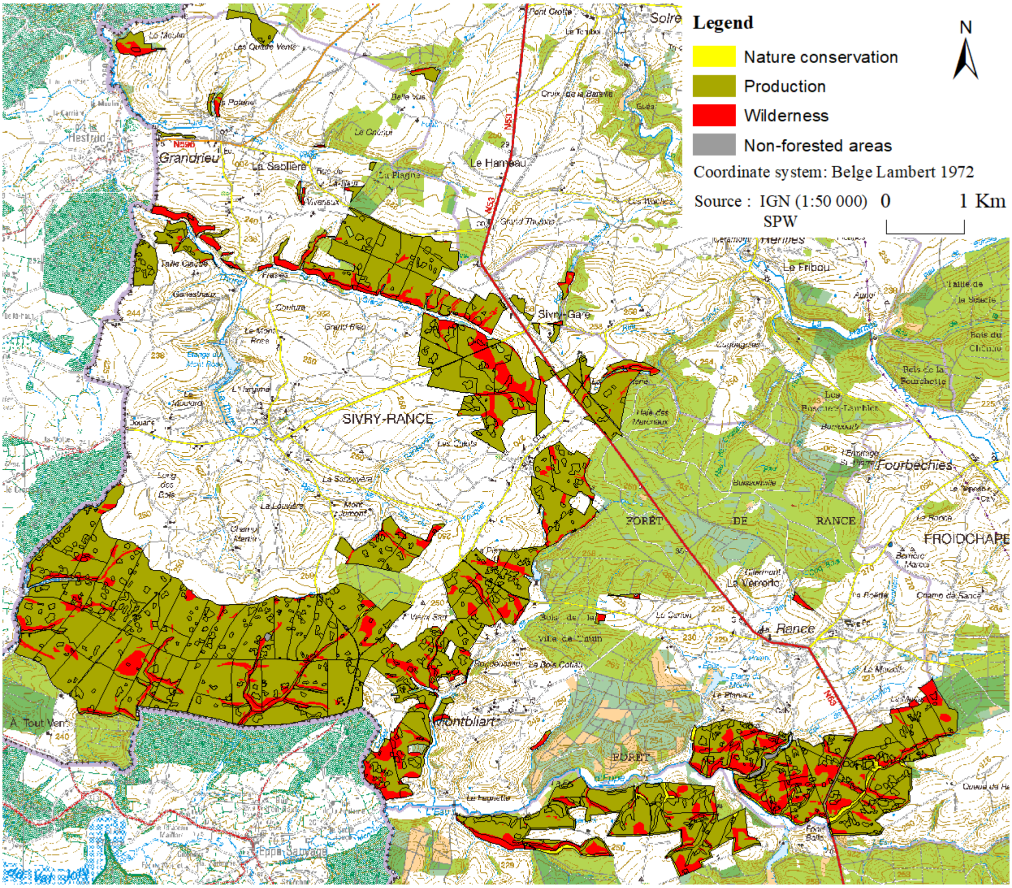

Figure 3-48. Objective areas of the management scenario Profitability for the municipal forest of Sivry-Rance.

3.2.6 Forest stands in the SSP1-2.6

About a half of the municipal forest of Sivry-Rance (44%) is covered by the old hornbeam forest because of the intense harvesting of oaks (**Figure 3-49**). A third is composed of uneven aged mixed hardwood forest (38%). The alluvial forest (9%), the forest edge (6%), the old oak hornbeam forest (2%), the old beech forest (0.5%) and the uneven aged hardwood and softwood forest (0.4%) share the rest of the forest.

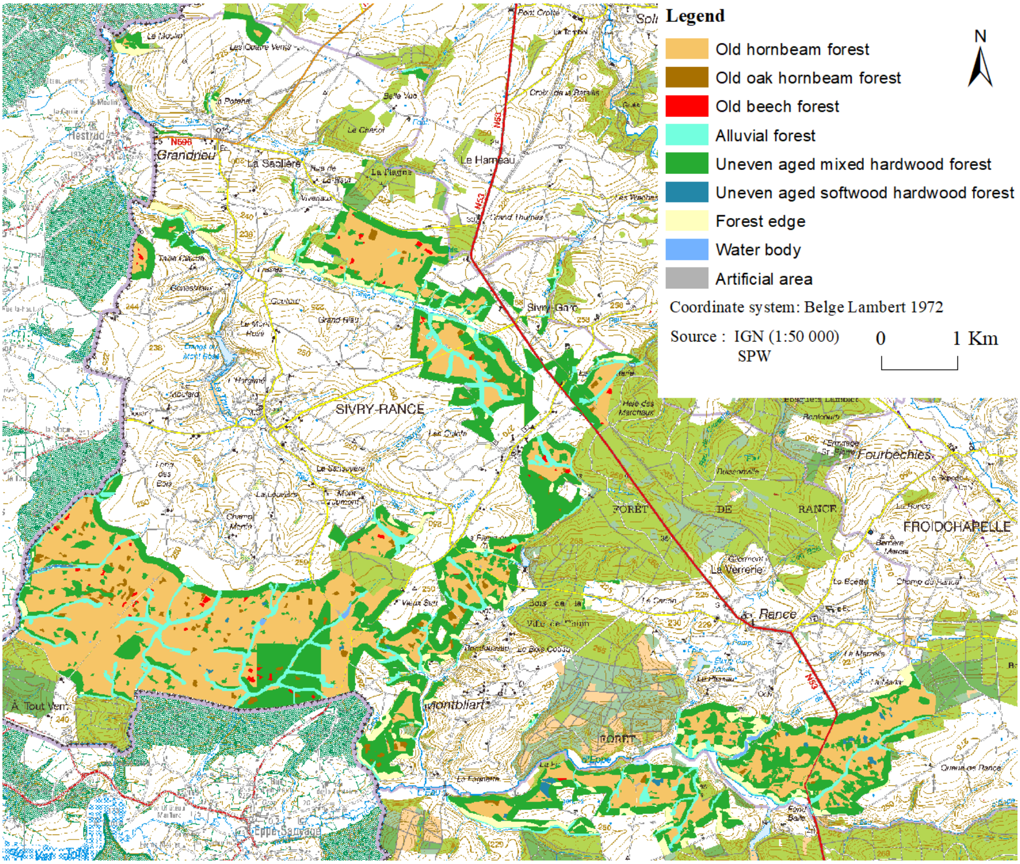

Figure 3-49. Forest stands of the municipal forest of Sivry-Rance in the pathway Profitability SSP1-2.6.

3.2.7 Forest stands in the SSP5-8.5

The distribution of the forest stands is almost the same as the one in the Profitability SSP1-2.6 pathway except that the old beech forest stands become uneven aged mixed hardwood forest (**Figure 3-50**).

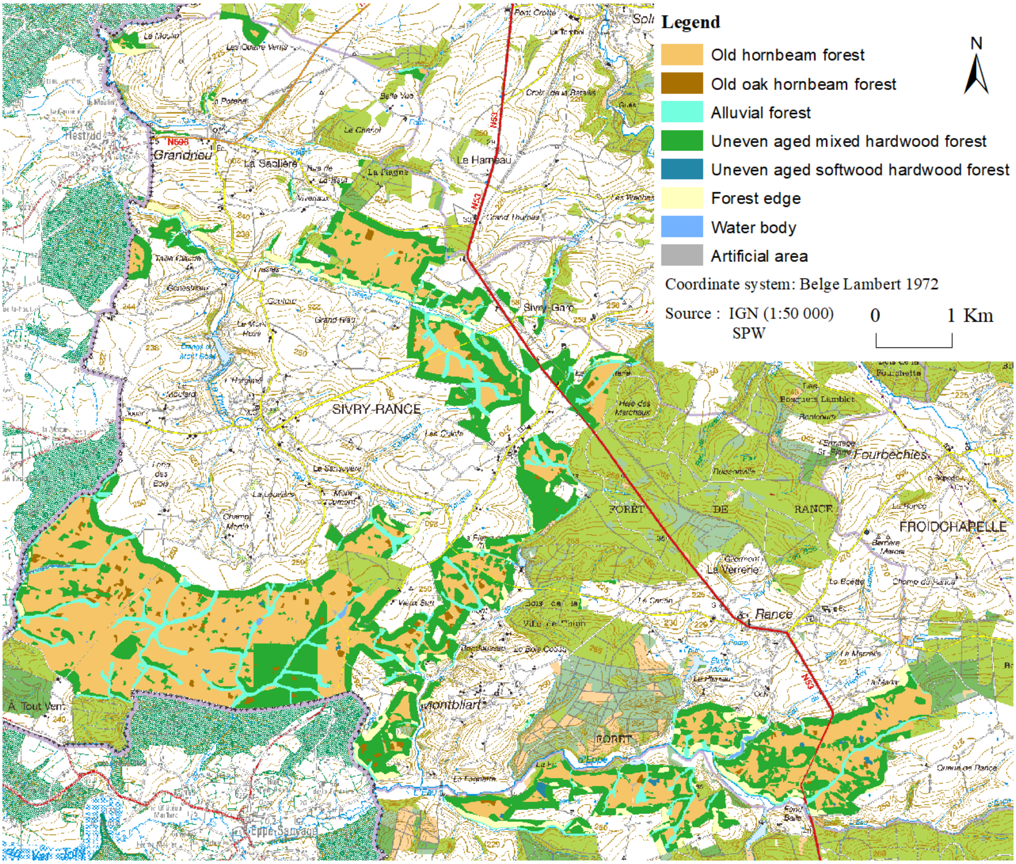

Figure 3-50. Forest stands of the municipal forest of Sivry-Rance in the pathway Profitability SSP5-8.5.

3.3 Recreation

The focus of this management scenario is the recreation function of the municipal forest of Sivry-Rance.

3.3.1 Management goals

To promote recreation, the management goals are the following:

- To increase the tourism infrastructures;
- The users can walk everywhere in the forest in the objective area Priority recreation;
- The trails are open all year long (no closing during the hunting season);
- Cultural and sportive events are organised in the forest as well as production workshops of local products;
- The elements of the cultural heritage are promoted;
- A standard information system is maintained (signposting, tourism office, brochures);
- The forest is managed to be welcoming with the visual features appreciated by the public.

3.3.2 Forestry

The forest stands are managed to have the visual characteristics appreciated by the public: hardwood continuous forest or with natural open areas with deadwood, uneven aged or with young and old trees. The actual municipal forest of Sivry-Rance is already greatly similar to this facies even if some improvements can be maid (i.e. increasing the amount of the deadwood and natural open areas). To maintain this facies, the forest is managed under the principles of continuous cover forestry (see Chapter 3 3.5.2. Forestry).

Ornamental species are introduced such as fruit trees (e.g. chestnut, apple tree, mountain ash) or aesthetic trees (e.g. red oak).

Safety fellings are conducted along the trails.

3.3.3 Nature conservation

The wilderness areas defined in the forest management plan are maintained as well as the nature restoration actions (Colson and Baix, 2021) to answer the preferences of the users. Ponds digging, the creation of forest edges and the restoration of natural open areas will be appreciated by the public.

3.3.4 Recreation activities

The recreation is promoted in the Priority recreation and Recreation objective areas by developing the tourism infrastructures mainly new trails with some basic infrastructures (e.g. bench, picnic table), organizing cultural and sportive events and promoting the elements of the cultural heritage (make them accessible, restore them and communicate (e.g. explanatory signs)). A standard information system is promoted by creating new signposting while maintaining the existing ones, by editing explanatory brochures and by revitalizing the tourism office.

The fishing activities are maintained.

The firewood harvesting by the inhabitants is also maintained except in the Priority recreation objective area.

The hunting activities are adapted to the recreation according to the hunting models of the forest of Hertogenwald Occidental (Colson et al., 2012) and the municipal forest of Plättscheid (Pieper et al., 2016). Hunting from a hide or tracking are the two main hunting methods and are performed early in the morning or late in the night. Hunting is not allowed during cultural or sportive events, during the weekends, public holidays or the holidays. Information posters are hung during the hunting season to inform on the hunting dates and the quiet game areas. Wildlife watching infrastructures are built.

3.3.5 Objectives areas

The main objective area is Multiple ES + biodiversity (63% of the forest) (**Figure 3-51**). The recreation objective areas are divided into Recreation (22%) and Priority recreation (8%). The wilderness (5%), the nature conservation (1%) and multiple ES (1%) areas cover the rest of the forest.

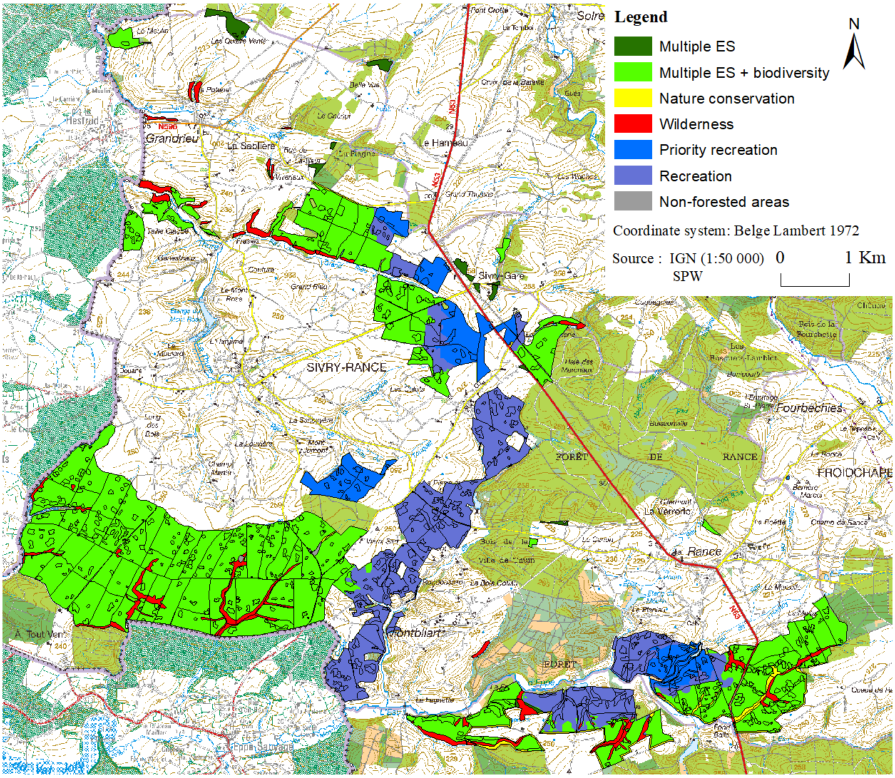

Figure 3-51. Objective areas of the management scenario Recreation for the municipal forest of Sivry-Rance.

3.3.6 Forest stands in the SSP1-2.6

More than a half of the municipal forest of Sivry-Rane is covered by the uneven aged mixed hardwood forest (60%) (**Figure 3-52**). Forest edges represent 30% of the forest and the alluvial forest, 9% of the forest. The last percent is divided into gaps, even aged softwood forest and uneven aged hardwood softwood forest.

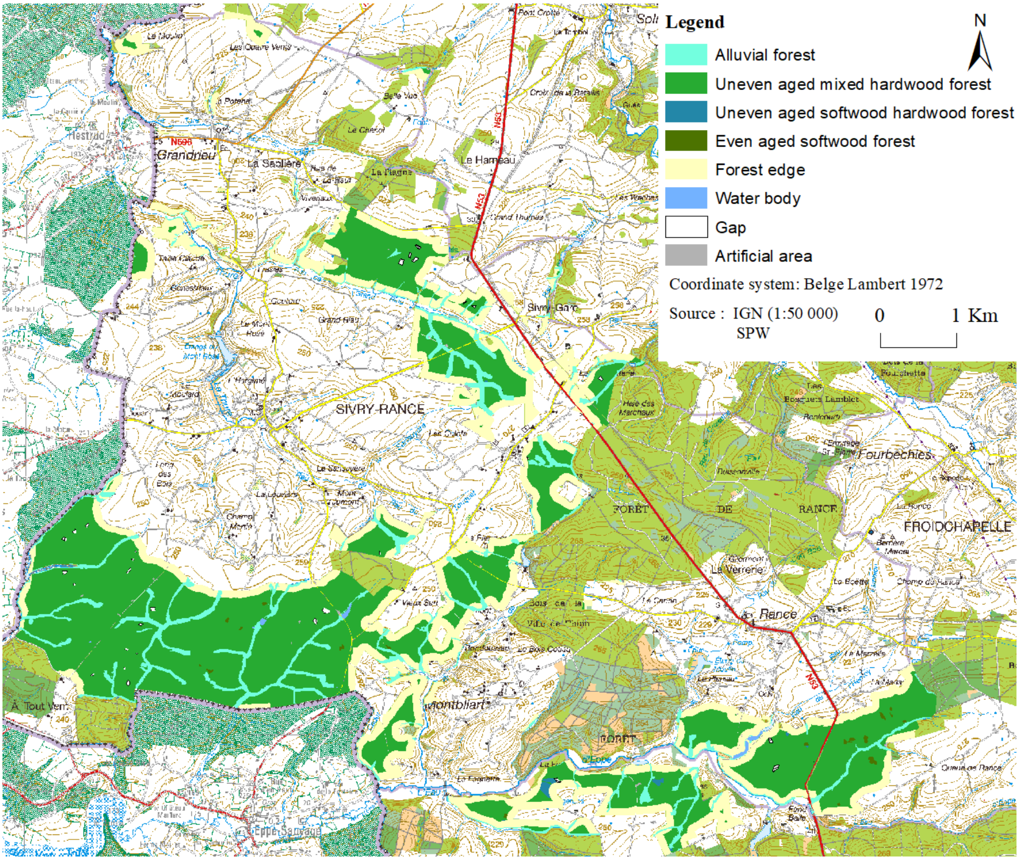

Figure 3-52. Forest stands of the municipal forest of Sivry-Rance in the pathway Recreation SSP1-2.6.

3.3.7 Forest stands in the SSP5-8.5

The distribution of the forest stands is almost the same as the one in the Recreation SSP1-2.6 pathway except that the even aged softwood stands become uneven aged hardwood softwood forest (**Figure 3-53**).

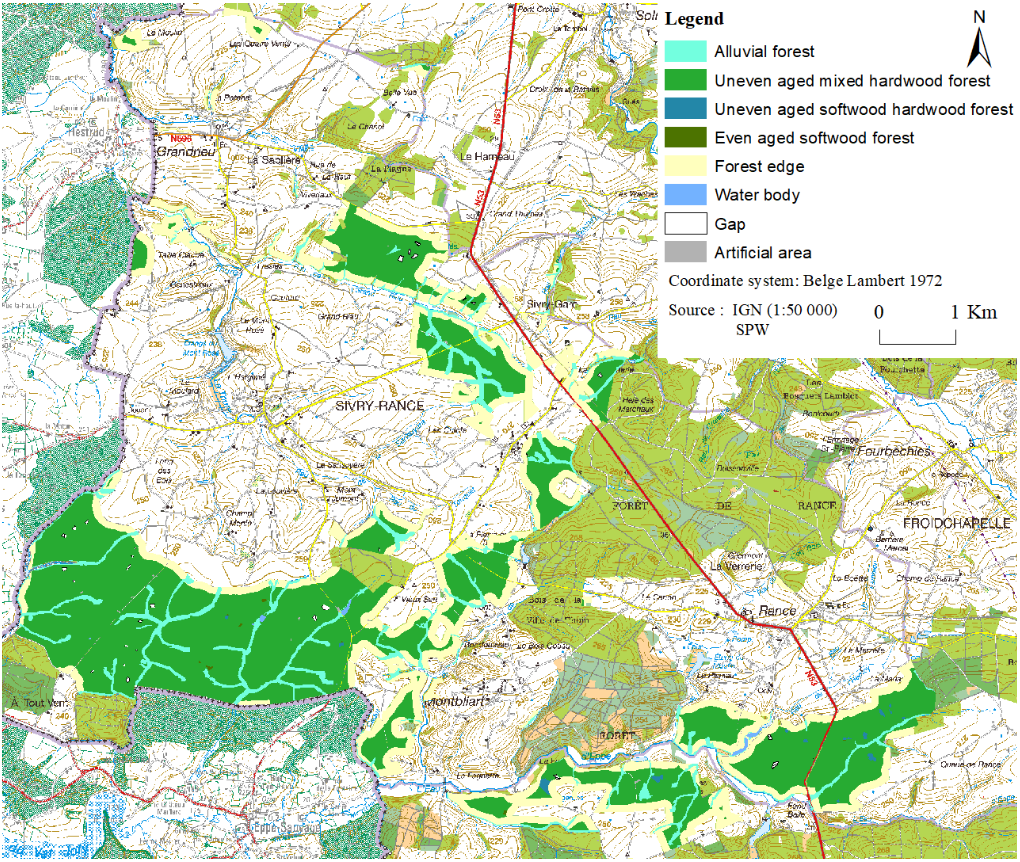

Figure 3-53. Forest stands of the municipal forest of Sivry-Rance in the pathway Recreation SSP5-8.5.

3.4 Biodiversity

This management scenario promotes biodiversity in the municipal forest of Sivry-Rance.

3.4.1 Management goals

To promote biodiversity, the management goals are the following:

- The entire forest is dedicated to nature conservation and restoration;
- The natural forest habitats are restored;
- The natural open areas are restored.

3.4.2 Forestry

In the remote parts of the municipal forest of Sivry-Rance, the forest stands are managed under the principles of continuous cover forestry (see Chapter 3 3.5.2. Forestry) while promoting biodiversity following the guidelines of Circulaire Biodiversité (Branquart, 2010) and Vallauri et al. (2016). The forest is managed in uneven aged stands with a continuous cover while promoting very old trees (individual trees and small senescence forest areas, at least 2% of the forest area and increasing of the exploitable size), habitat trees (at least 10 trees a hectare) and deadwood (at least 20m³ a hectare and leaving the tree crown in the forest).

In the other stands, no silvicultural intervention is performed.

3.4.3 Nature conservation

When the forest stands are part of a bigger forest and that their habitat has a good state of conservation, they become wilderness area where no management intervention is undertaken. If the habitat is not in a good state (e.g. softwood stand) or needs human intervention to be maintained (e.g. natural open areas, ponds), nature restoration actions are conducted (see Chapter 3 3.5.3. Nature conservation for some examples of nature restoration actions).

3.4.4 Recreation activities

The recreation is kept as it is now.

The fishing activities disappear for the benefit of the restoration of the fishing ponds.

The firewood harvesting by the inhabitants is only maintained in the Multiple ES + biodiversity objective area.

The hunting activities are adapted according to the hunting models of the forest of Hertogenwald Occidental (Colson et al., 2012) and the municipal forest of Plättscheid (Pieper et al., 2016) (see Chapter 3 3.3.4. Recreation activities).

3.4.5 Objectives areas

Two third of the municipal forest of Sivry-Rance is in the objective area Wilderness (68%) (**Figure 3-54**). The other third is divided into the Multiple ES + biodiversity objective area (18%) and the Nature conservation objective area (14%).

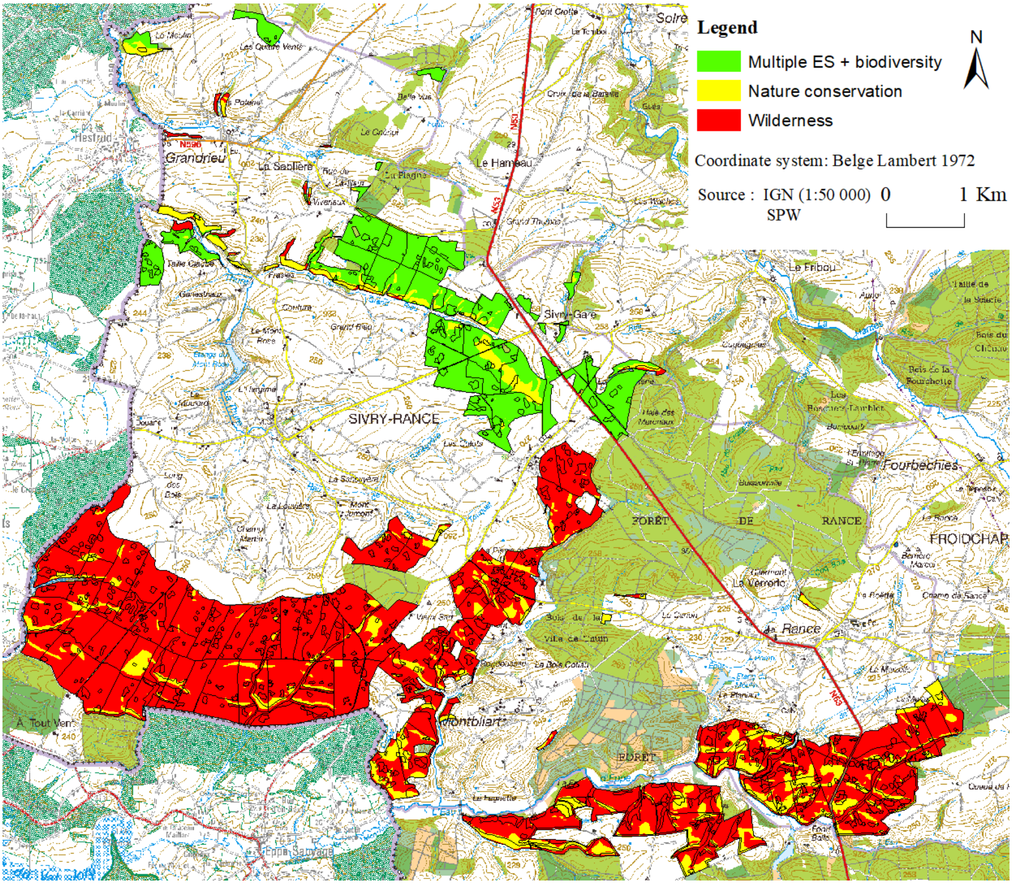

Figure 3-54. Objective areas of the management scenario Biodiversity for the municipal forest of Sivry-Rance.

3.4.6 Forest stands in the SSP1-2.6

More than a half of the municipal forest of Sivry-Rance is covered by uneven aged mixed hardwood forest (60%) (**Figure 3-55**). The other forest stands are respectively the forest edges (30%), the alluvial forest (9%) and the uneven aged hardwood softwood forest (0.4%).

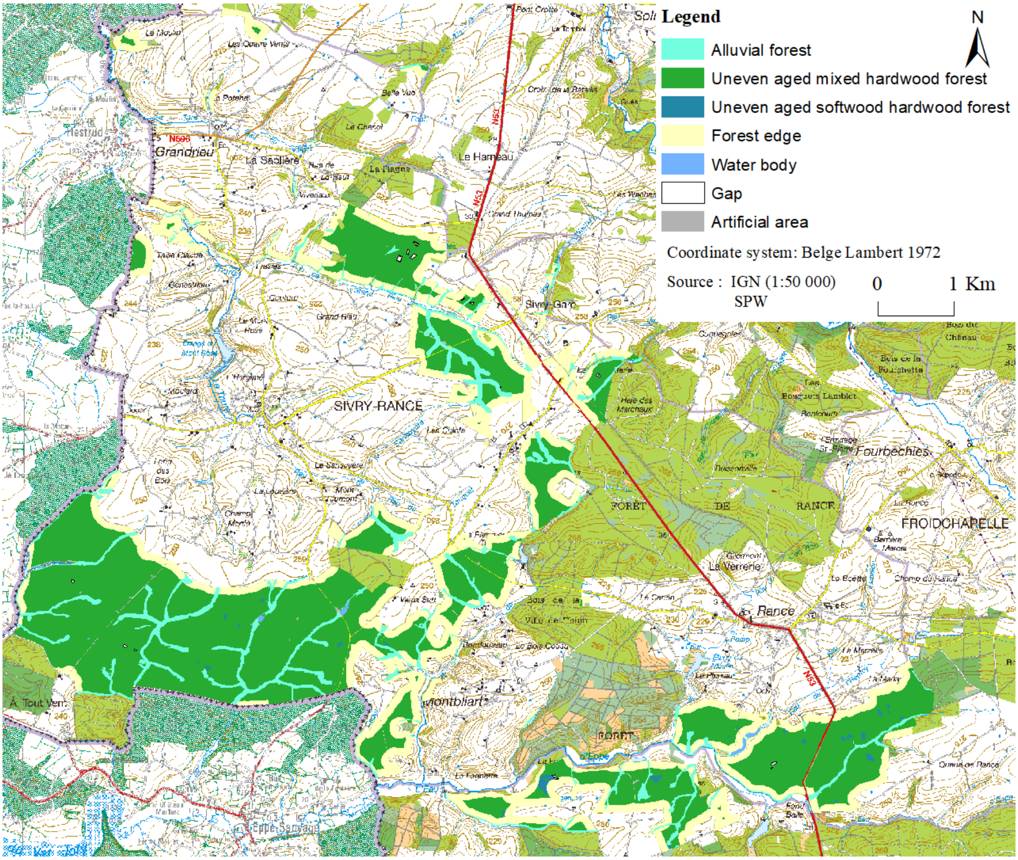

Figure 3-55. Forest stands of the municipal forest of Sivry-Rance in the pathway Biodiversity SSP1-2.6.

3.4.7 Forest stands in the SSP5-8.5

The distribution of the forest stands is almost the same as the one in the Biodiversity SSP1-2.6 pathway except that the uneven aged hardwood softwood stands on dry sites become uneven aged mixed hardwood forest (**Figure 3-56**).

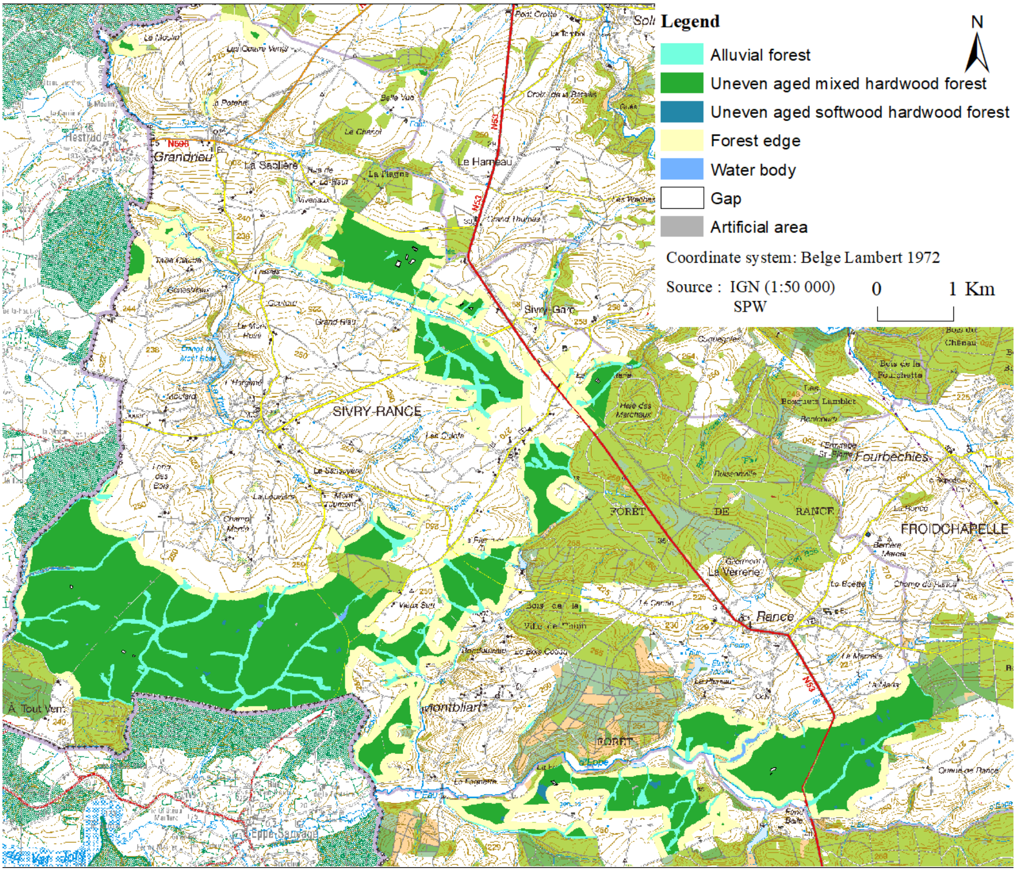

Figure 3-56. Forest stands of the municipal forest of Sivry-Rance in the pathway Biodiversity SSP5-8.5.

3.5 Multifunctional Forest

This management scenario is the forest management plan of the municipal forest of Sivry-Rance.

3.5.1 Management goals

The management goals are schematised in **Figure 3-57**.

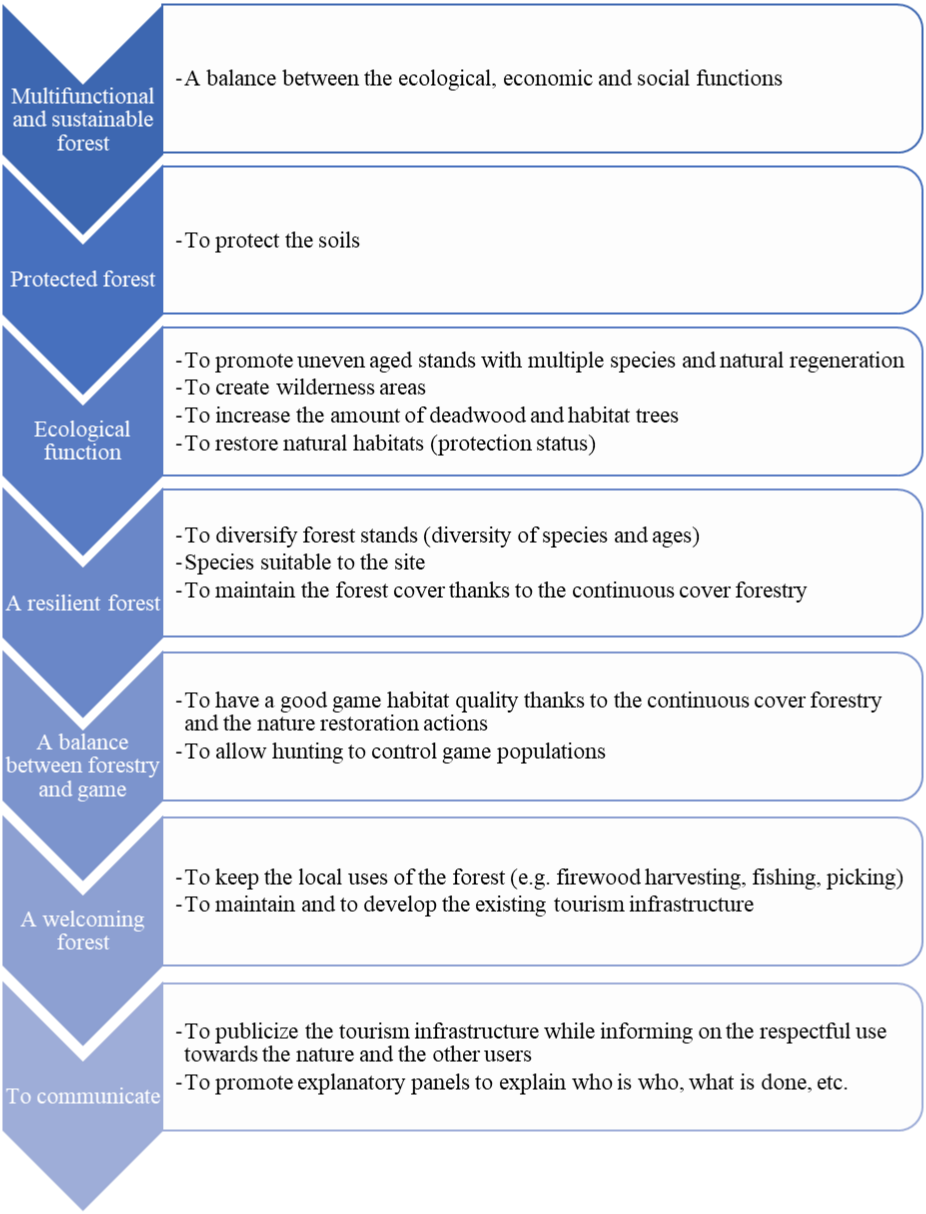

Figure 3-57. Management goals of the Multifunctional Forest management scenario.

The actual municipal forest of Sivry-Rance and its current management is very close to these management goals. Little changes are needed.

3.5.2 Forestry

The uneven aged mixed hardwood forest is managed under the principles of continuous cover forestry. The natural regeneration is promoted in the light cones and managed to promote the species diversification and tree quality. If there is no natural regeneration, small enrichment plantings are performed with high quality forest species suitable to the site. The maintenance of the uneven aged structure is performed during the tree marking by harvesting the large trees, the low-quality trees to promote the growth of high-quality trees and by promoting natural regeneration.

The young hardwood plantations are managed under the objective trees technique to promote the high-quality trees. The high-quality trees are shape pruned and pruned, then thinning is performed around them.

The even aged softwood stands are managed with regular thinnings (every six years). The even aged softwood stands with a lot of dead trees, due to *Ips typographus* L. outbreak and storms, are diversified by promoting natural regeneration and if necessary, by small enrichment plantings of a mix of indigenous forest species. Then, these stands are managed under the principles of continuous cover forestry.

To protect the soils, a permanent exploitation network is designed. The horse skidding is promoted in the thinning cuttings.

3.5.3 Nature conservation

To promote biodiversity, 6% of the forest area is designed as a wilderness area where no management intervention is undertaken. These wilderness areas are on the steep slopes, the alluvial sites and in small remote forest areas.

Nature restoration actions are also undertaken. The actual ponds are maintained by removing the vegetation around the pond to ensure its sunshine. New ponds are also created on the alluvial plains and on little intermittent streams. The natural wetlands are maintained. The forest edges are maintained by coppicing the trees on the first twenty to fifty meters to control their expansion. New forest edges are created by first cutting, pruning and coppicing the trees on the first ten meters and then, after about 10 years, coppicing the trees on the first twenty to fifty meters.

Deadwood and habitat trees are progressively increased to reach respectively two dead trees a hectare and one habitat tree per two hectares.

3.5.4 Recreation activities

The recreation activities are maintained. The tourism infrastructure is maintained and developed (40km of new trails, new explanatory panels). Some trails could be restricted to some users. Communication is improved to publicise the forest while informing on its respectful use toward the nature and the other users.

3.5.5 Objectives areas

Most of the municipal forest of Sivry-Rance is covered by the Multiple ES + biodiversity objective area (88%) (**Figure 3-58**). The Wilderness (6%), Multiple ES (4%) and Nature conservation objective areas (2%) share the rest of the forest.

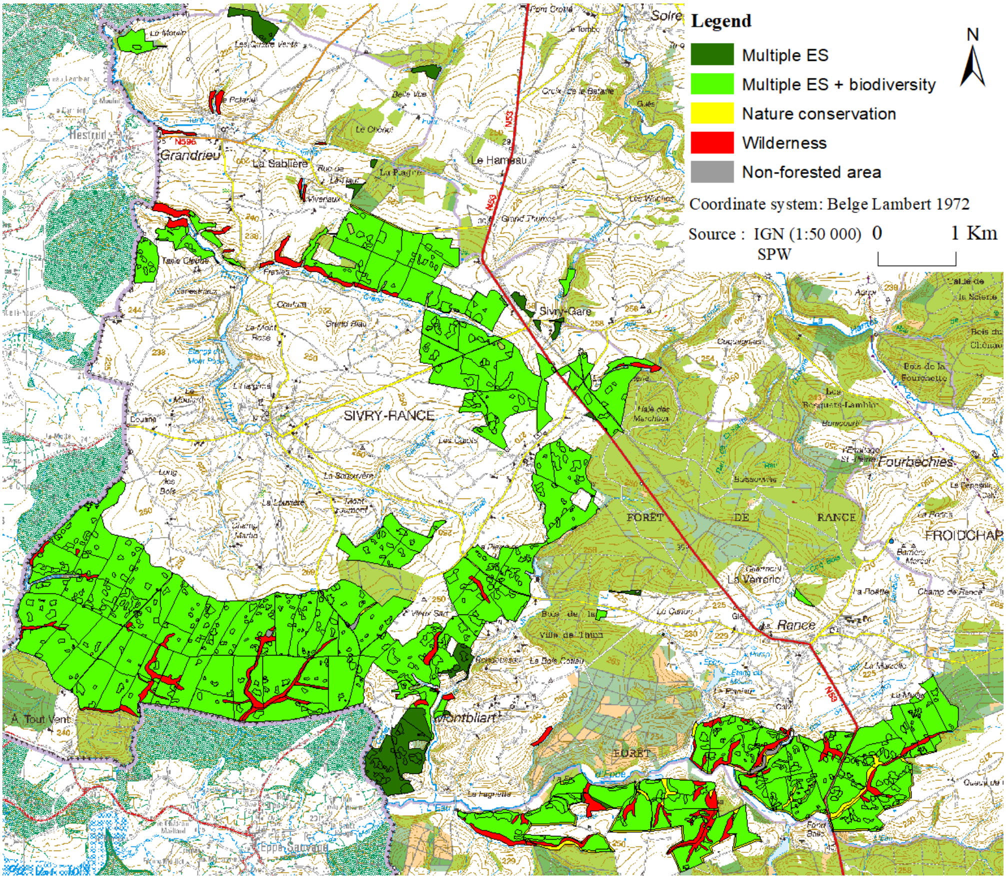

Figure 3-58. Objective areas of the management scenario Multifunctional Forest for the municipal forest of Sivry-Rance.

3.5.6 Forest stands in the SSP1-2.6

Two third of the municipal forest of Sivry-Rance is covered by uneven aged mixed hardwood forest (60%) (**Figure 3-59**). The forest edges represent a third of the forest (30%) and the alluvial forest a tenth of the forest (9%). The last percent is divided into the even aged softwood forest, the gaps, and the uneven aged hardwood softwood forest.

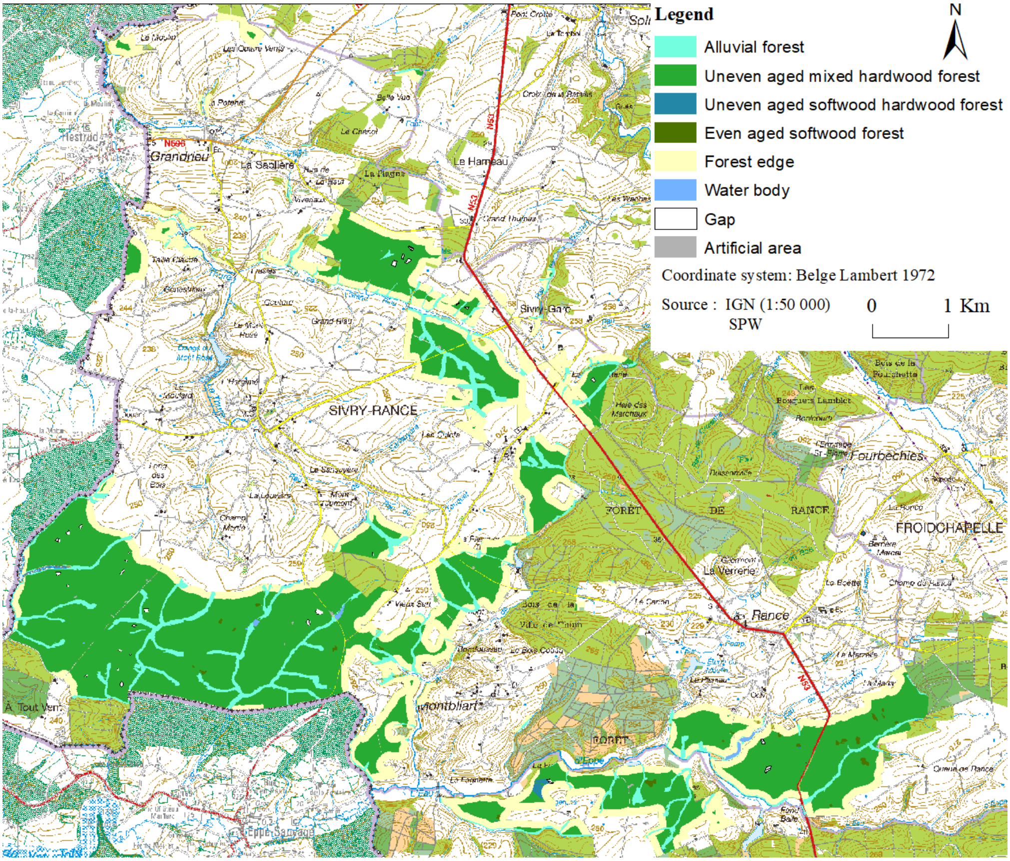

Figure 3-59. Forest stands of the municipal forest of Sivry-Rance in the pathway Multifunctional Forest SSP1-2.6.

3.5.7 Forest stands in the SSP5-8.5

The distribution of the forest stands is almost the same as the one in the Multifunctional Forest SSP1-2.6 pathway except that the even aged softwood stands become either uneven aged hardwood softwood stands on the cool plateau or slope site and uneven aged mixed hardwood forest on the dry sites and that the uneven aged hardwood softwood stands become uneven aged mixed hardwood forest on the dry sites (**Figure 3-60**).

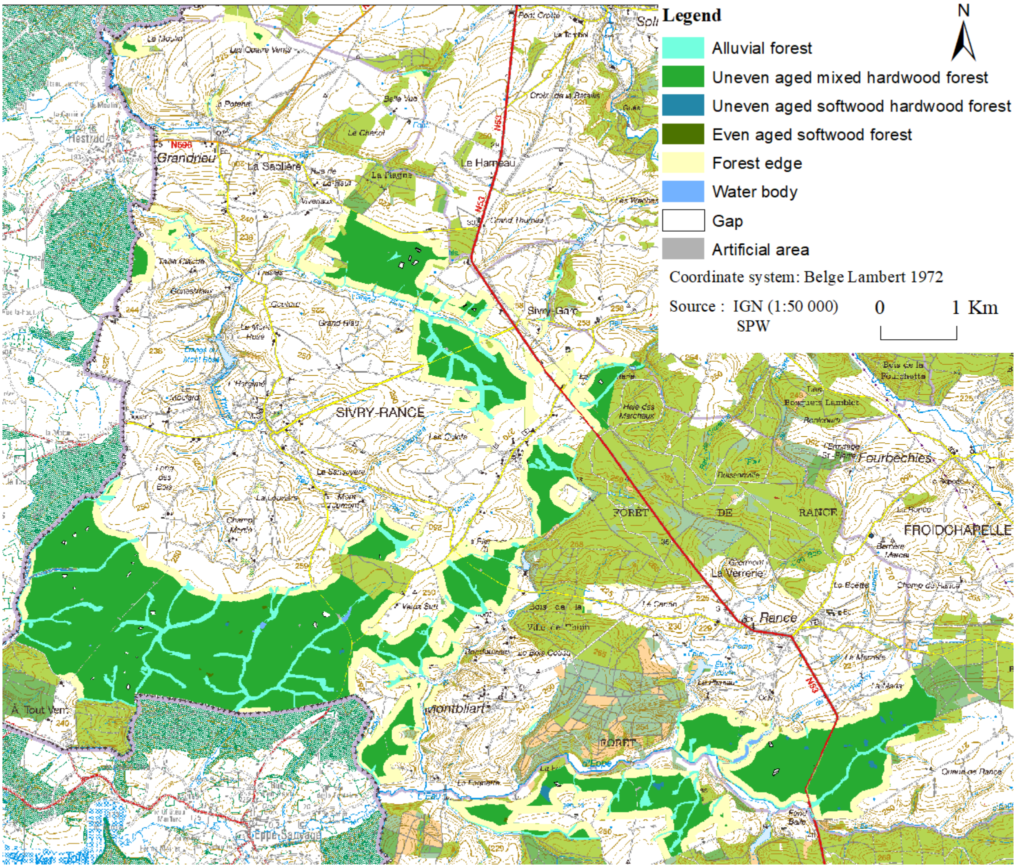

Figure 3-60. Forest stands of the municipal forest of Sivry-Rance in the pathway Multifunctional Forest SSP5-8.5.

3.6 Users' Forest

From the first participatory workshop, six ideal future forests were defined by the six groups of participants (**Table 3-23**). The six ideal future forests are quite similar except for some points such as the reduction of the tourism network or of the Natura 2000 constraints that were only mentioned by one group.

Table 3-23. A synthesis of the six ideal future forests defined by the six groups of participants during the first participatory workshop.

Group of participants	**Ideal future forest**
Group 1	A forest accessible to all, with a diversity of forest species, a preserved biodiversity and quiet game areas. The forest as it is now suits them in addition with a compliance with the rules and a forest circulation permit.
Group 2	A multifunctional forest with a balance between the hunting, social and ecological functions, with more information to the users notably on the rules.
Group 3	A diversified, preserved and sustainably managed (with regular harvestings) forest where all the users live together.
Group 4	A sustainably managed forest with a balance between the forestry and the game and where all the users live together. The tourism network should be cut down and some trails could be restricted to some users. Information on forest regulation and management should be popularized.
Group 5	A multifunctional forest with a diversification of the species. The actual forest suits them in addition with an improvement of the communication and the respect between the users. The signposting should be improved, and the Natura 2000 constraints should be reduced.
Group 6	An economically viable forest where the soils and the natural regeneration are protected. The regulations should be standardized, and a common minimum right should be established.

From the share elements of these six ideal future forests, the Users' Forest is defined as a multifunctional, natural, resilient, respected and sustainable forest where the different users live together and with a good communication.

3.6.1 Management goals

The management goals are schematised in **Figure 3-61**.

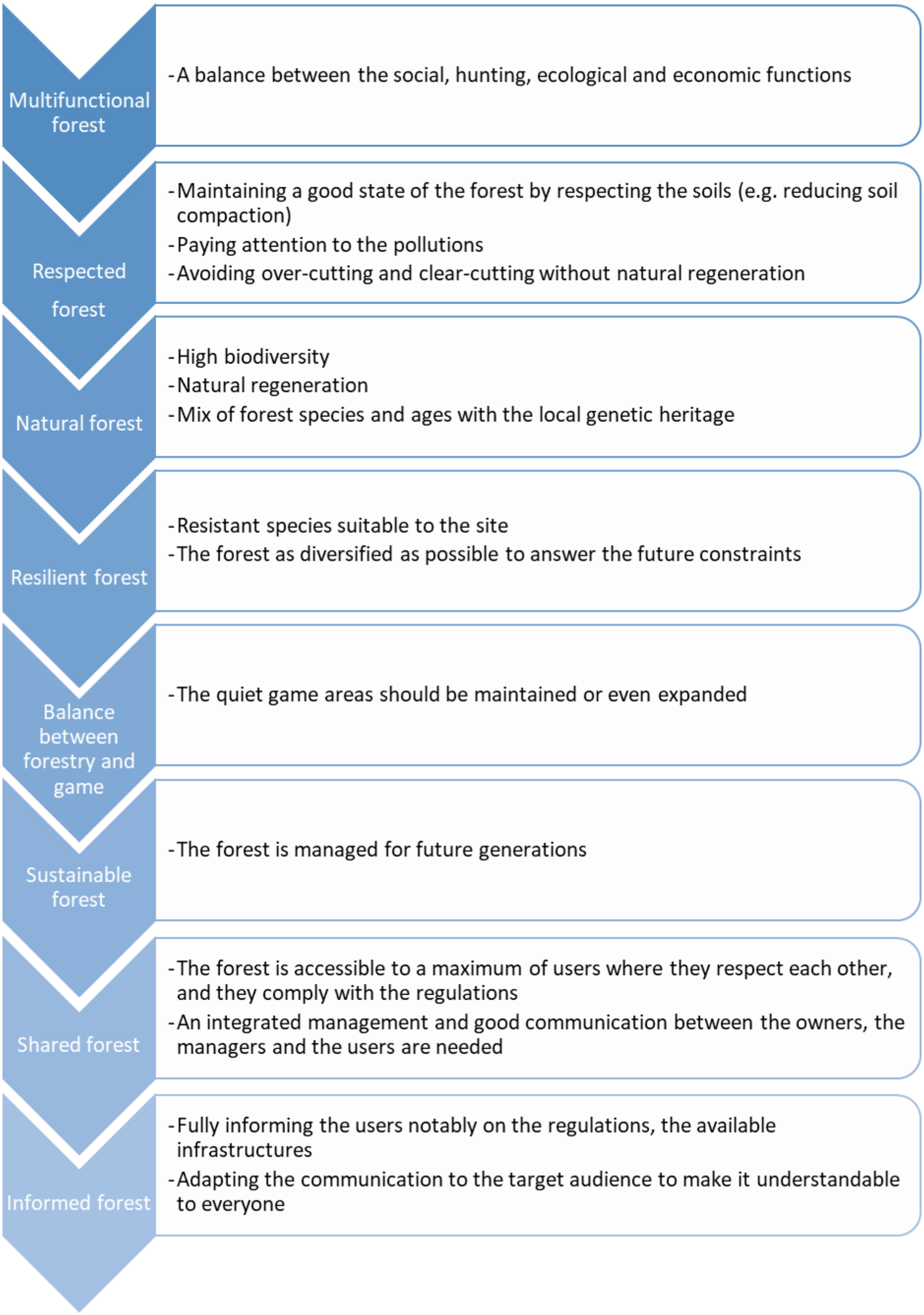

Figure 3-61. Management goals of the Users' Forest management scenario.

3.6.2 Forestry

The forest is managed under the principles of continuous cover forestry (see Chapter 3 3.5.2. Forestry) with an objective tree forestry increasing the exploitable size.

On the most fertile site (i.e. deep loamy clay and stony loamy soil), productive (exotic) species are planted in small enrichment plantings.

The even aged softwood stands are diversified by promoting natural regeneration and if necessary, by small enrichment plantings of a mix of indigenous forest species.

To protect the soils, a permanent exploitation network is designed. The horse skidding is promoted in the thinning cuttings.

3.6.3 Nature conservation

The area dedicated to nature conservation and restoration is increased compared to the forest management plan. In addition to the areas and the nature restoration actions provided in the forest management plan, the unproductive sites or with a high nature conservation value become wilderness areas where no management intervention is undertaken.

3.6.4 Recreation activities

The current recreation activities (i.e. recreation, fishing, firewood harvesting by the inhabitants and hunting) are maintained. The current tourism infrastructures are maintained with a special emphasis on communication (diversified communication means (e.g. information session, explanatory posters, articles, social media) adapted to the target audience) on the respect between the users and for nature as well as on the regulations.

3.6.5 Objectives areas

About two third of the municipal forest of Sivry-Rance is covered by the Multiple ES + biodiversity objective area (66%) (**Figure 3-62**). The Wilderness objective area (17%) along with the Nature conservation one (2%) cover a fifth of the forest. The Production objective area (12%) and the Multiple ES one (3%) share the rest of the forest.

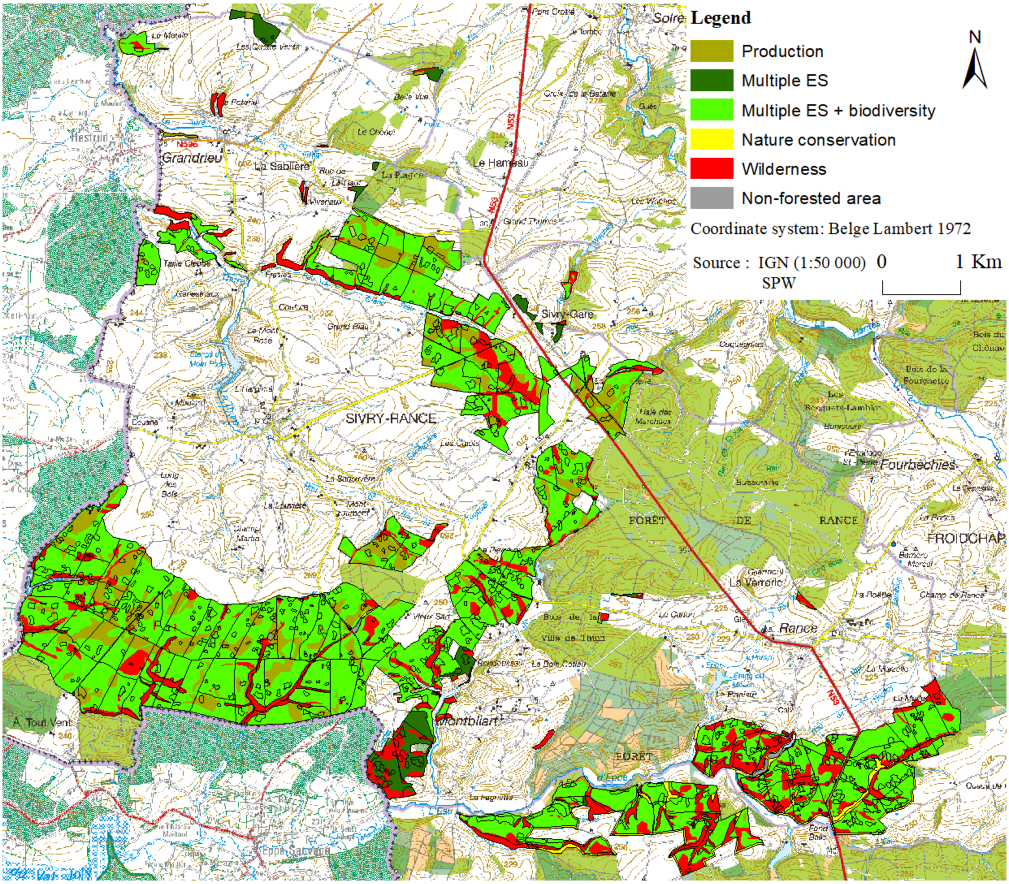

Figure 3-62. Objective areas of the management scenario Users' Forest for the municipal forest of Sivry-Rance.

3.6.6 Forest stands in the SSP1-2.6

Half of the forest is covered by uneven aged mixed hardwood forest (50%) (**Figure 3-63**). About a third of the forest is composed of forest edges (30%). The uneven aged hardwood softwood forest (10%) and the alluvial forest (9%) share the rest of the forest.

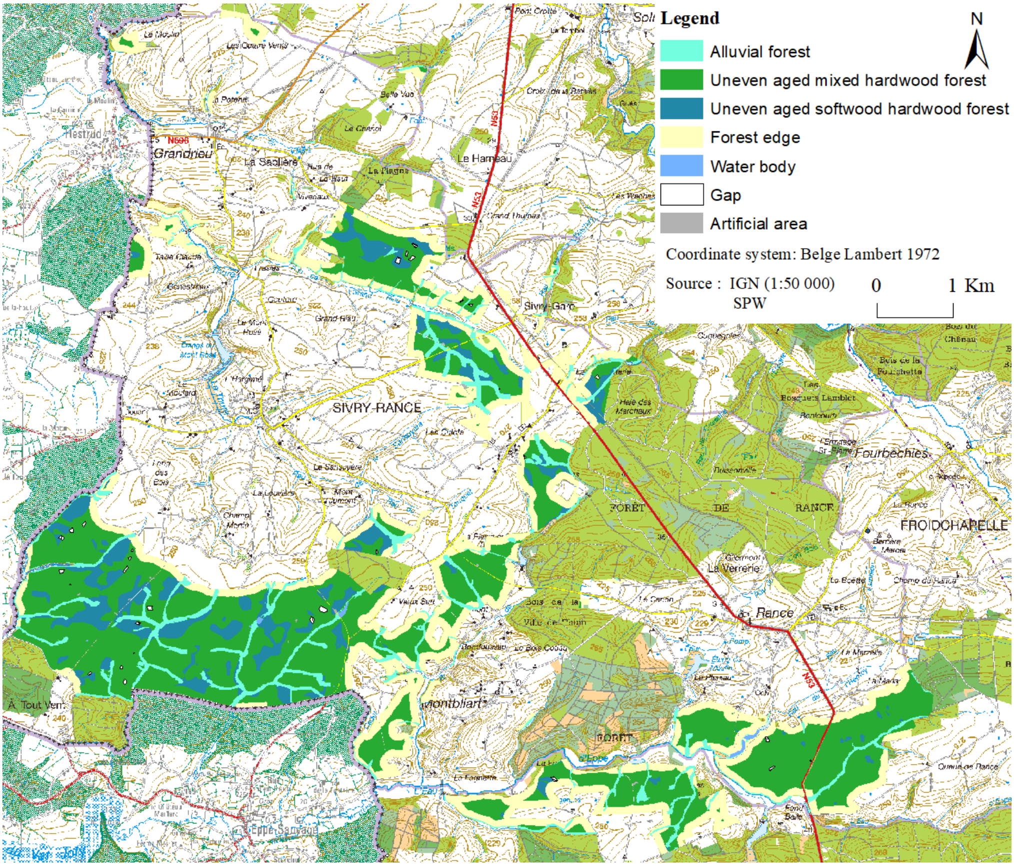

Figure 3-63. Forest stands of the municipal forest of Sivry-Rance in the pathway Users' Forest SSP1-2.6.

3.6.7 Forest stands in the SSP5-8.5

The distribution of the forest stands is almost the same as the one in the Users' Forest SSP1-2.6 pathway except that the uneven aged hardwood softwood stands on dry sites become uneven aged mixed hardwood forest (**Figure 3-64**).

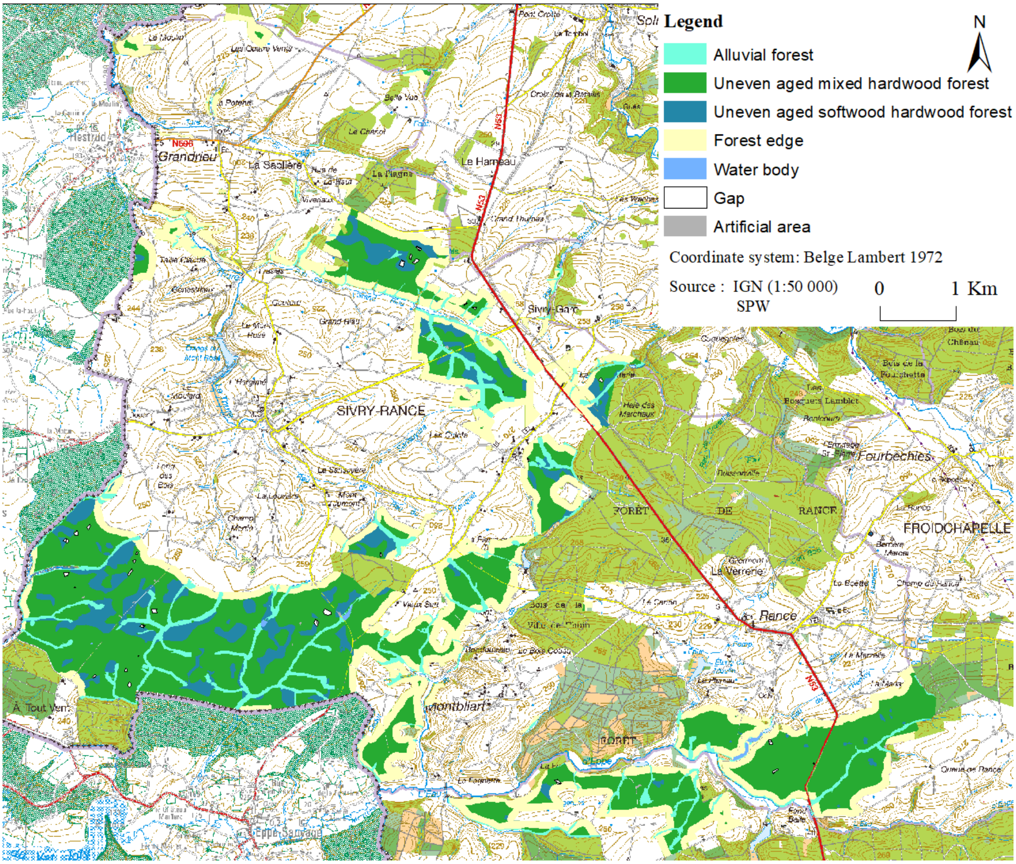

Figure 3-64. Forest stands of the municipal forest of Sivry-Rance in the pathway Users' Forest SSP5-8.5.

4. Step 4: Assess the ES

First, the social preferences are discussed. Then, the selected ES and methods to assess them are reminded. Then, the assessment of the selected ES is presented.

4.1 *Understand the social preferences*

From the second participatory workshop, the preferences regarding the ES can be synthetized for the four groups as following: (1) all the ES are important, (2) preference for the provisioning ES, (3) preference for the regulating ES, and (4) preference for the cultural ES. The preferences of these four groups are detailed in the next sections. For each group, the opinion, the weighting, the acceptable level, and the satisfactory level of the ES are given. Finally, the preferences of the four groups are compared.

4.1.1 Group who finds all the ES important

Even if they find all the ES important, some ES (e.g. Wood, Water quality and quantity) have a bigger weight than others (e.g. Fishing, Nature observation, learning and inspiration, Natural heritage) (**Table 3-24**). Globally, they want to maximize or keep at the same level most of the ES except the ES Picking and Recreation. The acceptable level is generally medium but for the regulating ES, it is higher and lower for Hunting and Fishing. For a majority of ES (e.g. Wood, Water quality and quantity, Nature observation, learning and inspiration), their satisfactory level is the same as the acceptable level while for the others, it is one level above the acceptable one and to a lesser extent, two levels above (i.e. Picking).

Table 3-24. Detailed preferences of the group who finds all the ES important obtained from the second participatory workshop.

ES	Opinion	Weighting	Acceptable level	Satisfactory level
Wood	Maximize	11	Medium	Medium
Hunting	Identical	8	Low	Medium
Picking	Minimize	8	Medium	Very high
Fishing	Identical	5	Low	Low
Water quality & quantity	Maximize	13	Very high	Very high
Control of soil erosion & flooding	Identical	9	Very high	Very high
Fauna and flora	Maximize	9	Very high	Very high
Climate regulation and air purification	Identical	9	High	High
Natural surroundings	Identical	9	Medium	High
Recreation	Minimize	9	Medium	High
Nature observation, learning and inspiration	Identical	5	Medium	Medium
Natural heritage	Maximize	5	Medium	High

In Annex 8, the opinion and weighting of the group are compared to the individual opinion and weighting of each person of the group. For some ES (i.e. Water quality & quantity, Fauna and flora and Natural heritage), their opinion and weighting are quite consensual. For the ES Control of soil erosion & flooding and Climate regulation and air purification, it is also quite consensual except for one person who gave a lower weighting. For the ES Wood and Fishing, some of them wanted to keep the ES identical and gave a lower weighting while the others wanted to maximize the ES and gave a higher weighting. For the ES Hunting, the weighting of the group is systematically higher than the individual one. Finally, for the ES Picking, Natural surroundings, Recreation and Nature observation, learning and inspiration, their opinion is variable as well as their weighting.

4.1.2 Group who prefers the provisioning ES

This group prefers the provisioning ES and in particular the ES Wood and Hunting (**Table 3-25**). They also gave a high weight to the ES Fauna and flora and a very low weight to the ES Picking, Climate regulation and air purification and Natural heritage. They mostly want to maximize the ES except the ES Picking and Fishing that they want to minimize and the ES Climate regulation and air purification and Natural heritage that they want to keep identical. The acceptable level is either very low (e.g. Picking, Climate regulation and air purification, Natural heritage), medium (e.g. Water quality and quantity, Natural surroundings) or high (e.g. Hunting, Fauna and flora). The satisfactory level gains one level for all the ES. Their opinion, weighting, acceptable and satisfactory levels are linked. For the most important ES (i.e. with the higher weighting), they want to maximize them, and their levels are high. For the least important ES and the ES Fishing, they either want to minimize or keep them identical and the levels are low.

Table 3-25. Detailed preferences of the group who prefers the provisioning ES obtained from the second participatory workshop.

ES	Opinion	Weighting	Acceptable level	Satisfactory level
Wood	Maximize	14	High	Very high
Hunting	Maximize	27	High	Very high
Picking	Minimize	1	Very low	Low
Fishing	Minimize	7	Very low	Low
Water quality & quantity	Maximize	7	Medium	High
Control of soil erosion & flooding	Maximize	7	Medium	High
Fauna and flora	Maximize	14	High	Very high
Climate regulation and air purification	Identical	1	Very low	Low
Natural surroundings	Maximize	7	Medium	High
Recreation	Maximize	7	Medium	High
Nature observation, learning and inspiration	Maximize	7	Medium	High
Natural heritage	Identical	1	Very low	Low

In Annex 9, the opinion and weighting of the group are compared to the individual opinion and weighting of each person of the group. For the ES Picking, their opinion and weighting is quite consensual while for the ES Climate regulation and air purification and Natural heritage, their opinion is variable but their weighting are quite consensual. For the ES Wood and Hunting, their opinion and weighting are quite consensual except for one person. For the ES Natural surroundings, some wanted to keep the ES identical and gave a low weighting while others wanted to maximize the ES and gave the same weighting as the one of the group. For the ES Control of soil erosion & flooding, Fauna and flora, Fishing and Recreation, their opinion and weighting are variable.

4.1.3 Group who prefers the regulating ES

This group gives a high importance to the regulating ES except Climate regulation and air purification (**Table 3-26**). The ES Natural surroundings was also important for them while Recreation and the provisioning ES except Fishing were of little importance. They want to maximize the ES Natural heritage and the regulating ES except Water quality and quantity while they want to minimize the ES Picking. They did not give the acceptable and satisfactory levels to the ES because the exercise was too fictional and too unclear for them. For them, the acceptable and satisfactory levels depend on the evolution of the forest (e.g. if the swine fever arrives in the forest, more game should be shot) and the indicator considered (e.g. the number of animals shot or the game population in the forest).

Table 3-26. Detailed preferences of the group who prefers the regulating ES obtained from the second participatory workshop.

ES	Opinion	Weighting	Acceptable level	Satisfactory level
Wood	Identical	3	/	/
Hunting	Identical	3	/	/
Picking	Minimize	3	/	/
Fishing	Identical	9	/	/
Water quality & quantity	Identical	16	/	/
Control of soil erosion & flooding	Maximize	16	/	/
Fauna and flora	Maximize	16	/	/
Climate regulation and air purification	Maximize	3	/	/
Natural surroundings	Maximize	12	/	/
Recreation	Identical	4	/	/
Nature observation, learning and inspiration	Identical	6	/	/
Natural heritage	Maximize	7	/	/

In Annex 10, the opinion and weighting of the group are compared to the individual opinion and weighting of each person of the group. For the ES Fauna and flora, their opinion and weighting are quite consensual. For the ES Picking, Control of soil erosion & flooding, Climate regulation and air purification, Natural surroundings and Natural Heritage, their opinion is consensual, but their weighting is variable. For the ES Water quality & quantity, it is the contrary. For the ES Wood, they wanted to maximize it (in contrast to the group) and their weighting is higher than the one of the group. Finally, for the ES Hunting, Fishing, Recreation and Nature observation, learning and inspiration, their opinion and weighting are variable.

4.1.4 Group who prefers the cultural ES

This group gave a high importance to the cultural ES especially Recreation, the ES Picking and Fauna and flora and a very low importance to the ES Hunting (**Table 3-27**). They want to maximize all the ES except Hunting. The acceptable level is very high for the cultural ES, Fauna and flora and Climate regulation and air purification and very low for the ES Hunting. The satisfactory level is always the same as the acceptable level. The weighting and the ES levels are linked: when they give a high importance to an ES, its levels are also high and vice versa.

Table 3-27. Detailed preferences of the group who prefers the cultural ES obtained from the second participatory workshop.

ES	Opinion	Weighting	Acceptable level	Satisfactory level
Wood	Maximize	6	Medium	Medium
Hunting	Minimize	1	Very low	Very low
Picking	Maximize	11	High	High
Fishing	Maximize	6	Medium	Medium
Water quality & quantity	Maximize	8	High	High
Control of soil erosion & flooding	Maximize	6	Medium	Medium
Fauna and flora	Maximize	13	Very high	Very high
Climate regulation and air purification	Maximize	6	Very high	Very high
Natural surroundings	Maximize	8	Very high	Very high
Recreation	Maximize	17	Very high	Very high
Nature observation, learning and inspiration	Maximize	9	Very high	Very high
Natural heritage	Maximize	11	Very high	Very high

In Annex 11, the opinion and weighting of the group are compared to the individual opinion and weighting of each person of the group. For some ES (i.e. Water quality & quantity, Fauna and flora and Climate regulation and air purification), their opinion and weighting are quite consensual. For most of the ES (i.e. Hunting, Picking, Control of soil erosion & flooding, Natural surroundings, Recreation, Nature observation, learning and inspiration and Natural heritage), their opinion is consensual and their weighting are quite variable but generally high except for the ES Hunting, Picking and Natural heritage where the weighting is more variable. For the ES Fishing, their opinion is variable but their weighting are quite consensual. Finally, for the ES Wood, their opinion and weighting are variable.

4.1.5 Comparison of the four groups

All the four groups want to maximize the ES Wood and Fauna and flora. They all find important the ES Fauna and flora and attributed high levels to it while the importance of Wood greatly varies from one group to another, and its levels range from medium to very high.

Similar trends are observed for the ES Fishing that has a medium importance with low levels in the four groups and for the ES Water quality and quantity, Control of soil erosion and flooding, Natural surroundings and Nature observation, learning and inspiration that all the groups want to maximize or keep identical, find quite important and gave (quite) high levels.

For the other ES (i.e. Hunting, Picking, Climate regulation and air purification, Recreation, Natural heritage), the preferences greatly vary from one group to another.

4.2 Select the ES

The selected ES and their grouping were already presented in **Table 2-18** (see Chapter 2 6.1. ES selection). In total, twelve groups of closed ES were retained.

4.3 Select the methods

The selected methods to assess the twelve groups of ES were synthetised in **Table 2-20** (see Chapter 2 6.2. Methods selection). The results of these methods are presented in the next section.

4.4 Assess the ES

The values are presented for each ES in the actual state and in the twelve pathways. Each indicator is discussed separately and then, all the indicators of each ES are compared. Finally, the interactions between the ES are discussed.

4.4.1 Wood

To assess the ES Wood, four indicators were calculated: (1) the growing stock, (2) the annual volume of harvested timber, (3) the annual profit from timber harvesting, and (4) the suitability level of the forest with the preferences of the inhabitants harvesting firewood. The first three ones are numerical values obtained from the data of the forest management plan and IPRFW adjusted by forest experts. The last one is a qualitative indicator derived from the survey of the inhabitants harvesting firewood.

4.4.1.1 Growing stock, annual volume of harvested timber and annual profit from timber harvesting

The growing stock is the highest in the Biodiversity management scenario as almost no timber is harvested (**Table 3-28**). The Wood Production management scenario also reaches its goal in maximizing timber production with a high growing stock. The lowest values are in the Profitability management scenario where a lot of timber is harvested each year and in the current state where the young plantations have not yet reached their maximal growing stock. The Recreation management scenario has higher growing stocks than the Users' Forest and the Multifunctional Forest ones because less timber is harvested (no timber is harvested in the Priority Recreation area except for safety reasons). The Users' Forest management scenario has higher values than the Multifunctional Forest one because some forest stands are dedicated to production with more productive species. The SSP5-8.5 climate change scenarios has a lower growing stock than the SSP1-2.6 due to higher mortality rates and less productive stands. The difference between these two climate change scenarios is particularly strong in the Wood Production management scenario because more than a half of the even aged softwood stands become, in the SSP5-8.5, even aged hardwood stands that are less productive.

The highest mean annual volume of harvested timber is unsurprisingly in the Profitability and Wood production management scenarios while the lowest values are in the Biodiversity one (**Table 3-28**). The Recreation, Multifunctional Forest and Users' Forest have almost the same values even if the Users' Forest is a little better thanks to its more productive species in the Production objective area. The SSP5-8.5 climate change scenarios has a lower mean annual volume of harvested timber than SSP1-2.6 due to less productive stands that are not compensated by higher mortality rates (the declining trees are harvested) except in the Recreation management scenario. Again, the difference between the two climate change scenarios is particularly strong in the Wood Production management scenario.

The mean annual profit from timber harvesting is unsurprisingly the highest in the Profitability management scenario (**Table 3-28**). In contrast, it is low in the Wood Production management scenario because even if the mean annual volume of harvested timber is high its economic value is lower compared to high quality wood produced in the other management scenarios. The SSP5-8.5 climate change scenarios have a lower mean annual profit from timber harvesting than the SSP1-2.6 except in the Wood Production and Recreation management scenarios where there is almost no difference. Indeed, in the Wood Production management scenario, the hardwood species have a higher economic value than the softwood. In the Recreation management scenario, even if more timber is harvested in the SSP5-8, this economic value is lower because the high commercial value species are less present.

When comparing the three indicators, no management scenario outperforms the others even if the Wood Production and Profitability management scenarios are a bit better than the others.

Table 3-28. Growing stock, mean annual volume of harvested timber and mean annual profit from timber harvesting in the current state and in the twelve pathways of the municipal forest of Sivry-Rance.

Forest state		**Growing stock** (m³/ha)	**Mean annual volume of harvested timber** (m³/ha*year)	**Mean annual profit from timber harvesting** (€/ha*year)
Current state		191	3.3	152
Wood Production	SSP1-2.6	368	6.0	197
	SSP5-8.5	326	4.7	196
Profitability	SSP1-2.6	191	6.9	334
	SSP5-8.5	191	6.1	298
Recreation	SSP1-2.6	234	3.9	171
	SSP5-8.5	219	4.2	171
Biodiversity	SSP1-2.6	438	0.8	33
	SSP5-8.5	412	0.8	32
Multifunctional Forest	SSP1-2.6	198	4.2	180
	SSP5-8.5	186	3.9	161
Users' Forest	SSP1-2.6	212	4.4	211
	SSP5-8.5	194	3.9	174

4.4.1.2 Suitability level of the forest with the preferences of the inhabitants harvesting firewood

The inhabitants harvesting firewood prefer a hardwood continuous forest or with natural open areas with deadwood and young and old trees, calm and quiet, with a high biodiversity, accessible with a respectful forest management, with elements of the cultural heritage, with possibilities for walking and some tourism infrastructures, clean (no waste, no pollution) and a respect between the users. The management of firewood and its availability are also important for them. Climate change has no real impact on the use of this ES because the inhabitants go to the forest to harvest firewood for their pleasure and not for the buffering effect of the forest on the climate. The impacts of climate change were thus only considered in terms of changes in the visual features of the forest.

The Multifunctional Forest and Users' Forest management scenarios are the most preferred ones by the inhabitants harvesting firewood while the Wood Production and Profitability ones are the least preferred (**Table 3-29**). The current state is also appreciated while the Recreation and Biodiversity management scenarios are less preferred.

Table 3-29. Suitability level of the forest with the preferences of the inhabitants harvesting firewood for the current state and the twelve pathways of the municipal forest of Sivry-Rance with its justification.

Forest state	Level	Justification
Current state	High	The actual forest is close to their ideal forest even if some improvements can be made concerning biodiversity, the respect between the users, the cleanliness, and the accessibility.
Wood Production SSP1-2.6 and SSP5-8.5	Very low	Firewood harvesting by the inhabitants disappears.
Profitability SSP1-2.6 and SSP5-8.5		
Recreation SSP1-2.6 and SSP5-8.5	Medium	Firewood harvesting by the inhabitants is not allowed in the Priority Recreation objective area. The forest is their ideal forest but the calm and quiet decreases in the most frequented areas. Its accessibility is improved, and the tourism infrastructures are developed. Conflicts may arise with the recreation users. The forest management is respectful.
Biodiversity SSP1-2.6 and SSP5-8.5	Low	Firewood harvesting by inhabitants is not allowed in the Wilderness and Nature conservation objective areas which cover a large part of the forest. Recreation is kept as it is now (which is quite good). The forest is their ideal forest. Conflicts may arise with the recreation users. The forest management is very respectful.
Multifunctional Forest SSP1-2.6 and SSP5-8.5	Very high	Firewood harvesting by the inhabitants is maintained. Recreation is promoted with the development of new infrastructures. The forest is their ideal forest. The biodiversity (including deadwood), the accessibility and the maintenance are a little improved. The respect between the users is quite good. The forest management is respectful.
Users' Forest SSP1-2.6 and SSP5-8.5		

4.4.1.3 Comparison of the indicators

Looking at the four indicators of the ES Wood, no pathway outperforms the others, it depends on the indicator considered.

4.4.2 Hunting

Four qualitative indicators were assessed to value ES Hunting: (1) habitat quality of game, (2) deer impact mitigation, (3) the mean annual profit from hunting leases, and, (4) the suitability level of the forest with the preferences of the hunters. The first three ones were assessed from a literature review of the relevant factors influencing them and the last one was derived from the survey of the hunters.

4.4.2.1 Habitat quality for game

The factors that influence the habitat quality for game are synthetised in **Figure 3-65**.

Climate

- The game prefers the buffering conditions of the forest (the colder winters, the hotter summers, the droughts and the heavy rains are not appreciated by the game)
- The storms, by creating open areas where the game can feed, are favourable

The human infrastructures and activities including hunting

- The more they are present, the more the game is disturbed

Forest cover

- A dense forest cover creates sanctuaries for game
- Open areas are needed for the game to feed.
- A spatial heterogeneity of the forest cover is thus ideal (e.g. management with clear-cutting)

The ground vegetation

- Important source of food, the more it is present, the better it is (e.g. natural regeneration, clear-cutting, indigenous species)

Shrubs and bushes

- Sanctuaries for the game

The forest species

- Some forest species are more palatable (e.g. maple, oak, ash, Douglas fir, larch) than others.
- A diversity of forest species is favourable especially a mix of hardwood and softwood species to have both species to feed on (e.g. mostly hardwood species) and sanctuaries even during the winter (i.e. softwood species)

The stand height

- The big trees are appreciated when it is raining

The open areas

- They are used for feeding
- They are particularly appreciated next to a forest to also have sanctuaries

The ponds and streams

- The more they are, the better it is (they are used for drinking)

Figure 3-65. Factors, that can vary from pathway to pathway, influencing the habitat quality for game, from the literature review (Colson and Baix, 2021; Morelle and Lejeune, 2015; Reimoser et al., 2009; Vospernik and Reimoser, 2008).

On average, the habitat quality for game is quite high in the current state and in the twelve pathways (Table 3-30). It is higher in the Biodiversity management scenario and lower in the Wood Production management scenario and in the Profitability SSP5-8.5 pathway.

Table 3-30. The level of habitat quality for game in the current state and in the twelve pathways of the municipal forest of Sivry-Rance with its justification.

Forest state	Level	Justification
Current state	High	Positive factors: The climate is quite good with a few storms. The continuous cover forest is globally favourable. Natural open areas are quite present as well as water points. Mixed effects: The human infrastructures are quite present, with a medium attendance and a moderate hunting.
Wood Production SSP1-2.6	Medium	Positive factors: few human infrastructures and low forest attendance, management with clear-cutting. Mixed effects: moderate hunting, ground vegetation highly present in the clear-cuttings but not in the softwood stands. Negative factors: low forest species diversity with individual protection of the palatable species, few open natural areas and forest ponds.
Wood Production SSP5-8.5	Medium	Compared to Wood Production SSP1-2.6, the ground vegetation quite good in the clear-cuttings and hardwood stands, there is a mix of hardwood and softwood species with a higher forest species diversity.
Profitability SSP1-2.6	High	Positive factors: few human infrastructures and low forest attendance, lot of ground vegetation, bushes and shrubs, quite high forest species diversity, little clear-cuttings, substantial presence of natural open areas and water ponds. Negative factors: intensive hunting, quite low forest cover with a low spatial heterogeneity, the tree height is quite low.
Profitability SSP5-8.5	Medium	The conditions are the same as in Profitability SSP1-2.6 with higher negative impacts of climate change.
Recreation SSP1-2.6	High	Positive factors: very moderate hunting, ground vegetation, shrubs and bushes are quite present, high forest species diversity, high stand height, substantial presence of natural open areas and water ponds. Mixed effects: quite dense forest cover with a low spatial heterogeneity. Negative factors: no clear-cutting, a lot of human infrastructures and high forest attendance.
Recreation SSP5-8.5	High	Even if climate change has a negative impact, the forest species diversity remains high.

Biodiversity SSP1-2.6	Very high	Positive factors: very moderate hunting, ground vegetation, shrubs and bushes are highly present, high forest species diversity, big trees, substantial presence of natural open areas and forest ponds. Mixed effects: quite dense forest cover with a quite low spatial heterogeneity. Quite a few human infrastructures and medium forest attendance.
Biodiversity SSP5-8.5	Very high	Even if climate change has a negative impact, the higher tree mortality will create more natural open areas.
Multifunctional Forest SSP1-2.6	High	Positive factors: ground vegetation, shrubs and bushes quite present, quite high forest species diversity, high stand height, substantial presence of natural open areas and water points. Mixed effects: moderate hunting, quite dense forest cover with little clear-cuttings, quite low spatial heterogeneity. Negative factors: quite high forest attendance with a certain number of human infrastructures.
Multifunctional SSP5-8.5	Medium	The conditions are the same as in Multifunctional Forest SSP1-2.6 with higher negative impacts of climate change.
Users' Forest SSP1-2.6	High	Positive factors: ground vegetation, shrubs and bushes quite present, high forest species diversity, high stand height, substantial presence of natural open areas and water points. Mixed effects: moderate hunting, quite dense forest cover with little clear-cuttings, quite low spatial heterogeneity. Negative factors: quite high forest attendance with a certain number of human infrastructures.
Users' Forest SSP5-8.5	Medium	The conditions are the same as in Users’ Forest SSP1-2.6 with higher negative impacts of climate change.

4.4.2.2 Deer impact mitigation

From the literature review, the deer impact increases with:

- Extreme weather conditions in dense forest cover where they find a sanctuary;
- An increase in disturbing (human infrastructure, forest attendance, hunting);
- Inappropriate hunting (e.g. hunting that maintains high game density, modifies the structure of the population, on large areas and time periods);
- A low supply of forage (e.g. ground vegetation not present all over the year);
- The palatable forest species;
- Forest cover especially in the softwood stands and if the ground vegetation is low;
- A decrease in bushes and shrubs;
- Plantations (it decreases the natural regeneration);
- Clear-cuttings;
- Visually striking, linear and abrupt edges;
- A decrease in the woody debris abundance. (Gerhardt et al., 2013; Spake et al., 2020)

The deer impact mitigation is the highest in the Biodiversity SSP1-2.6 pathway and the lowest in the Wood Production and Profitability management scenarios (**Table 3-31**). It is quite high in the other pathways with a negative impact of climate change.

Table 3-31. The level of deer impact mitigation in the current state and in the twelve pathways of the municipal forest of Sivry-Rance with its justification.

Forest state	**Level**	**Justification**
Current state	High	Positive factors: Continuous cover forestry, small enrichment plantings, layered edges. Mixed effects: The human infrastructures are quite present, with a medium attendance and a moderate hunting. Negative factors: palatable forest species.
Wood Production SSP1-2.6	Very low	Positive factors: few human infrastructures and low forest attendance. Mixed effects: moderate hunting, ground vegetation highly present in the clear-cuttings but not in the softwood stands. Negative factors: plantations, clear-cuttings, visually striking, linear and abrupt edges, low presence of woody debris.
Wood Production SSP5-8.5	Very low	Negative impact of the climate change but they are more hardwood species that are less dense (compared to Wood Production SSP1-2.6)
Profitability SSP1-2.6	Very low	Positive factors: substantial presence of ground vegetation, natural regeneration, low forest cover, shrubs and bushes. Mixed effects: small clear-cuttings.

		Negative factors: palatable forest species, visually striking, linear and abrupt edges, low presence of woody debris, highly disturbing and inappropriate hunting.
Profitability SSP5-8.5	Very low	High impact of climate change because of the low forest cover.
Recreation SSP1-2.6	High	Positive factors: very moderate hunting, ground vegetation, woody debris, shrubs and bushes are quite present, no clear-cutting, layered edges. Mixed effects: palatable species but only a problem in the areas where timber is harvested. Negative factors: Quite dense forest cover, quite high disruption.
Recreation SSP5-8.5	Medium	The conditions are the same as in Recreation SSP1-2.6 with higher negative impacts of climate change.
Biodiversity SSP1-2.6	Very high	Positive factors: very moderate hunting, substantial presence of ground vegetation, woody debris, bushes and shrubs, natural regeneration, layered edges. Mixed effects: quite high forest cover but with small open areas, quite low disruption, palatable species but only a problem in the areas where timber is harvested.
Biodiversity SSP5-8.5	High	The conditions are the same as in Biodiversity SSP1-2.6 with higher negative impacts of climate change.
Multifunctional Forest SSP1-2.6	High	Positive factors: ground vegetation, woody debris, shrubs and bushes quite present, layered edges. Mixed effects: moderate hunting, quite dense forest cover with little clear-cuttings. Negative factors: palatable forest species, quite high disruption.
Multifunctional Forest SSP5-8.5	Medium	The conditions are the same as in Multifunctional Forest SSP1-2.6 with higher negative impacts of climate change.
Users' Forest SSP1-2.6	High	Positive factors: ground vegetation, woody debris, shrubs and bushes quite present, layered edges. Mixed effects: moderate hunting, quite dense forest cover with little clear-cuttings. Negative factors: palatable forest species, high disruption.
Users' Forest SSP5-8.5	Medium	The conditions are the same as in Users’ Forest SSP1-2.6 with higher negative impacts of climate change.

4.4.2.3 Suitability level of the forest with the preferences of the hunters

The hunters prefer a beautiful clean continuous hardwood forest or with natural open areas, with deadwood, with a high biodiversity, calm and quiet, easily accessible, with hunting infrastructures, where the different users respect each other and where they can hunt freely. Climate change has no real impact on the use of this ES because the hunters go hunting in the forest for their pleasure and not for the buffering effect of the forest on the climate. The impacts of climate change were thus only considered in terms of changes in the visual features of the forest.

The forest answers perfectly the preferences of the hunters in the Profitability, Multifunctional Forest and Users' Forest management scenarios (**Table 3-32**). The suitability level is low in the Wood Production SSP1-2.6 pathway and quite good in the others.

Table 3-32. Suitability level of the forest with the preferences of the hunters for the current state and in the twelve pathways of the municipal forest of Sivry-Rance, with its justification.

Forest state	**Level**	**Justification**
Current state	High	The actual forest is close to their ideal forest even if some improvements can be made concerning biodiversity, the respect between the users, the cleanliness, the accessibility, and the hunting infrastructures.
Wood Production SSP1-2.6	Low	Most of the forest is composed of softwood stands, with low biodiversity and more noise due to an increase in timber harvesting. The hunting infrastructures are kept. The recreation is lower which limits the conflicts with the hunters.
Wood Production SSP5-8.5	Medium	A significant part of the forest is composed of softwood stands, with quite low biodiversity and more noise due to an increase in timber harvesting. The hunting infrastructures are kept. The recreation is lower which limits the conflicts with the hunters.
Profitability SSP1-2.6 and SSP5-8.5	Very high	The forest is composed of hardwood stands, with a few deadwood and natural open areas. Medium biodiversity. The hunting infrastructures are developed, and the recreation is limited in favour of hunting.
Recreation and Biodiversity SSP1-2.6 and SSP5-8.5	Medium	The forest is their ideal forest but the calm and quiet decrease. The users respect each other as the hunting is adapted to the recreation activities. The hunting method is less preferred by the hunters.
Multifunctional Forest and Users' Forest SSP1-2.6 and SSP5-8.5	Very high	The forest is their ideal forest. The users quite respect each other. It is the same hunting method as in the current state.

4.4.2.4 The mean annual profit from hunting leases

The mean annual profit from hunting leases is influenced by the following factors:

- The habitat quality for game: the best it is, the highest is the profit;
- The level of satisfaction of the hunters: the highest it is, the highest is the profit;
- The hunting method.

The mean annual profit for hunting is unsurprisingly the highest in the Profitability SPP1-2.6 and the lowest in the Recreation management scenario (**Table 3-33**). It is low in the Wood Production and Biodiversity management scenarios. It is quite high in the other pathways.

Table 3-33. The level of mean annual profit for hunting in the current state and in the twelve pathways of the municipal forest of Sivry-Rance with its justification.

Forest state	Level	Justification
Current state	Medium	High habitat quality for game and high level of satisfaction of the hunters. Medium income from the actual hunting method.
Wood Production SSP1-2.6	Low	Medium habitat quality for game and low level of satisfaction of the hunters. Same hunting method as in the current state.
Wood Production SSP5-8.5	Low	Medium habitat quality for game and medium level of satisfaction of the hunters. Same hunting method as in the current state.
Profitability SSP1-2.6	Very high	High habitat quality for game and very high level of satisfaction of the hunters. Optimal hunting method for the hunters.
Profitability SSP5-8.5	High	Medium habitat quality for game and very high level of satisfaction of the hunters. Optimal hunting method for the hunters.
Recreation SSP1-2.6 and SSP5-8.5	Very low	High habitat quality for game and medium level of satisfaction of the hunters. Hunting method that strongly decreases the income.
Biodiversity SSP1-2.6 and SSP5-8.5	Low	Very high habitat quality for game and medium level of satisfaction of the hunters. Hunting method that strongly decreases the income.
Multifunctional Forest and Users' Forest SSP1-2.6	High	High habitat quality for game and very high level of satisfaction of the hunters. Same hunting method as in the current state.
Multifunctional Forest and Users' Forest SSP5-8.5	Medium	Medium habitat quality for game and very high level of satisfaction of the hunters. Same hunting method as in the current state.

4.4.2.5 Comparison of the indicators

For some management scenarios (i.e. Profitability, Recreation, Biodiversity), the trends of the ES Hunting is extremely variable depending on the indicator considered. For others (i.e. current state, Multifunctional Forest, Users’ Forest), they are quite good, for the four indicators, in supplying this ES while the Wood Production management scenario is not good. Generally, the SSP5-8.5 provides at a lowest level the ES Hunting.

4.4.3 Picking

Two indicators were assessed to value the ES Picking: (1) the fungal potential distribution, and (2) the suitability level of the forest with the preferences of the pickers. Both these indicators are qualitative. The first one was assessed from a literature review based on the relevant factors that influence the fungal potential distribution while the second one was derived from the surveys of the forest users.

4.4.3.1 Fungal potential distribution

From a literature review (Olah et al., 2020; Pilz et al., 2001; Tomao et al., 2020, 2017), the factors that influence the fungal potential distribution are given in **Figure 3-66**.

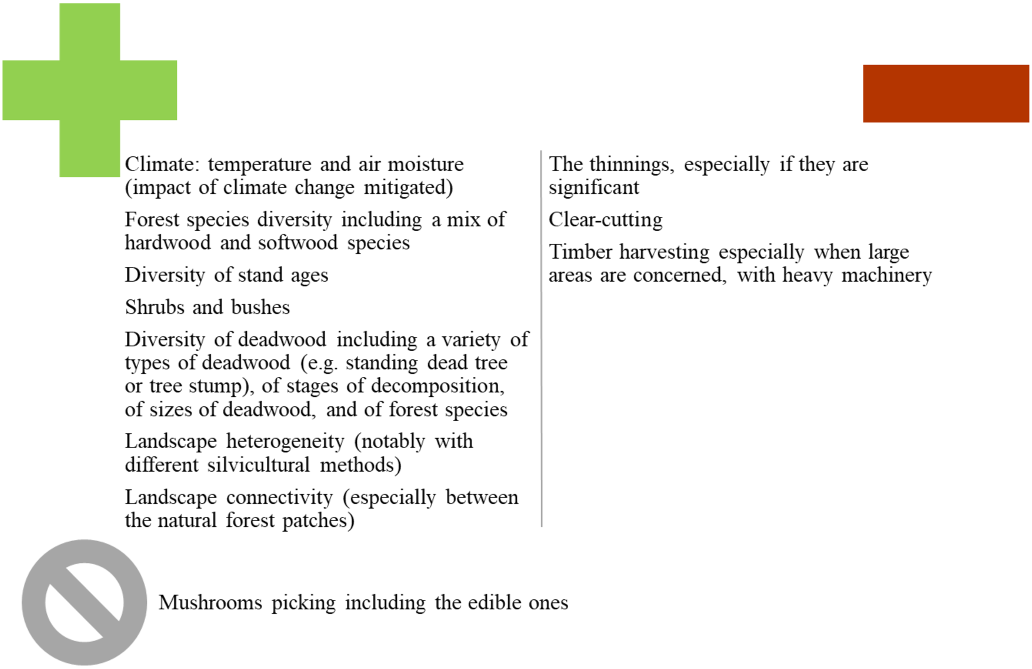

Figure 3-66. Factors that influence the fungal potential distribution (occurrence, abundance and diversity) and that can vary from pathway to pathway from the literature review (Olah et al., 2020; Pilz et al., 2001; Tomao et al., 2020, 2017). The factors that have a positive effect on the fungal potential distribution are listed next to the green cross, the ones that have a negative effect next to the red rectangle, and the ones that have no effect next to the grey obstructed circle.

The fungal distribution potential is unsurprisingly the highest in the Biodiversity management scenario and the lowest in the Wood Production and Profitability ones (**Table 3-34**). The others are quite good.

Table 3-34. The level of fungal distribution potential in the current state and in the twelve pathways of the municipal forest of Sivry-Rance with its justification.

Forest state	**Level**	**Justification**
Current state	Medium	Positive factors: forest species and age diversity, shrubs and bushes, permanent exploitation network. Mixed effects: quite low spatial heterogeneity, thinnings and small clear-cuttings, a small part of the forest is a wilderness area, continuous cover forestry. Negative factors: quite low landscape connectivity, little deadwood.
Wood Production SSP1-2.6	Very low	Positive factors: quite high spatial heterogeneity. Mixed effects: wilderness areas are quite present. Negative factors: low forest species diversity, very little shrubs and bushes and deadwood. Significant thinnings and clear-cuttings. Intensive timber harvesting. Quite low landscape heterogeneity and connectivity.
Wood Production SSP5-8.5	Low	Compared to Wood Production SSP-2.6, the forest species diversity is higher.
Profitability SSP1-2.6 and SSP5-8.5	Low	Positive factors: quite high forest species diversity, shrubs and bushes quite present. Mixed effects: wilderness areas are quite present. Negative factors: low forest cover with significant thinnings and small clear-cuttings, intensive timber harvesting. Little deadwood. Quite low landscape heterogeneity and connectivity.
Recreation SSP1-2.6 and SSP5-8.5	High	Positive factors: high forest species diversity, shrubs and bushes are present. Wilderness areas are present. Permanent exploitation network. Mixed effects: continuous cover forestry with small thinnings. Deadwood quite present. Quite high landscape connectivity and age diversity. Negative factors: low spatial heterogeneity.
Biodiversity SSP1-2.6 and SSP5-8.5	Very high	Positive factors: high forest species diversity, shrubs and bushes are present. Wilderness areas and deadwood are highly present. Permanent exploitation network and low timber harvesting. High landscape heterogeneity and connectivity. Small thinnings. Negative factors: quite low spatial heterogeneity.
Multifunctional Forest and Users' Forest SSP1-2.6 and SSP5-8.5	Medium	Positive factors: high forest species diversity, shrubs and bushes are quite present. Permanent exploitation network. Mixed effects: quite low spatial heterogeneity, thinnings and small clear-cuttings, Wilderness areas and deadwood are quite present. Continuous cover forestry. Negative factors: quite low landscape heterogeneity and connectivity.

4.4.3.2 Suitability level of the forest preferences of the pickers

The pickers prefer a beautiful clean continuous hardwood forest or with natural open areas, with deadwood, with a high biodiversity, calm and quiet, easily accessible, with maintained infrastructures and where the different users respect each other. Climate change has no real impact on the use of this ES because the pickers go in the forest for their pleasure and not for the buffering effect of the forest on the climate.

The forest answers perfectly the preferences of the pickers in the Recreation, Biodiversity and Users' Forest management scenarios while the suitability level is (very) low in the Wood Production and Profitability ones (**Table 3-35**).

Table 3-35. Suitability level of the forest with the preferences of the pickers for the current state and in the twelve pathways of the municipal forest of Sivry-Rance with its justification.

Forest state	Level	Justification
Current state	High	The actual forest is close to their ideal forest even if some improvements can be made concerning biodiversity, the respect between the users, the cleanliness, the accessibility, and the recreation infrastructures.
Wood Production SSP1-2.6	Very low	Most of the forest is composed of softwood stands, with low biodiversity and more noise due to an increase in timber harvesting. The recreation activities are restricted to the wilderness areas without a maintenance of the infrastructures.
Wood Production SSP5-8.5	Low	A significant part of the forest is composed of softwood stands, with quite low biodiversity and more noise (increase in timber harvesting). The recreation activities are restricted to the wilderness areas without a maintenance of the infrastructures.
Profitability SSP1-2.6 and SSP5-8.5	Very low	The forest is composed of hardwood stands, with little deadwood and few open natural areas. Medium biodiversity. The recreation activities are restricted to the municipal trails without a maintenance of the recreation infrastructures. Timber harvesting becomes a priority, harming the respect between the users. Low maintenance of the infrastructures.
Recreation SSP1-2.6 and SSP5-8.5	Very high	The forest is their ideal forest but the calm and quiet decrease. The users respect each other as the hunting is adapted to the recreation activities. The recreation activities are promoted with cleaned and maintained recreation infrastructures.
Biodiversity SSP1-2.6 and SSP5-8.5	Very high	The forest is their ideal forest. The users respect each other as the hunting is adapted to the recreation activities. The recreation activities are kept as it is now.
Multifunctional Forest SSP1-2.6 and SSP5-8.5	High	The forest is their ideal forest. The users quite respect each other. The biodiversity, deadwood, the accessibility and the maintenance are a little improved. The recreation activities are promoted with some new infrastructures.
Users' Forest SSP1-2.6 and SSP5-8.5	Very high	The forest is their ideal forest. The users respect each other. The biodiversity, deadwood, accessibility and maintenance are a little improved. The recreation activities are promoted (some new infrastructures).

4.4.3.3 Comparison of the indicators

The Wood Production and Profitability management scenarios do not provide well the ES Picking. On the contrary, the Recreation and Biodiversity ones are the best scenarios while the others are quite good. The two climate change scenarios gave the same results except in the Wood Production management scenario.

4.4.4 Fishing

The only indicator assessed for the ES Fishing is the suitability level of the forest with the preferences of the fishers.

The fishers prefer a beautiful clean continuous hardwood forest or with natural open areas, with deadwood, with a high biodiversity, calm and quiet, with maintained infrastructures and where the different users respect each other. The availability of the fishing ponds is also important. Fishing would be even more appreciated at the edge of the forest with an increase of the temperature.

The forest answers perfectly the preferences of the fishers in the Recreation, Multifunctional SSP5-8.5 and Users' Forest SSP5-8.5 pathways while the suitability level is (very) low in the Wood Production SSP1-2.6 and Biodiversity ones (**Table 3-36**). The others forest states are quite good.

Table 3-36. Suitability level of the forest with the preferences of the fishers for the current state and in the twelve pathways of the municipal forest of Sivry-Rance with its justification.

Forest state	Level	Justification
Current state	High	The actual forest is close to their ideal forest even if some improvements can be made concerning biodiversity, the respect between the users, the cleanliness, the accessibility, and the fishing infrastructures.
Wood Production SSP1-2.6	Low	Most of the forest is composed of softwood stands, with low biodiversity and more noise due to an increase in timber harvesting. The fishing activities and infrastructures are kept. The recreation is limited which decreases the potential conflicts with the fishers.
Wood Production SSP5-8.5	Medium	A significant part of the forest is composed of softwood stands, with quite low biodiversity and more noise due to an increase in timber harvesting. The fishing activities and infrastructures are kept. The recreation is limited which decreases the potential conflicts with the fishers. The buffering capacity of the forest in summer is more appreciated.
Profitability SSP1-2.6 and SSP5-8.5	Medium	The forest is composed of hardwood stands, with little deadwood and a few open natural areas. Medium biodiversity. The fishing infrastructures and activities are kept. The calm and quiet decrease with an increase in timber harvesting. The buffering capacity of the forest is limited because of the forest canopy opening.
Recreation SSP1-2.6 and SSP5-8.5	Very high	The forest is their ideal forest but the calm and quiet decrease. The users respect each other as the hunting is adapted to the recreation activities. The fishing activities and infrastructures are kept. The buffering capacity of the forest in summer is more appreciated in the SSP5-8.5 but because the level already reaches its maximum, it does not further increase.
Biodiversity SSP1-2.6 and SSP5-8.5	Very Low	The fishing activities and infrastructures disappear.
Multifunctional Forest SSP1-2.6	High	The forest is their ideal forest. The users quite respect each other. The biodiversity, deadwood, the accessibility and the maintenance are a little improved. The fishing activities and infrastructures are kept.
Multifunctional Forest SSP5-8.5	Very high	The buffering capacity of the forest in summer is more appreciated.
Users' Forest SSP1-2.6	High	The forest is their ideal forest. The users respect each other. The biodiversity, deadwood, the accessibility and the maintenance are a little improved. The fishing activities and infrastructures are kept.
Users' Forest SSP5-8.5	Very high	The buffering capacity of the forest in summer is more appreciated.

4.4.5 Water quality & quantity

Three indicators were assessed to value the ES Water quality and quantity: (1) the proportion of riparian woodland in the buffer width for water purification, (2) the water purification capacity score, and (3) the percentage of evapotranspiration. The three indicators are quantitative. The first one was derived from the review of Broadmeadow and Nisbet (2004) giving the minimal and ideal buffer width of the riparian woodland for water purification. The second one was calculated based on the EcoServ-GIS tool. The last one was estimated from the review of Bansept (2013) giving the minimal and maximal percentage of evapotranspiration of different land covers.

4.4.5.1 Proportion of riparian woodland in the buffer width for water purification

The Recreation, Biodiversity and Multifunctional Forest management scenarios have a full riparian woodland in the minimal and ideal buffer width while this proportion decreases in the other forest states, especially in the current state, and in the Wood Production and Profitability management scenarios (**Table 3-37**).

Table 3-37. Percentage of riparian woodland in the minimal and ideal buffer width for water purification in the current state and in the twelve pathways of the municipal forest of Sivry-Rance.

Forest state		**Proportion of riparian woodland in the buffer width** (%)	
		15m (minimal)	**100m** (ideal)
Current state		83	54
Wood Production	SSP1-2.6	94	48
	SSP5-8.5	94	48
Profitability	SSP1-2.6	95	62
	SSP5-8.5	95	63
Recreation	SSP1-2.6	100	100
	SSP5-8.5	100	100
Biodiversity	SSP1-2.6	100	100
	SSP5-8.5	100	100
Multifunctional Forest	SSP1-2.6	100	100
	SSP5-8.5	100	100
Users' Forest	SSP1-2.6	98	89
	SSP5-8.5	98	89

4.4.5.2 Water purification capacity score

The water purification score theoretically ranges from 0 to 60 and the higher it is, the higher is the capacity of the forest to purify water. The differences between the pathways are low (**Table 3-38**) because this score is influenced by the land cover which is defined in broad categories only differentiating the hardwood stands from the softwood ones and the mixed hardwood and softwood ones. This score is lower in the

Wood Production scenario especially in SSP1-2.6 because of the softwood stands that have a lower water purification capacity.

Table 3-38. Water purification capacity score for the current state and the twelve pathways of the municipal forest of Sivry-Rance.

Forest state		**Water purification capacity score**
Current state		53
Wood Production	SSP1-2.6	47
	SSP5-8.5	51
Profitability	SSP1-2.6	54
	SSP5-8.5	54
Recreation	SSP1-2.6	54
	SSP5-8.5	54
Biodiversity	SSP1-2.6	54
	SSP5-8.5	54
Multifunctional Forest	SSP1-2.6	54
	SSP5-8.5	54
Users' Forest	SSP1-2.6	53
	SSP5-8.5	53

4.4.5.3 Percentage of evapotranspiration

The differences in the minimal percentage of evapotranspiration between the pathways are low (**Table 3-39**) because this percentage is influenced by the land cover which is defined in broad categories only differentiating the hardwood stands from the softwood ones and the mixed hardwood and softwood ones. This minimal percentage of evapotranspiration is lower in the Wood Production scenario especially in SSP1-2.6 and, to a lesser extent, in the Users’ Forest one because of the softwood(-hardwood) stands that have a lower water purification capacity. The maximal percentage of evapotranspiration varies even less because this percentage is the same in all the types of forest, only the areas covered by the gaps can change this percentage.

Table 3-39. Minimal and maximal percentage of evapotranspiration of the current state and in the twelve pathways of the municipal forest of Sivry-Rance.

Forest state		**Percentage of evapotranspiration** (%)	
		Minimal	**Maximal**
Current state		47.8	71.7
Wood Production	SSP1-2.6	43.8	71.8
	SSP5-8.5	46.2	71.8
Profitability	SSP1-2.6	47.8	71.8
	SSP5-8.5	47.8	71.8
Recreation	SSP1-2.6	47.8	71.7
	SSP5-8.5	47.8	71.8
Biodiversity	SSP1-2.6	47.8	71.8
	SSP5-8.5	47.8	71.8
Multifunctional Forest	SSP1-2.6	47.8	71.7
	SSP5-8.5	47.8	71.7
Users' Forest	SSP1-2.6	47.5	71.7
	SSP5-8.5	47.5	71.7

4.4.5.4 Comparison of the indicators

The Recreation, Biodiversity, Multifunctional Forest and Users' Forest management scenarios provide a good quantity of quality water compared to the Wood Production one. The results are more mitigated for the current state and the Profitability management scenario depending on the indicator considered. The proportion of riparian woodland in the buffer width is a more accurate indicator because it differentiates more finely the different forest stands than the water purification capacity score and the percentage of evapotranspiration.

4.4.6 Control of soil erosion & flooding

Two groups of indicators were assessed to value the ES Control of soil erosion and flooding: (1) the proportion of riparian woodland in the buffer width for soil erosion and flooding control, and (2) the percentage of precipitation interception and infiltration. Both are quantitative. The first one is based on the review of Broadmeadow and Nisbet (2004) and the second one on the review of Bansept (2013).

4.4.6.1 Proportion of riparian woodland in the buffer width for soil erosion and flooding control

The Recreation, Biodiversity and Multifunctional Forest management scenarios have a full riparian woodland in the minimal and ideal buffer width while this proportion decreases in the other scenarios, especially in the current state, Wood Production and Profitability ones (**Table 3-40**).

Table 3-40. Percentage of riparian woodland in the minimal and ideal buffer width for soil erosion and flooding control in the current state and in the twelve pathways of the municipal forest of Sivry-Rance.

Forest state		**Proportion of riparian woodland in the buffer width** (%)	
		25m (minimal)	**100m** (ideal)
Current state		100	54
Wood Production	SSP1-2.6	86	48
	SSP5-8.5	86	48
Profitability	SSP1-2.6	87	62
	SSP5-8.5	87	63
Recreation	SSP1-2.6	100	100
	SSP5-8.5	100	100
Biodiversity	SSP1-2.6	100	100
	SSP5-8.5	100	100
Multifunctional Forest	SSP1-2.6	100	100
	SSP5-8.5	100	100
Users' Forest	SSP1-2.6	96	89
	SSP5-8.5	96	89

4.4.6.2 Percentage of precipitation interception and infiltration

The differences in the percentages of precipitation interception and infiltration between the pathways are quite low (**Table 3-41**) because these percentages are influenced by the land cover which is defined in broad categories only differentiating the hardwood stands from the softwood ones and the mixed hardwood and softwood ones. The percentages of precipitation interception are higher in the Wood Production scenario especially the SSP1-2.6 and, to a lesser extent, in the Users' Forest one because of the softwood(-hardwood) stands that have a higher capacity to intercept precipitations. It is the contrary for the percentages of precipitation infiltration.

Table 3-41. Minimal and maximal percentage of precipitation interception and infiltration of the current state and in the twelve pathways of the municipal forest of Sivry-Rance.

Forest state		Percentage of precipitation (%)			
		Interception		Infiltration	
		Minimal	Maximal	Minimal	Maximal
Current state		14.9	44.8	32.0	55.7
Wood Production	SSP1-2.6	18.3	51.6	22.0	45.9
	SSP5-8.5	16.3	35.0	27.9	51.8
Profitability	SSP1-2.6	15.0	44.9	32.1	56.0
	SSP5-8.5	15.0	44.9	32.1	56.0
Recreation	SSP1-2.6	14.9	44.8	32.0	55.9
	SSP5-8.5	14.9	44.8	32.0	55.9
Biodiversity	SSP1-2.6	15.0	44.9	32.1	56.0
	SSP5-8.5	15.0	44.9	32.1	56.0
Multifunctional Forest	SSP1-2.6	14.9	44.8	32.0	55.9
	SSP5-8.5	14.9	44.8	32.0	55.9
Users' Forest	SSP1-2.6	15.2	45.3	31.3	55.2
	SSP5-8.5	15.2	45.3	31.3	55.2

4.4.6.3 Comparison of the indicators

No pathway outperforms the others, it depends on the indicator considered.

4.4.7 Fauna and flora

Four indicators were assessed to value the ES Fauna and flora: (1) the proportion of riparian woodland in the buffer width for water habitat quality, (2) the habitat biological quality, (3) the forest undesirable species regulation capacity, and (4) the mean pollinator abundance. The first and the last indicators are quantitative while the two others are qualitative. The first one was based on the review of Broadmeadow and Nisbet (2004). The second and the third ones were estimated from a literature review based on the relevant factors that influence the habitat biological quality and the forest undesirable species regulation capacity. The last one was calculated from the InVEST Crop pollination model.

4.4.7.1 Proportion of riparian woodland in the buffer width for water habitat quality

The Recreation, Biodiversity and Multifunctional Forest management scenarios have a full riparian woodland in the minimal and ideal buffer width while this proportion decreases in the other forest states, especially in the current state, Wood Production and Profitability management scenarios (**Table 3-42**).

Table 3-42. Percentage of riparian woodland in the minimal and ideal buffer width for water habitat quality in the current state and in the twelve pathways of the municipal forest of Sivry-Rance.

Forest state		**Proportion of riparian woodland in the buffer width** (%)	
		15m (minimal)	**70m** (ideal)
Current state		93	60
Wood Production	SSP1-2.6	94	58
	SSP5-8.5	94	58
Profitability	SSP1-2.6	95	68
	SSP5-8.5	95	68
Recreation	SSP1-2.6	100	100
	SSP5-8.5	100	100
Biodiversity	SSP1-2.6	100	100
	SSP5-8.5	100	100
Multifunctional Forest	SSP1-2.6	100	100
	SSP5-8.5	100	100
Users' Forest	SSP1-2.6	98	90
	SSP5-8.5	98	90

4.4.7.2 Habitat biological quality

From the literature review, the following factors, that can vary from pathway to pathway, influence the habitat biological quality:

- The threats on the habitat (i.e. climate change, recreation activities, forest management and invasive species) including their impact, their distance from the habitat and the sensitivity of the habitat;
- The legal protection of the habitat (e.g. Natura 2000, protected areas, remarkable tree);
- The rarity of the habitat and its patrimonial interest;
- The abundance of priority species (threatened, protected and rare species);
- The naturalness of the habitat;
- Conservation measures. (Colson and Baix, 2021; Dorioz et al., 2018; Lejeune et al., 2007; Natural Capital Project, n.d.)

The habitat biological quality is unsurprisingly the highest in the Biodiversity SSP1-2.6 pathway and the lowest in the Wood Production and Profitability management scenarios (**Table 3-43**). It is quite good for the other forest states.

Table 3-43. Level of the habitat biological quality in the current state and in the twelve pathways of the municipal forest of Sivry-Rance with its justification.

Forest state	Level	Justification
Current state	High	**Threats**: low threat from the recreation activities that are well regulated, despite some abuses (e.g. some walkers leave the trails). Some impacts of climate change (e.g. droughts). Low impact of invasive species (only some small infested areas). Continous cover forestry in general positive for biodiversity. **Legal protection**: 95% of the forest is in Natura 2000, Life project BNIP, 1 ZHIB. **Patrimonial interest**: 7 habitats of Community interest. **Abundance of priority species**: 8 protected or of interest plant species, 21 protected or of interest animal species including 6 of Community interest, 3 Community interest plant species and 3 remarkable species. **Habitat naturalness**: old-growth forest, well preserved wet tall-herbs and meadows, quality water points. **Conservation measures**: forest ponds digging and maintenance, wetland restoration, deadwood (0.5 tree/ha) and habitat tree (0.2 tree/ha).
Wood Production SSP1-2.6	Low	**Threats**: low threat from the recreation activities. Quite low impact of climate change. The impact of invasive species increases with the plantation of exotic forest species. Intensive forest management on 70% of the forest. **Legal protection**: Natura 2000 status disappears in 70% of the forest. **Patrimonial interest**: in the wilderness areas (30% of the forest), the habitats of Community interest are well preserved but disappear in the other areas. **Abundance of priority species**: their abundance decreases in the productive forest and is preserved or even increases in the wilderness areas. **Habitat naturalness**: the naturalness is improved in the wilderness areas but decreases in the other areas. **Conservation measures**: they disappear.
Wood Production SSP5-8.5	Very low	It is almost the same conditions as the Wood Production SSP1-2.6 except that more than a half of the softwood stands become regular hardwood stands and that the impacts of climate change increase.
Profitability SSP1-2.6	Low	**Threats**: low threat from the recreation activities except the intensive hunting. Quite low impact of climate change. The impact of invasive species increases with the opening of the forest cover. Intensive forest management on 82% of the forest area. **Legal protection**: 17% in wilderness area et 1% in nature conservation area.

		Patrimonial interest: 44% of the forest becomes a hornbeam forest which is less positive for biodiversity and the forest cover decreases. **Abundance of priority species**: in general, their abundance decreases in the productive forest and is maintained or even increased in the rest of the forest. **Habitat naturalness**: it is improved in the wilderness and nature conservation areas but decreases in the productive forest. **Conservation measures**: they are maintained in the nature conservation area.
Profitability SSP5-8.5	Very low	It is the same as the Profitability SSP1-2.6 except that the impacts of climate change increase.
Recreation SSP1-2.6	High	**Threats**: the recreation activities are well regulated, but their impacts could increase as recreation is promoted. Quite low impact of invasive species (some exotic species are planted). Quite low impact of climate change. Continuous cover forestry. **Legal protection**: 95% of the forest in Natura 2000, 2 ZHIB, 5% in wilderness area et 1% in nature conservation. **Patrimonial interest**: the actual habitats are preserved except in the Priority Recreation area (30% of the forest area) where some exotic species are planted. **Abundance of priority species**: Their abundance can decrease a little in the Priority Recreation area. It is maintained or even increased in the wilderness and nature conservation areas. **Habitat naturalness**: it is improved in the wilderness and nature conservation areas, it slightly decreases in the Priority Recreation area and it is maintained in the rest of the forest. **Conservation measures**: deadwood increases and the nature conservation measures are maintained.
Recreation SSP5-8.5	Medium	It is the same as the Recreation SSP1-2.6 except that the impacts of climate change increase.
Biodiversity SSP1-2.6	Very high	**Threats**: the recreation activities are well regulated and even restricted to some forest areas. The invasive species are managed in the nature conservation areas. Quite low impact of climate change. Continuous cover forestry with additional measures to promote biodiversity. **Legal protection**: 95% of the forest in Natura 2000, 68% in wilderness area et 1% in nature conservation area. **Patrimonial interest**: it increases in the entire forest. **Abundance of priority species**: it increases in the entire forest. **Habitat naturalness**: it increases in the entire forest. **Nature conservation measures**: they are applied in the entire forest except in the wilderness area.

Biodiversity SSP5-8.5	High	It is the same as the Biodiversity SSP1-2.6 except that the impacts of climate change increase.
Multifunctional Forest SSP1-2.6	High	**Threats**: the recreation activities are well regulated even if they are a little promoted. The invasive species are managed. Quite low impact of climate change. Continuous cover forestry. **Legal protection**: 95% of the forest in Natura 2000, 5% in wilderness area and 1% in nature conservation area, 2 ZHIB. **Patrimonial interest**: it increases in wilderness area (5%) and in nature conservation area (1%) and is maintained in the rest of the forest. **Abundance of priority species**: it is maintained in almost all the forest and slightly increases in the wilderness and nature conservation areas. **Habitat naturalness**: old-growth forest, it increases in the wilderness and nature conservation areas. **Conservation measures**: increase in deadwood (2 trees/ha) and habitat tree (0.5 tree/ha), the nature conservation measures are maintained and even increase in the nature conservation area.
Multifunctional Forest SSP5-8.5	Medium	It is the same as the Multifunctional Forest SSP1-2.6 except that the impacts of climate change increase.
Users' Forest SSP1-2.6	High	**Threats**: the recreation activities are well regulated even if they are a little promoted. The invasive species are managed. Quite low impact of climate change. Continuous cover forestry but a little more intensive in the production area (12% of the forest). **Legal protection**: 82% of the forest in Natura 2000, 17% in wilderness area and 2% in nature conservation area, 2 ZHIB. **Patrimonial interest**: it increases in wilderness and nature conservation areas, it slightly decreases in the production area and is maintained in the rest of the forest. **Abundance of priority species**: it slightly increases in the wilderness and nature conservation areas, it slightly decreases in the production area and is maintained in the rest of the forest. **Habitat naturalness**: old-growth forest, it increases in the wilderness and nature conservation areas and slightly decreases in the production area. **Conservation measures**: increase in deadwood (2 trees/ha) and habitat tree (0.5 tree/ha), the nature conservation measures are maintained and even increase in the nature conservation area.
Users' Forest SSP5-8.5	Medium	It is the same as the Users’ Forest SSP1-2.6 except that the impacts of climate change increase.

4.4.7.3 Forest undesirable species regulation capacity

From the literature review (Brockerhoff et al., 2017; Jactel et al., 2021; Marini et al., 2022; Shao et al., 2022; Staab and Schuldt, 2020), the factors that influence the capacity of the forest to regulate undesirable species are given in **Figure 3-67**.

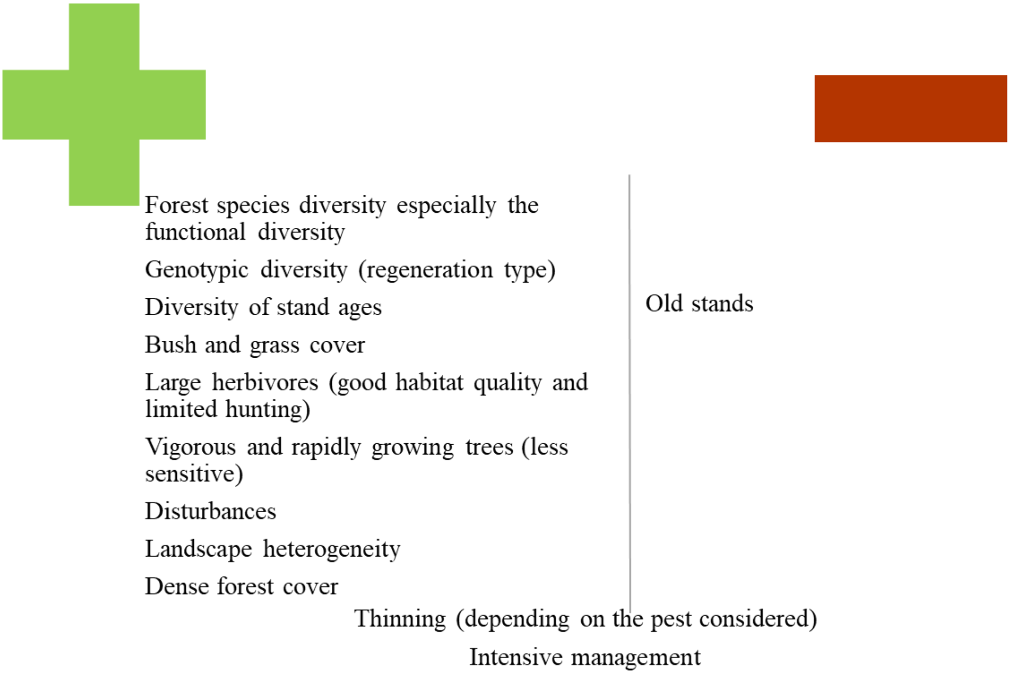

Figure 3-67. Factors that influence the capacity of the forest to regulate undesirable species and that can vary from pathway to pathway, from the literature review (Brockerhoff et al., 2017; Jactel et al., 2021; Marini et al., 2022; Shao et al., 2022; Staab and Schuldt, 2020). The factors that have a positive effect on the capacity of the forest to regulate undesirable species are listed next to the green cross, the ones that have a negative effect next to the red rectangle, and the ones that have a mitigated effect are central.

The current state provides the best forest undesirable species regulation capacity (**Table 3-44**). This capacity is (very) low in the Wood Production and Profitability management scenarios and is quite high in the others.

Table 3-44. Level of the forest undesirable species regulation capacity in the current state and in the twelve pathways of the municipal forest of Sivry-Rance with its justification.

Forest state	Level	Justification
Current state	Very high	Positive factors: quite high forest species and genotypic diversity, shrubs and bushes quite abundance, thinnings and small clear-cuttings that improve structural complexity and simulate natural disturbances, quite high age diversity, continuous cover forestry, high game habitat quality. Negative factors: small clear-cutting opening the canopy.
Wood Production SSP1-2.6	Very low	Positive factors: landscape heterogeneity with stands of different species and ages. Mixed effects: medium game habitat quality with a moderate hunting. Negative factors: low forest species and genotypic diversity, low presence of shrubs and bushes, even aged stands, strong thinnings and important clear-cuttings.
Wood Production SSP5-8.5	Low	The only difference with Wood Production SSP1-2.6 is a better landscape heterogeneity with a highest forest species diversity.
Profitability SSP1-2.6	Low	Positive factors: quite high forest species diversity, bushes and shrubs quite abundant, high game habitat quality. Negative factors: low cover with strong thinnings and small clear-cuttings, quite low landscape heterogeneity. Intensive hunting, almost no mixed hardwood-softwood stands.
Profitability SSP5-8.5	Very low	The landscape heterogeneity (lower forest species diversity) and the game habitat quality are lower than SSP1-2.6.
Recreation SSP1-2.6 and SSP5-8.5	High	Positive factors: high forest species and genotypic diversity, shrubs and bushes abundant, continuous cover forestry, small thinnings that simulate natural disturbances without clear-cutting, quite high structural complexity, high age diversity, high game habitat quality with moderate hunting. Negative factors: quite low landscape heterogeneity, almost no mixed hardwood-softwood stands.
Biodiversity SSP1-2.6 and SSP5-8.5	High	Positive factors: high forest species and genotypic diversity, shrubs and bushes abundant, quite dense forest cover, small thinnings that simulate natural disturbances without clear-cutting, quite high structural complexity, high age diversity, very high game habitat quality with moderate hunting. Negative factors: old stands in the wilderness areas, almost no mixed hardwood-softwood stands.
Multifunctional Forest SSP1-2.6	Medium	Positive factors: quite high forest species and genotypic diversity, shrubs and bushes quite abundant, thinnings with small clear-cuttings that simulate natural disturbances, quite high age diversity, high game habitat quality with moderate hunting, continuous cover forestry.

		Negative factors: small clear-cuttings opening the canopy, quite low landscape heterogeneity.
Multifunctional Forest SSP5-8.5	Medium	Even if the game habitat quality is a bit lower than Multifunctional Forest SSP1-2.6, it is not enough to lower the level.
Users' Forest SSP1-2.6	High	Positive factors: high forest species diversity (mix of hardwood and softwood), shrubs and bushes quite abundant, thinnings with small clear-cutting that simulate natural disturbances, quite high age diversity, continuous cover forestry, high game habitat quality with moderate hunting. Negative factors: small clear-cuttings opening the canopy, quite low landscape heterogeneity.
Users' Forest SSP5-8.5	High	Even if the game habitat quality is a bit lower than Users' Forest SSP1-2.6, it is not enough to lower the level.

4.4.7.4 Mean pollinator abundance

First, we present the mean pollinator abundance of the current state and in each pathway. Then, we discuss the spatial distribution of pollinator abundance with some examples of the maps of pollinator abundance.

Globally, the mean pollinator abundance varies little between the different pathways except for the Wood Production and Profitability management scenarios which have lower values (**Table 3-45**).

Table 3-45. Mean pollinator abundance obtained from the Crop pollinator InVEST model for the current state and the twelve pathways of the municipal forest of Sivry-Rance.

Forest state		**Mean pollinator abundance**
Current state		0.22
Wood Production	SSP1-2.6	0.16
	SSP5-8.5	0.17
Profitability	SSP1-2.6	0.17
	SSP5-8.5	0.17
Recreation	SSP1-2.6	0.22
	SSP5-8.5	0.22
Biodiversity	SSP1-2.6	0.21
	SSP5-8.5	0.22
Multifunctional Forest	SSP1-2.6	0.22
	SSP5-8.5	0.22
Users' Forest	SSP1-2.6	0.21
	SSP5-8.5	0.21

But if we look at the spatial distribution of pollinator abundance, it can greatly vary between the forest states. For instance, in the current state, the pollinators are abundant in the main forest stands (e.g. coppice with standards, old oak hornbeam forest) and almost absent in the young stands (**Figure 3-68**) while they are highly abundant in the edges, moderately abundant in the main forest stands (i.e. uneven aged mixed hardwood forest) and almost absent in the even aged softwood stands in Recreation SSP1-2.6 (**Figure 3-69**). For other management and climate change scenarios where the distribution of the forest stands are quite similar (i.e. Recreation, Biodiversity, Multifunctional Forest and to a lesser extent, Users' Forest), the spatial distribution of pollinator abundance varies little (**Figure 3-70**).

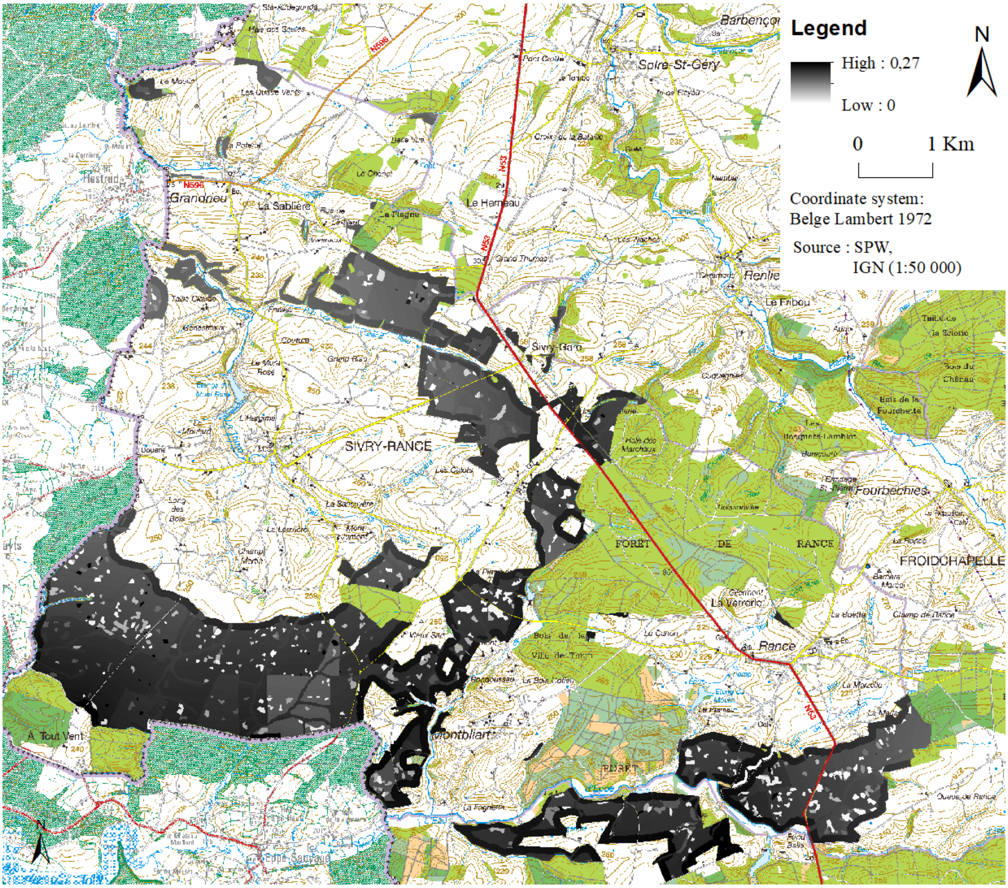

Figure 3-68. Pollinator abundance obtained from the InVEST Crop pollination model in the current state of the municipal forest of Sivry-Rance.

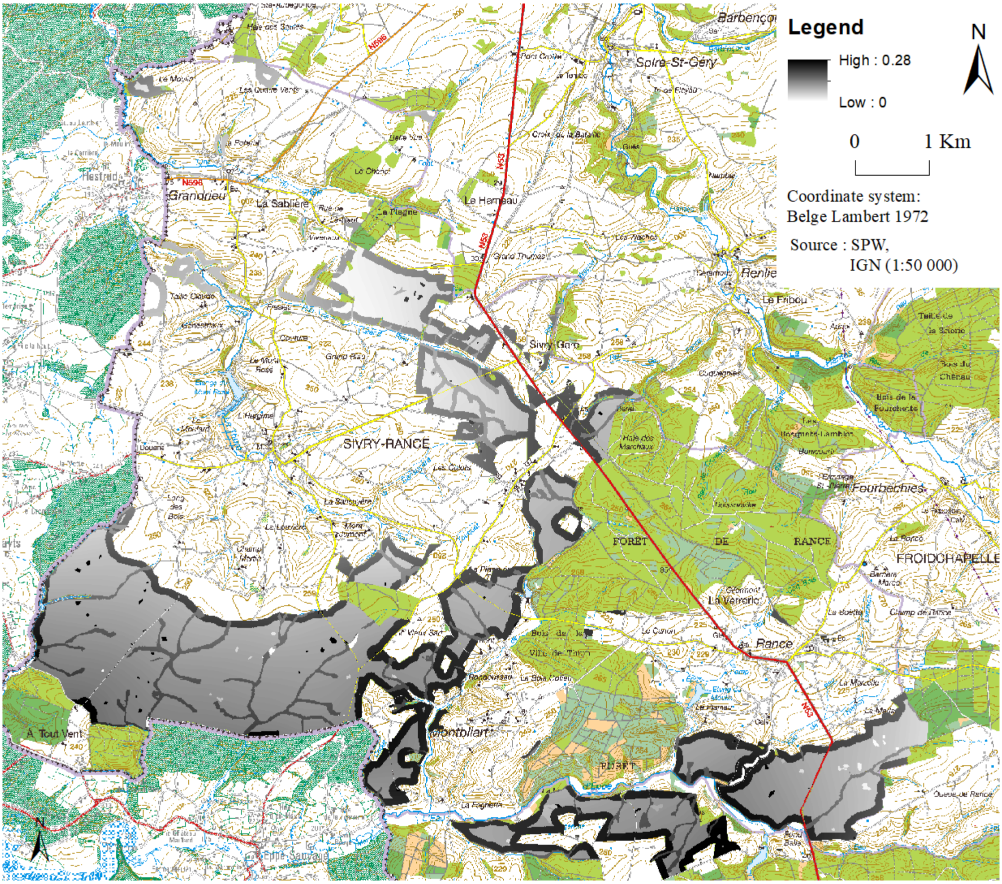

Figure 3-69. Pollinator abundance obtained from the InVEST Crop pollination model in Recreation SSP1-2.6 of the municipal forest of Sivry-Rance.

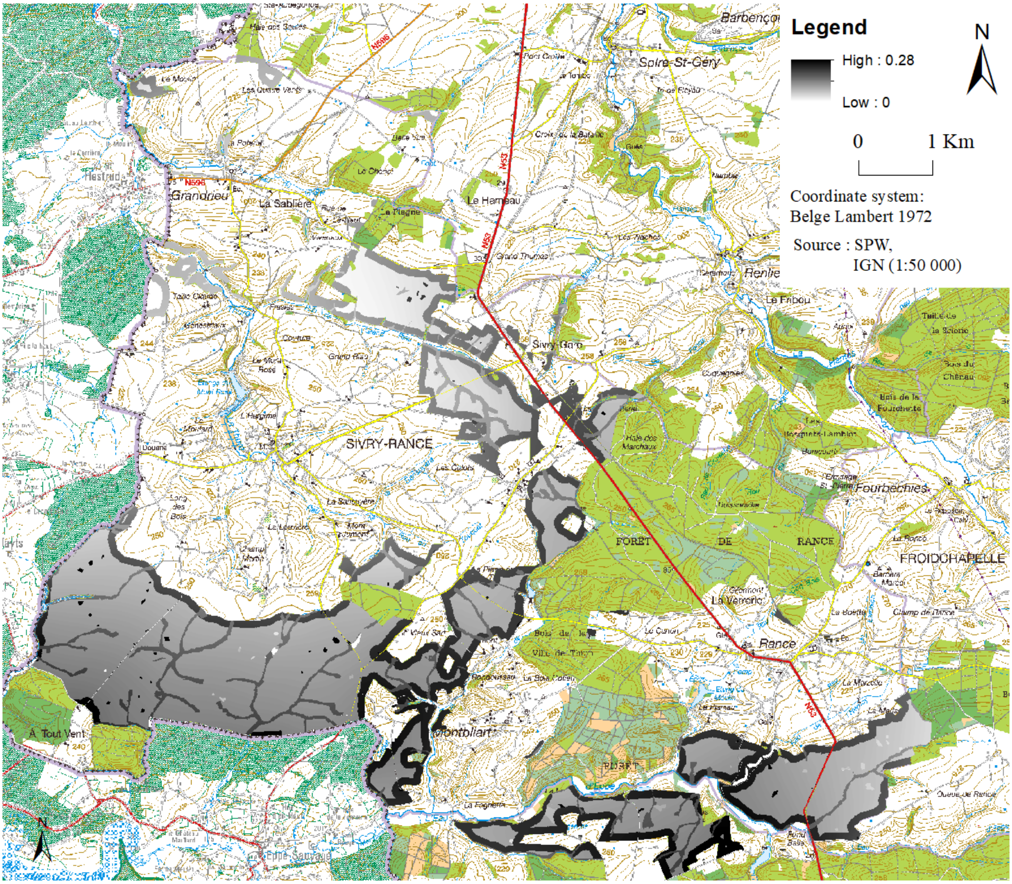

Figure 3-70. Pollinator abundance obtained from the InVEST Crop pollination model in Multifunctional forest SSP5-8.5 of the municipal forest of Sivry-Rance.

4.4.7.5 Comparison of the indicators

The Recreation, Biodiversity, Multifunctional Forest and Users' Forest management scenarios have a good capacity to support the fauna and flora while the Wood Production one and, to a lesser extent the Profitability one, have a low capacity. The trends are more mitigated for the current state depending on the indicator considered. The two climate change scenarios differ only a little or not at all, depending on the management scenario.

4.4.8 Climate regulation and air purification

Three indicators were assessed to value the ES Climate regulation and air purification: (1) the fine particles capture, (2) the forest temperature buffering capacity, and (3) the total carbon stock. The first and the last indicators are quantitative while the other one is qualitative. The first indicator was calculated from NVE. The second one was derived from a literature review based on the relevant factors that influence the forest temperature buffering capacity. The last one was estimated using the methodology and data from Latte et al. (2013).

4.4.8.1 Fine particles capture

Wood Production SSP1-2.6 and, to a lesser extent Wood Production SSP5-8.5, capture the most the fine particles thanks to their softwood stands (**Table 3-46**). The other forest states capture fewer fine particles especially the Recreation management scenario and the Multifunctional SSP5-8.5 pathway that have more gaps and only a very small proportion of softwood stands.

Table 3-46. Fine particles capture by the municipal forest of Sivry-Rance in the current state and the twelve pathways calculated from NVE.

Forest state		**Fine particles capture** (kg/year)
Current state		38,338
Wood Production	SSP1-2.6	48,716
	SSP5-8.5	42,628
Profitability	SSP1-2.6	38,370
	SSP5-8.5	38,367
Recreation	SSP1-2.6	38,325
	SSP5-8.5	38,306
Biodiversity	SSP1-2.6	38,347
	SSP5-8.5	38,341
Multifunctional Forest	SSP1-2.6	38,331
	SSP5-8.5	38,308
Users' Forest	SSP1-2.6	39,032
	SSP5-8.5	39,027

4.4.8.2 Forest temperature buffering capacity

From the literature review, the following factors, that can vary from pathway to pathway, influence the capacity of the forest to buffer temperatures:

- Air temperature: the more it increases, the better is the capacity of the forest to buffer temperatures. However, climate change can reduce forest cover and lessens or even reverses this effect;
- Deciduous species: they have a lower capacity to buffer temperatures in winter because they lose their leaves;
- Canopy cover: the denser it is, the best it is;
- Forest density: the denser it is, the best it is;
- Forest structure: the buffering capacity increases with the height of the stand and its structural complexity. (De Frenne et al., 2021, 2019; Frey et al., 2016; Haesen et al., 2021; Zellweger et al., 2019)

The forest temperature buffering capacity is the highest in the Biodiversity management scenario while it is the lowest in Wood Production SSP5-8.5 and the Profitability management scenario (**Table 3-47**). It is quite good in the other forest states.

Table 3-47. Level of the forest temperature buffering capacity in the current state and in the twelve pathways of the municipal forest of Sivry-Rance with its justification.

Forest state	Level	Justification
Current state	Medium	Mainly an uneven aged deciduous forest with a medium forest cover and density and with big trees.
Wood Production SSP1-2.6	Medium	Mix of softwood species, with a dense cover except in the plantations and clear-cuttings, and hardwood species with a medium forest cover and density. Mainly even aged stands with different trees heights depending on the developmental stage.
Wood Production SSP5-8.5	Low	Climate change will probably negatively affect the plantations and decrease the forest cover and density.
Profitability SSP1-2.6	Low	Hardwood forest with a low density and cover, medium tree height and quite low structural complexity.
Profitability SSP5-8.5	Very low	Climate change will probably negatively affect the over-exploited forest and decrease the forest cover and density.
Recreation SSP1-2.6	High	Mostly uneven aged hardwood forest quite dense with big trees.
Recreation SSP5-8.5	High	The buffering capacity could increase with climate change in the sites where water is available but decreases elsewhere.
Biodiversity SSP1-2.6	Very high	Mostly uneven aged hardwood dense forest with very big trees.
Biodiversity SSP5-8.5	Very high	The buffering capacity could increase with climate change in the sites where water is available but decreases elsewhere.
Multifunctional Forest SSP1-2.6	Medium	Mostly uneven aged hardwood forest with a medium density and cover with big trees.
Multifunctional SSP5-8.5	Medium	The buffering capacity could increase with climate change in the sites where water is available but decreases elsewhere.
Users' Forest SSP1-2.6	High	Mostly uneven aged hardwood forest with some softwood species quite dense with big trees.
Users' Forest SSP5-8.5	High	The buffering capacity could increase with climate change in the sites where water is available but decreases elsewhere.

4.4.8.3 Total carbon stock

The total carbon stock is the highest in the Biodiversity management scenario because this scenario has the highest growing stock and amount of dead trees (**Table 3-48**). Then, the second-best scenario is Wood Production that has also a high growing stock. The other forest states have lower carbon stocks especially the Profitability management scenario, the current state and Multifunctional SSP5-8.5 where the growing stocks are low. The differences between the two climate change scenarios are quite low, even if the SSP1-2.6 has generally a better carbon stock than the SPP5-8.5.

Table 3-48. Carbon stock in the four pools (i.e. living biomass, dead trees, litter and soil biomass) for the current state and the twelve pathways of the municipal forest of Sivry-Rance, based on the methodology and data of Latte et al. (2013).

Forest state		**Carbon stock** (Mg C/year)				
		Living biomass	**Dead trees**	**Litter**	**Soil biomass**	**Total**
Current state		63	1	3	81	148
Wood Production	SSP1-2.6	101	3			188
	SSP5-8.5	90	3			177
Profitability	SSP1-2.6	65	2			151
	SSP5-8.5	65	2			152
Recreation	SSP1-2.6	70	3			157
	SSP5-8.5	70	3			157
Biodiversity	SSP1-2.6	139	8			232
	SSP5-8.5	131	9			224
Multifunctional Forest	SSP1-2.6	70	2			156
	SSP5-8.5	65	3			152
Users' Forest	SSP1-2.6	80	3			168
	SSP5-8.5	70	3			158

4.4.8.4 Comparison of the indicators

No pathway outperforms the others, it depends on the indicator considered. Nevertheless, the current state, the Profitability and the Multifunctional Forest management scenarios provide at a lower level this ES. Little or even no difference is observed between the two climate change scenarios.

4.4.9 Natural surroundings

Only one indicator was assessed for the ES Natural surroundings: the percentage of visible valued forest. From the surveys of the forest users, the preferences of the inhabitants of the municipal forest of Sivry-Rance are the following: hardwood forest with young or old trees. The Wood Production management scenario has the lowest proportion of visible valued forest (**Table 3-49**) and to a lesser extent, the Users' Forest one. For the others, there is no difference because this indicator only varies with the type of forest stands that are similarly preferred in these scenarios.

Table 3-49. Proportion of visible valued forest in the current state and the twelve pathways of the municipal forest of Sivry-Rance.

Forest state		**Proportion of visible valued forest** (%)
Current state		3.2
Wood Production	SSP1-2.6	1.0
	SSP5-8.5	1.0
Profitability	SSP1-2.6	3.2
	SSP5-8.5	3.2
Recreation	SSP1-2.6	3.2
	SSP5-8.5	3.2
Biodiversity	SSP1-2.6	3.2
	SSP5-8.5	3.2
Multifunctional Forest	SSP1-2.6	3.2
	SSP5-8.5	3.2
Users' Forest	SSP1-2.6	3.0
	SSP5-8.5	3.0

4.4.10 Recreation

Two indicators were assessed to value the ES Recreation: (1) the suitability level of the forest with the preferences of the recreation users, and (2) the recreation supply. These two indicators are qualitative. The first one was derived from the survey of the recreation users and the second one from a literature review to determine the relevant factors influencing the recreation supply.

4.4.10.1 Suitability level of the forest with the preferences of the recreation users

The recreation users prefer a beautiful clean continuous uneven aged hardwood forest or with natural open areas, with deadwood, with a high biodiversity, calm and quiet, easily accessible, with maintained recreation infrastructures and where the different users respect each other. They prefer narrow trails, with a standard information system, available local products, and well promoted elements of cultural heritage. The cooling effect of the forest in summer is likely to become more important with an increase of temperatures due to climate change.

The best pathways are Recreation, Biodiversity SSP5-8.5, Multifunctional forest SSP5-8.5 and Users’ Forest SSP5-8.5 (**Table 3-50**). Wood Production and Profitability have low values and the others are quite good.

Table 3-50. Suitability level of the forest with the preferences of the recreation users for the current state and the twelve pathways of the municipal forest of Sivry-Rance with its justification.

Forest state	Level	Justification
Current state	Medium	The actual forest is close to their ideal forest even if some improvements can be made concerning biodiversity, the respect between the users, the cleanliness, the accessibility, the recreation infrastructures, the promotion of the elements of the cultural heritage and the availability of local products.
Wood Production SSP1-2.6	Very low	Recreation is restricted to the wilderness areas without a maintenance of the recreation infrastructures, without a promotion of the elements of the cultural heritage and with no information system. Most of the forest is composed of softwood even aged stands, with low biodiversity and more noise due to an increase in timber harvesting.
Wood Production SSP5-8.5	Low	The proportion of hardwood stands increases, and the cooling effect of the forest becomes more important.
Profitability SSP1-2.6 and SSP5-8.5	Very low	The recreation activities are limited to the municipal trails, without a maintenance of the recreation infrastructures, without a promotion of the elements of the cultural heritage, and with a low information system and availability of local products. Hunting and wood harvesting become a priority increasing the conflicts with the recreation users. The forest is composed of hardwood stands, with a few deadwood and open natural areas. Medium biodiversity. The cooling effect of the forest is limited by the canopy opening.
Recreation SSP1-2.6 and SSP5-8.5	Very high	Recreation is promoted with clean and maintained infrastructures, well promoted elements of the cultural heritage, an information system adapted to the different users and the availability of local products is improved. The forest is their ideal forest. The calm and quiet decrease in the busiest areas. The users respect each other as the hunting is adapted to the recreation activities. The cooling effect of the forest is more appreciated in the SSP5-8.5 but the level is already at its highest.
Biodiversity SSP1-2.6	High	The forest is their ideal forest. The users respect each other as the hunting is adapted to the recreation activities. The recreation activities are kept as it is now.
Biodiversity SSP5-8.5	Very high	The cooling effect of the forest is more appreciated.
Multifunctional Forest and Users' Forest SSP1-2.6	High	The forest is their ideal forest. The users quite respect each other. The biodiversity, deadwood, the accessibility and the maintenance are a little improved. The recreation activities are promoted with some new infrastructures.
Multifunctional Forest and Users' Forest SSP5-8.5	Very high	The cooling effect of the forest is more appreciated.

4.4.10.2 Recreation supply

The following factors, that vary from pathway to pathway, influence the recreation supply:

- The legal constraints (e.g. nature conservation);
- The trails characterized by their density, condition, accessibility and marking;
- Other tourism infrastructures such as benches, panels, parking lots characterized by their density, condition and accessibility;
- The features of the landscape that positively influence the recreation supply:
  - ✓ Water bodies;
  - ✓ Natural open areas;
  - ✓ Particular features (e.g. rock, view);
  - ✓ Forest species diversity.
- The calm and quiet;
- The black spots (e.g. waste);
- Visual disturbance: their visibility varies with the cover density.

The recreation supply is the highest in the Recreation, Multifunctional Forest and Users' Forest management scenarios and the lowest in the Wood Production and Profitability ones (**Table 3-51**). It is high in the other forest states.

Table 3-51. The level of the recreation supply in the current state and in the twelve pathways of the municipal forest of Sivry-Rance with its justification.

Forest state	Level	Justification
Current state	High	Quite high density of trails, most of them are marked and in a good condition. Several reception areas with benches or picnic tables and a bivouac zone, small parking lots and explanatory panels. Numerous streams, several ponds and natural open areas. Several views. Quite high forest species diversity. Beautiful landscape in general. Calm and quiet. Some waste. Little visual disturbance even if the cover is more open in some areas.
Wood Production SSP1-2.6	Very low	Recreation is restricted to the wilderness areas without a maintenance of the recreation infrastructures, few ponds and natural open areas, quite low forest species diversity. The density of the cover is high except in the plantations and clear-cuttings. The forest is less calm because of the intensive harvesting.
Wood Production SSP5-8.5	Low	Compared to Wood Production SSP1-2.6, the forest species diversity increases.
Profitability SSP1-2.6 and SSP5-8.5	Very low	The recreation activities are limited to the municipal trails, without a maintenance of the recreation infrastructures, few ponds and natural open areas, the diversity of forest species decreases a bit as well as the cover density. The calm decreases with the intensive harvesting and hunting as well as the cleanliness.
Recreation SSP1-2.6 and SSP5-8.5	Very high	Recreation is promoted with clean and maintained infrastructures and an increase of trails density. Numerous streams, several ponds and natural open areas. Several views. High forest species diversity. Beautiful landscape in general. The calm and quiet decrease in the busiest areas.
Biodiversity SSP1-2.6 and SSP5-8.5	High	The recreation activities are kept as it is now. Numerous streams, several ponds and natural open areas. Several views. High forest species diversity. Beautiful landscape in general. Calm and quiet (hunting is adapted to the recreation activities).
Multifunctional Forest SSP1-2.6 and SSP5-8.5	Very high	The recreation activities are promoted with some new infrastructures. They are well maintained. Numerous streams, several ponds and natural open areas. Several views. Quite high forest species diversity. Beautiful landscape in general. Quite calm and quiet.
Users' Forest SSP1-2.6 and SSP5-8.5	Very high	The recreation activities are promoted with some new infrastructures. They are well maintained. Numerous streams, several ponds and natural open areas. Several views. High forest species diversity. Beautiful landscape in general. Quite calm and quiet.

4.4.10.3 Comparison of the two indicators

Recreation is the highest in the Recreation, Multifunctional Forest SSP5-8.5 and Users' Forest SSP5-8.5 pathways and the lowest in the Wood Production SSP-2.6 and Profitability management scenario. It is quite good in the current state and in the other pathways. In some management scenarios, there is a little difference between the two climate change scenarios.

4.4.11 Nature observation, learning and inspiration

Two indicators were assessed to value the ES Nature observation and inspiration: (1) the suitability level of the forest with the preferences of the nature watchers or in search of inspiration, and (2) the supply of nature watching, learning and inspiration areas. Both are qualitative. The first one was derived from the surveys of the forest users and the second one from a literature review to determine the relevant factors influencing the supply of nature watching, learning and inspiration areas.

4.4.11.1 Suitability level of the forest with the preferences of the nature watchers or in search of inspiration

The preferences of the nature watchers or in search of inspiration are the same as the recreation users. The levels of the current state and the twelve pathways are the same as the ones presented in **Table 3-50**.

4.4.11.2 Supply of nature watching, learning and inspiration areas

The supply of nature watching, learning and inspiration areas is influenced by the same factors as the ones developed for the recreation supply (see Chapter 3 4.4.10.2 Recreation supply) and two additional factors: (1) the tourism infrastructures allowing nature watching (e.g. watchtower) and learning (e.g. explanatory panels), and (2) the historic and cultural elements. Only these two additional factors are developed in **Table 3-52** (see **Table 3-51** for the other factors).

The levels are the same (**Table 3-52**) as the ones obtained for the recreation supply because an improvement in the recreation supply goes hand in hand with an improvement of the supply of nature watching, learning and inspiration areas.

Table 3-52. The level of the supply of nature watching, learning and inspiration areas in the current state and the twelve pathways of the municipal forest of Sivry-Rance with its justification. Only the two additional factors: (1) tourism infrastructures dedicated to nature watching or learning, and (2) historic and cultural elements are discussed in the justification. The other factors have already been detailed in **Table 3-51**.

Forest state	Level	Justification
Current state	High	Several explanatory panels. Several historic and cultural elements (remarkable tree, cross, chapel, memorial).
Wood Production SSP1-2.6	Very low	No maintenance of the existing nature watching and learning infrastructures. Low accessibility of the historic and cultural elements.
Wood Production SSP5-8.5	Low	
Profitability SSP1-2.6 and SSP5-8.5	Very low	No maintenance of the existing nature watching and learning infrastructures. Low accessibility of the historic and cultural elements.
Recreation SSP1-2.6 and SSP5-8.5	Very high	Maintenance of the existing nature watching and learning infrastructures and development of new ones. Historic and cultural elements well promoted.
Biodiversity SSP1-2.6 and SSP5-8.5	High	Maintenance of the existing nature watching and learning infrastructures. Maintenance of the historic and cultural elements.
Multifunctional Forest and Users' Forest SSP1-2.6 and SSP5-8.5	Very high	Maintenance of the existing nature watching and learning infrastructures and development of new ones. Historic and cultural elements well promoted.

4.4.11.3 Comparison of the two indicators

Because the levels of the two indicators of nature observation, learning and inspiration are the same as the two indicators of recreation, the same conclusions can be drawn (see Chapter 3 4.4.10.3 Comparison of the two indicators).

4.4.12 Natural heritage

The ES Natural heritage is assessed by the supply of nature heritage areas. This supply is influenced almost by the same factors as the ones developed for the recreation supply (see Chapter 3 4.4.10.2 Recreation supply). For the features of the landscape, we only considered the typical landscapes and emblematic species. One additional factor was also added: the historic and cultural elements. Only the factor typical landscape and emblematic species is developed in **Table 3-53** (see **Table 3-52** for the historic and cultural elements and **Table 3-51** for the other factors not considering the factor Features of the landscape).

The supply of nature heritage areas is the highest in the Recreation, Biodiversity, Multifunctional Forest and Users' Forest management scenarios while it is the lowest in the Wood Production and Profitability ones. (**Table 3-53**).

Table 3-53. The level of the supply of nature heritage areas in the current state and the twelve pathways of the municipal forest of Sivry-Rance with its justification. Only the factor typical landscapes and emblematic species is discussed in the justification. The other factors have been already detailed in **Table 3-51** and **Table 3-52**.

Forest state	Level	Justification
Current state	High	Typical landscape with some emblematic species.
Wood Production SSP1-2.6 and SSP5-8.5	Very low	No typical landscape.
Profitability SSP1-2.6 and SSP5-8.5	Low	Less typical landscape.
Recreation SSP1-2.6 and SSP5-8.5	Very high	Typical landscape with some emblematic species.
Biodiversity SSP1-2.6 and SSP5-8.5	Very high	Typical landscape. The emblematic species are promoted.
Multifunctional Forest SSP1-2.6 and SSP5-8.5	Very high	Typical landscape with some emblematic species.
Users' Forest SSP1-2.6 and SSP5-8.5	Very high	Quite typical landscape with some emblematic species.

4.4.13 Interactions between the ES

As we have seen in the assessment of some ES (i.e. Wood, Hunting, Control of soil erosion and flooding, and Climate regulation and air purification), different indicators can show contrasting trends on the pathways.

No pathway provides all the ES at a good level even if the Recreation, Biodiversity, Multifunctional Forest and the Users' Forest management scenarios provide a greater diversity of ES than the Wood Production and Profitability ones. In the Users' Forest SSP1-2.6 pathway, all the ES (and their respective indicators) are at least provided at a medium level.

In a same management scenario, the two climate change scenarios have similar trends. This is particularly true in the Profitability, Recreation and Biodiversity management scenarios where almost no difference is observed. In the Wood Production management scenarios, most of the indicators show a difference between the two climate change scenarios but these differences are low (the value of an indicator generally varies from one level to the previous or next one).

5. Step 5: Assess resilience

Two forms of resilience were assessed: (1) the resilience of ES, and (2) social resilience. These assessments are discussed in the next two sections.

5.1 Resilience of the ES

As a reminder, the resilience of ES is analysed by looking at the diversity of ES that answer the needs of the stakeholders. For the four groups of social preferences, two results from the PROMETHEE software were used: (1) the ranking of the twelve pathways and the current state, and (2) the contribution of each ES to the ranking of the pathways. For the ranking, we analysed the graph from the PROMETHEE software based on the partial ranking (PROMETHEE I) (i.e. comparison of the outgoing and incoming flows, an alternative is better than another when its outgoing flow is higher than the outgoing flow of the other one and when its incoming flow is lower than the outgoing flow of the other one) and the complete ranking (PROMETHEE II) (i.e. ranking based on the net flow, the higher it is the better is the alternative). On this graph, an alternative is better than another when the alternative has both a higher partial and complete ranking than the others. When the alternative is higher in its rank than another for only one of these two rankings, we cannot distinguish which one is the best. The 'good' scenarios are the ones having a $\Phi>0$ while 'bad' scenarios have a $\Phi<0$. The higher is the Φ of a scenario, the better it is. For the contribution of each ES to the ranking, we analysed a histogram that represents the positive or negative contribution of each ES to the performance of the pathway.

5.1.1 Group who finds all the ES important

The best management scenarios are the Users' Forest and Multifunctional Forest ones (**Figure 3-71**). Next come the Recreation management scenario and the current state. The Biodiversity management scenario has a lower ranking than the Recreation one but it is not distinguishable from the current state. The Profitability and Wood Production management scenarios are the bad scenarios, especially Wood Production SSP1-2.6.

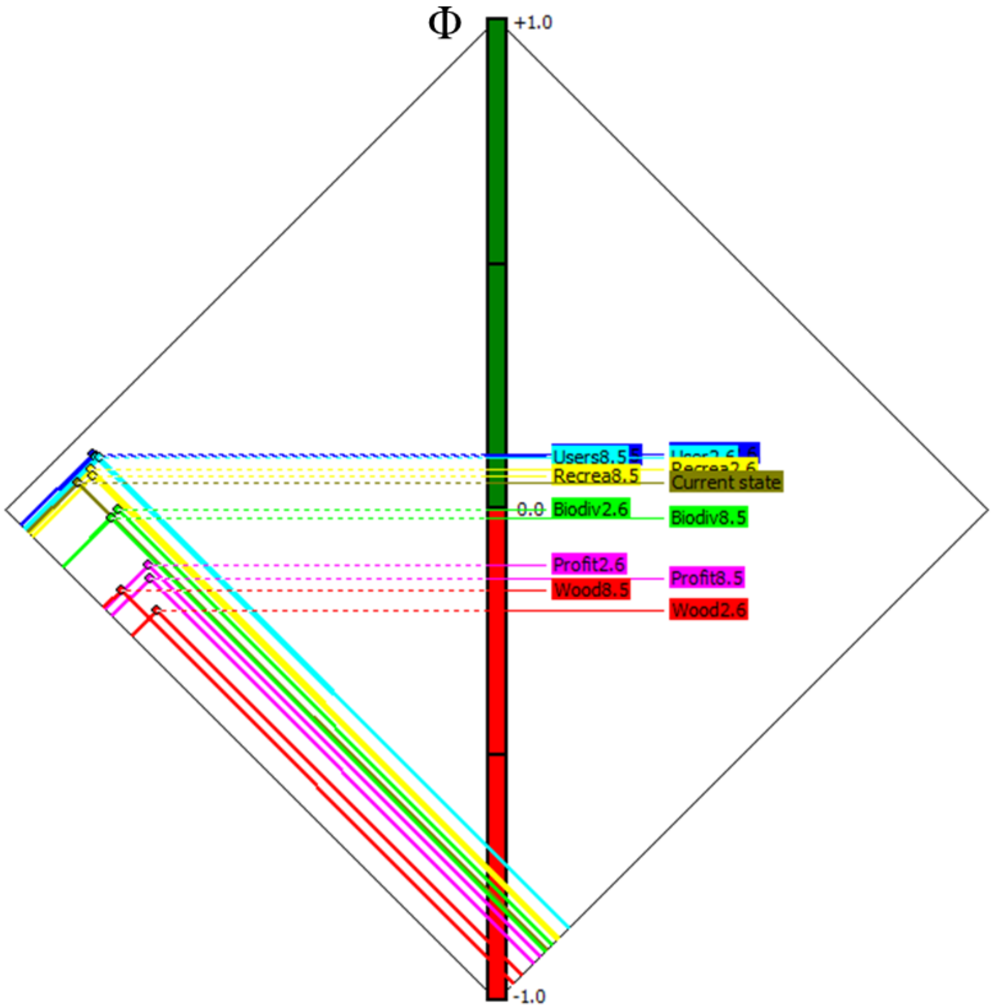

Figure 3-71. Ranking of the current state and the twelve pathways of the municipal forest of Sivry-Rance from the PROMETHEE software (partial ranking PROMETHEE I and complete ranking PROMETHEE II) for the group who finds all the ES important.

In the Multifunctional Forest, Users' Forest and Recreation management scenarios and in the current state, almost all the ES answer the needs of the group who finds all the ES important except the ES Picking and/or Hunting (**Figure 3-72**). In the Biodiversity management scenario, the ES Wood, Picking and Fishing do not answer the needs of this group while in the Profitability and Wood Production ones, the ES Wood, Fishing, Recreation, Nature watching, learning and inspiration and Natural Heritage do not answer the needs of this group.

Figure 3-72. Disaggregated representation of the complete ranking (PROMETHEE II) of each ES for the group who finds all the ES important.

5.1.2 Group who prefers the provisioning ES

Surprisingly, the Biodiversity management scenario is the best one for the group who prefers the provisioning ES (**Figure 3-73**). Indeed, this group has not only a preference for this category of ES but also for the ES Fauna and flora which has high values for all its indicators in this management scenario. Next come the Multifunctional Forest and Users' Forest. The Recreation and Wood production management scenarios and the current state cannot be distinguished from one another while the Profitability SSP5-8.5 pathway is the worst.

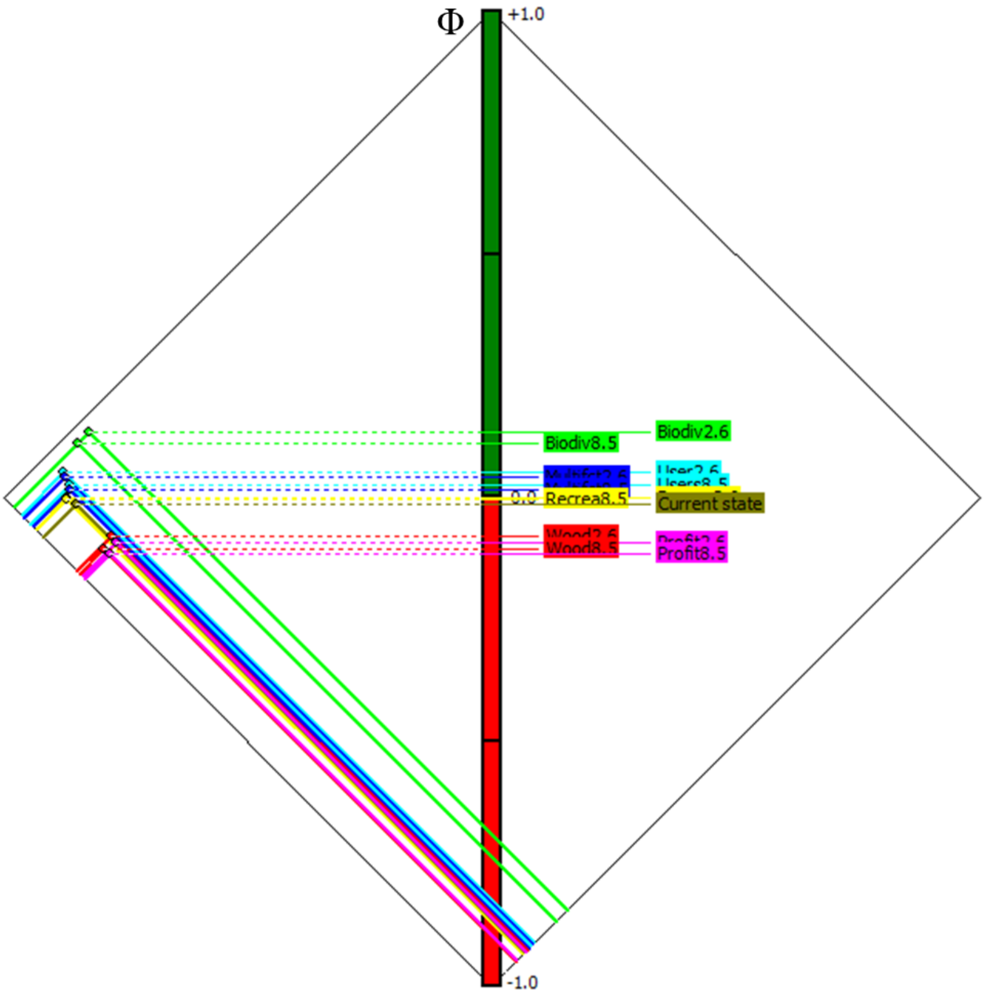

Figure 3-73. Ranking of the current state and the twelve pathways of the municipal forest of Sivry-Rance from the PROMETHEE software (partial ranking PROMETHEE I and complete ranking PROMETHEE II) for the group who prefers the provisioning ES.

In the Biodiversity, Multifunctional Forest and Users' Forest management scenarios, almost all the ES answer the needs of the group who prefers the provisioning ES except the ES Picking, Wood, Fishing and/or Climate regulation and air purification (**Figure 3-74**). The SSP5-8.5 climate change scenario of the Multifunctional Forest and Users' Forest management scenarios is not as good as the SSP1-2.6. In the Recreation management scenario, the ES Hunting, Picking, Fishing and Climate regulation and air purification do not answer the needs of this group while in the Profitability and Wood Production ones, five to six ES among the following ES: Wood, Hunting, Fauna and flora, Climate regulation and air purification, Recreation, Nature watching, learning and inspiration and/or Natural Heritage do not answer their needs.

Figure 3-74. Disaggregated representation of the complete ranking (PROMETHEE II) of each ES for the group who prefers the provisioning ES.

5.1.3 Group who prefers the regulating ES

The best pathway is Recreation SSP5-8.5, followed closely by Recreation SSP1-2.6 and the Multifunctional Forest (**Figure 3-75**). Next come the Biodiversity and the Users' Forest management scenarios that cannot be distinguished from each other. The 'bad' scenarios are the current state, the Profitability and especially the Wood production management scenarios. We would have expected that the Biodiversity management scenario would be the most preferred one. However, this group also finds the ES Fishing and the cultural ES important, and they are provided at higher levels in the Recreation management scenario than the biodiversity one.

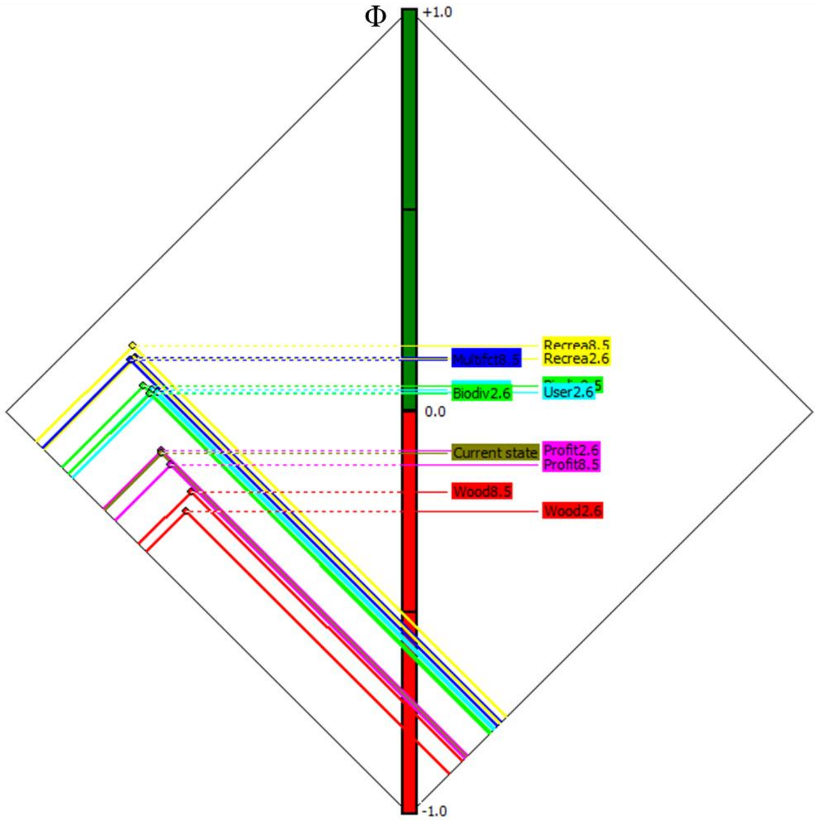

Figure 3-75. Ranking of the current state and the twelve pathways of the municipal forest of Sivry-Rance from the PROMETHEE software (partial ranking PROMETHEE I and complete ranking PROMETHEE II) for the group who prefers the regulating ES.

In the Recreation, Multifunctional Forest and Users' Forest management scenarios and Biodiversity SSP5-8.5, almost all the ES answer the needs of the group who prefers the regulating ES except the ES Wood, Hunting, Picking and/or Water quality and quantity (**Figure 3-76**). The current state, the Profitability and Wood Production management scenarios do not answer the needs of this group for four to eight of the following ES: Wood, Hunting, Fishing, Water quality and quantity, Fauna and flora, Climate regulation and air purification, Recreation, Nature watching, learning and inspiration and/or Natural Heritage.

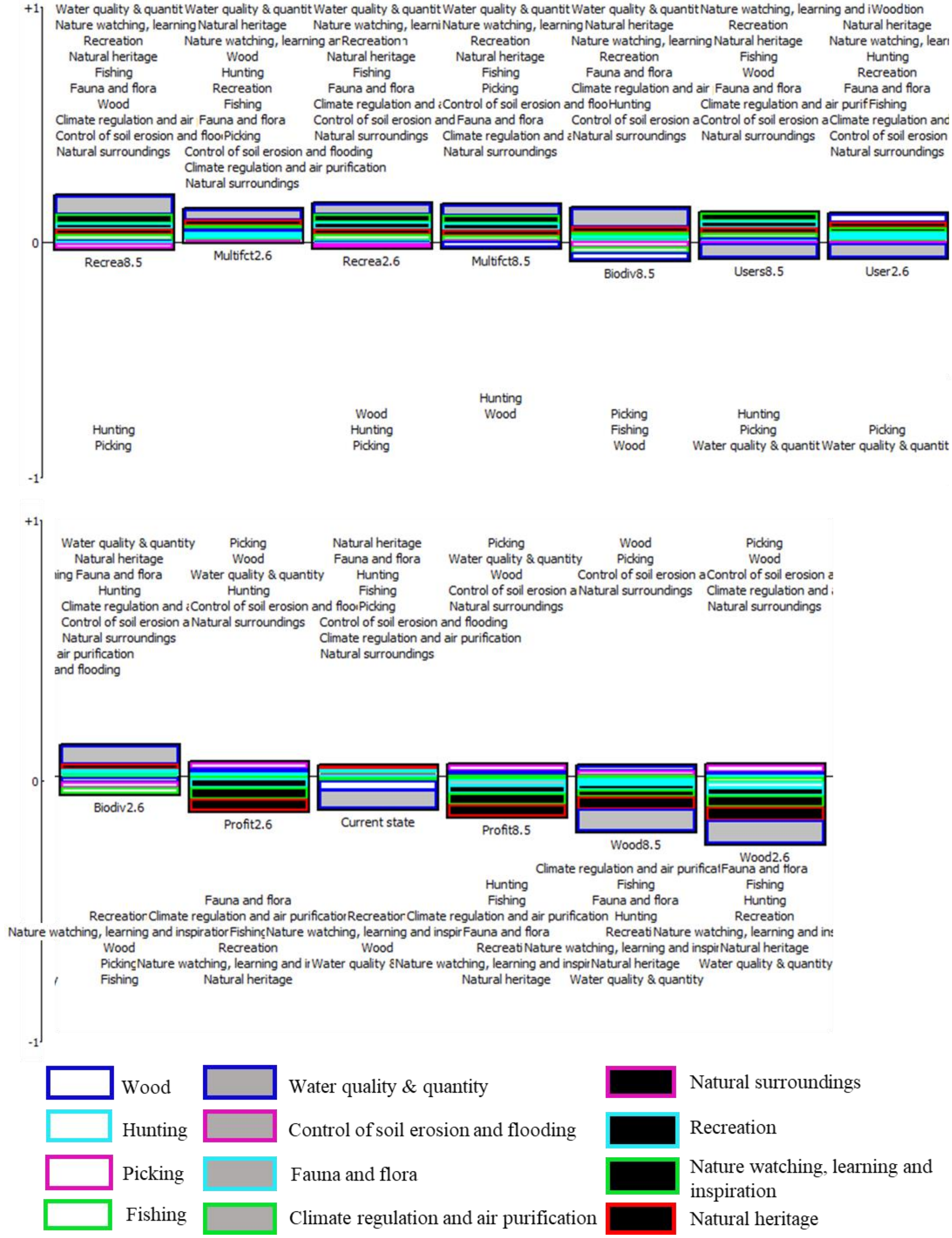

Figure 3-76. Disaggregated representation of the complete ranking (PROMETHEE II) of each ES for the group who prefers the regulating ES.

5.1.4 Group who prefers the cultural ES

The different pathways cannot be distinguished from each other (**Figure 3-77**) because no pathway really outperforms the others. Surprisingly, the Recreation management scenario did not outperform the others because this group had very high expectations regarding the regulating and cultural ES that are not met by any pathway.

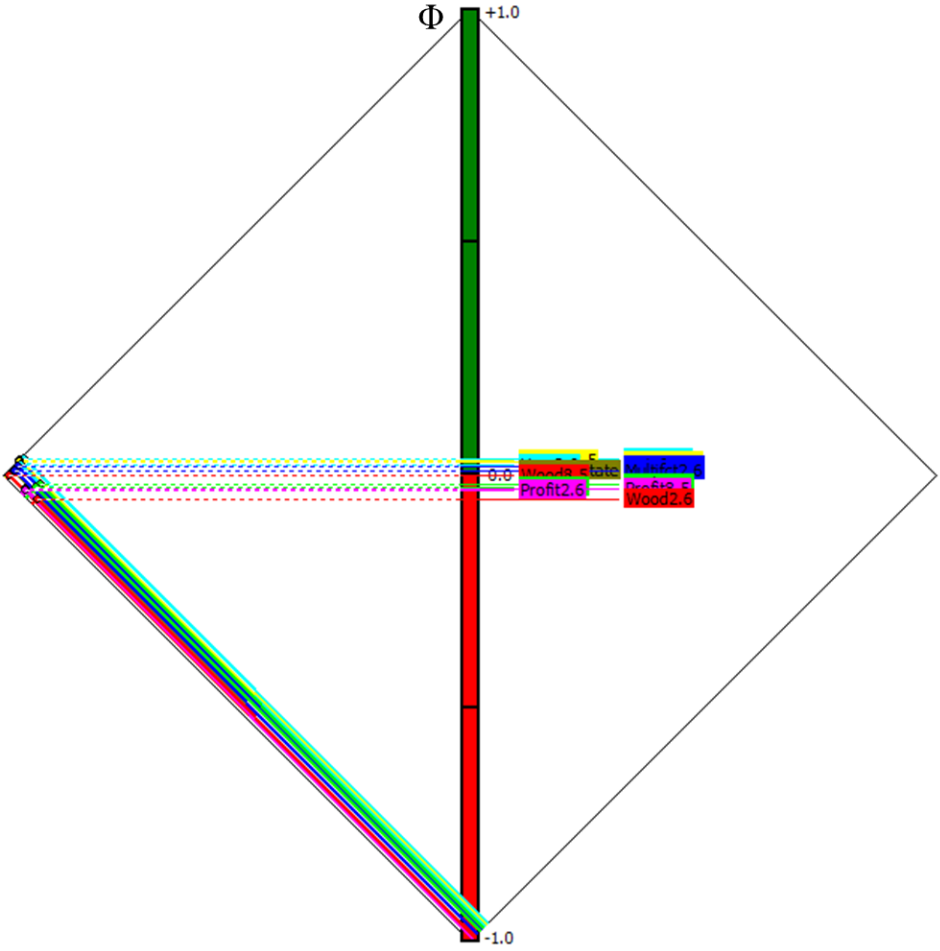

Figure 3-77. Ranking of the current state and the twelve pathways of the municipal forest of Sivry-Rance from the PROMETHEE software (partial ranking PROMETHEE I and complete ranking PROMETHEE II) for the group who prefers the cultural ES.

Indeed, all the pathways provide a diversity of ES but their positive contribution to the ranking are low (**Figure 3-78**). This group was demanding regarding the acceptable and satisfactory levels that the ES should have especially for the cultural ES and some regulating ES, ensuring that no pathway is able to sufficiently answer their needs.

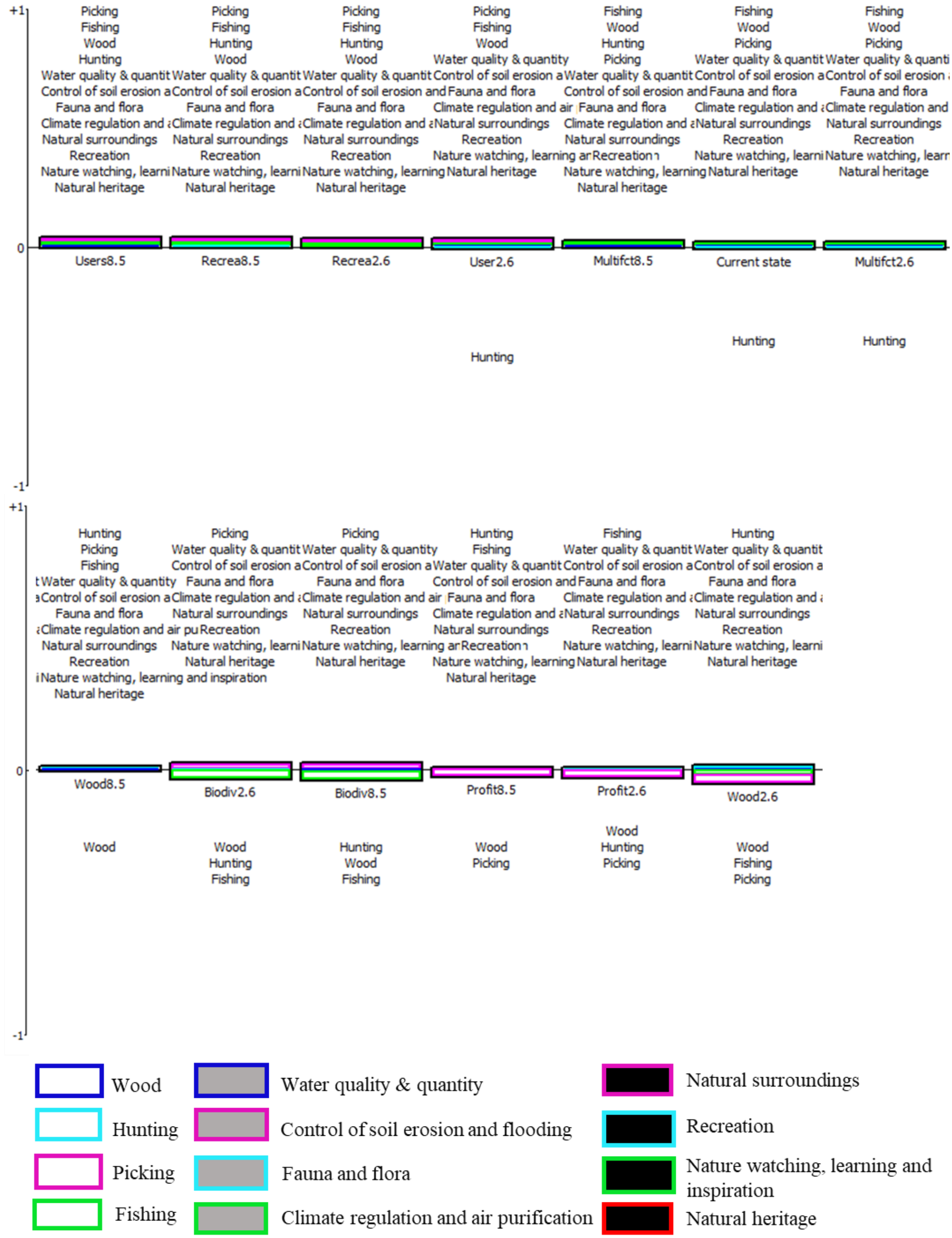

Figure 3-78. Disaggregated representation of the complete ranking (PROMETHEE II) of each ES for the group who prefers the cultural ES.

5.1.5 Conclusion

The best pathway is not always the one expected regarding the broad preferences of each group. Indeed, even if the stakeholders prefer a category of ES, they also have preferences for other ES that influence the ranking of the pathways.

5.2 Social resilience

The best pathways differ among the social preferences groups, illustrating the impacts of varying social demands on the ranking of the pathways (i.e. social resilience) (**Figure 3-79**). It is especially true for the current state and the Biodiversity management scenario and to a lesser extent the Recreation one. Indeed, for one of the four groups of social preferences, these management scenarios are the best one while for other groups, they are not good. Anyway, we can illustrate some good management scenarios irrespective of the social preferences: Users' Forest and Multifunctional Forest. Indeed, these two management scenarios stand out as they meet fairly well the various needs of the stakeholders. They represent a compromise between the different needs of the various stakeholders. On the contrary, the Wood Production and Profitability management scenarios are always 'bad' scenarios that do not answer sufficiently the needs of the stakeholders.

The differences between the two climate change scenarios are quite low and vary from one group of social preferences to another. Depending on the group, sometimes the best climate change scenario is SSP1-2.6 while for other groups, it is the contrary, except for the Profitability SSP1-2.6 that is always the best one compared to Profitability SSP5-8.5.

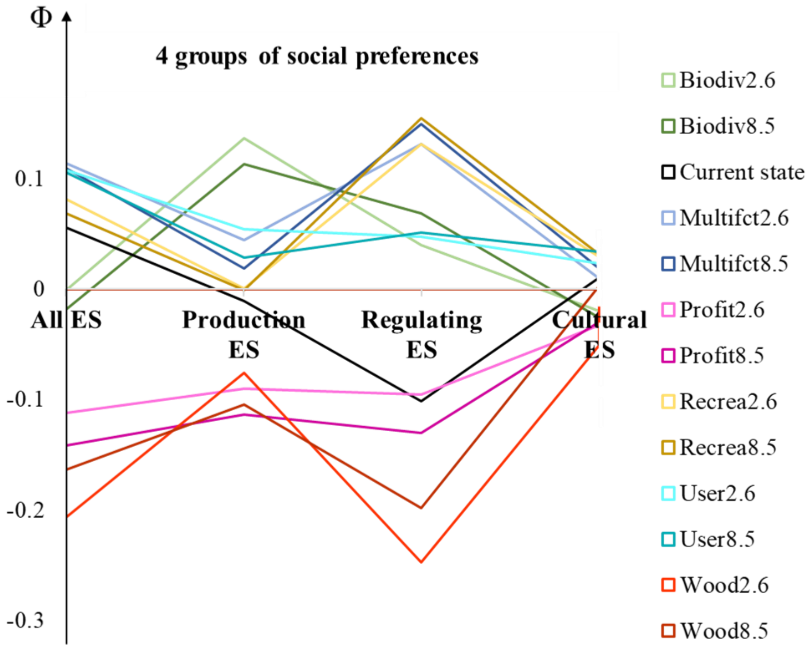

Figure 3-79. Ranking of the current state and the twelve pathways of the municipal forest of Sivry-Rance based on the ES they provide and the social preferences of the four groups from the PROMETHEE software (complete ranking PROMETHEE II).

The vulnerability of the stakeholders is now discussed. The hunters seem to be the most vulnerable group as the hunting ES has on average lower values in SSP5-8.5 than in SSP1-2.6. For the other ES and their stakeholders, there is no clear impact of climate change.

6. Step 6: Take action

6.1 Select the best pathway(s)

The sustainability of the pathways is now discussed. The ranking of the pathways in PROMETHEE (**Figure 3-79**) shows which pathways stay in the social boundaries: the pathways that have a negative Φ (i.e. Wood production and Profitability management scenarios) are the ones that do not answer the needs of the different stakeholders and thus the ones that exceed the social boundaries. The Biodiversity management scenario (especially in RCP8.5) has a slight negative Φ, for some social preferences groups. The Recreation management scenario has a zero Φ, for one social preference group. The biophysical boundaries were not directly assessed in our study (i.e. the resilience of the ecosystem was not assessed, see Chapter 4 2.3 Step 3: Establish the scope of valuation) but can be analysed according to the pathway ability to provide the different ES. The Wood production and Profitability management scenarios are not able to provide all the ES at a good level and thus, are more likely to exceed the biophysical boundaries. Therefore, these two management scenarios are unsustainable.

If we put aside the Biodiversity and Recreation management scenarios which are a bit borderline, two management scenarios (i.e. Multifunctional forest and Users' Forest) are truly sustainable. Indeed, they are the ones that answer the needs of the stakeholders regardless their preferences.

6.2 Develop the action plan

The management plan of the forest was thus designed to balance the different ES provided by the forest dedicating some areas of the forest to wood production, others to biodiversity restoration and conservation, recreation, etc. In this way, the differentiated preferences of the various stakeholders are met. Several measures are planned to manage potential conflicts between the users notably by improving communication (e.g. the closing of the hiking paths during the hunting season is the subject of a significant communication program) and by adapting the trails to the users (e.g. some paths are dedicated to the horse riders while others to the bikers).

The forest management plan is synthetized in Chapter 3 3.5. Multifunctional Forest and detailed by Colson et Baix (2021). This plan has promoted multifunctionality from the start and was a bit improved based on the results of this study. These improvements concern mainly the communication effort and the development of new hiking paths.

6.3 Implementation of the action plan

The forest management plan was officially adopted by the municipality of Sivry-Rance on February, 10 2022 (Direction des Ressources Forestières (SPW) and Commune de Sivry-Rance, 2022).

The implementation of this plan is conducted by the DNF in the field with the support of the municipality of Sivry-Rance. Two main tools are used by the DNF: (1) the forest management unit notebook (De Potter, 2011), and (2) the maps including the parcel system and their data that regroup all the descriptive data of the forest. These data are annually updated with the management actions.

This plan and the main results of this study were also presented to the stakeholders of the municipal forest of Sivry-Rance during the information session on March, 9 2023. This information session demonstrated that the forest management plan is suited to answer the diversity of the needs of the stakeholders but that a balance between these different needs must be found because it is not possible to fully supply all the ES. Questions were raised by the participants on the channelling of the recreation users on the authorized trails. The DNF explained the impacts of recreation on the forest: damage on the natural regeneration, fauna disturbing, soil compaction and its multifunctionality. So, communication is key to explain why certain measures are taken and to engage a dialogue with the different forest users to avoid conflicts between them.

6.4 Monitor the effects

The DNF and the municipality of Sivry-Rance are continuously adapting this plan to the field depending on the health state of the forest, the users ’demands, and the lessons learnt from the implementation of this plan. For this purpose, an evaluation report is annually generated based on the maps and descriptive data of the forest parcel system to follow the evolution of the management and to adapt consequently the management actions. The plan was already improved by increasing the recreation supply to meet the demand of the recreation users: development of new hiking paths, renewal of signposting and new explanatory panels. Finally, a new forest area was bought by the municipality of Sivry-Rance: Bois de la ville de Thuin to increase the forest cover of the municipal forest of Sivry-Rance and the different ES it provides.

Chapter 4

Discussion

1. Evaluation of the conceptual part of the Navigate framework

The conceptual part of the Navigate framework demonstrates the advantages of pairing resilience and ES to have a better representation of the complexity of the SES in answer to the current challenges in this increasingly uncertain world. If we only examine the ES, we could get lost on our way toward sustainability because we will miss considering the disturbances that are likely to affect the ES. If we only examine resilience, we will find it difficult to determine what management to implement without knowing what we want to maintain. By considering ES and resilience together, we are better able to navigate safely toward sustainability, knowing the way we should follow (i.e. which ES the stakeholders want to have now and in the future) while considering the dynamic properties of the SES and the increasing social and ecological uncertainties that lie ahead (i.e. resilience).

Despite the attempt to be as holistic as possible, our framework, like any other, remains subjective and incomplete. As a result, the Navigate framework needs to be reflective and transparent about the ontological, epistemological and political assumptions and the limits of the study (Tozzi, 2021; B. L. Turner et al., 2003). In the conceptual part of the framework, nature, society and their interactions were studied through the concept of SES. This concept promotes the image of a world consisting of a series of interconnected systems working as a functioning unit, where objects can be fully classified as either social or natural, and their relations explained through interactions across nested scales of analysis (Bell, 2005; Kwa, 2002). This concept thus often hides the messiness, disjuncture and multiplicity that are a key part of resilience (Folke et al., 2010) and ignores how the very act of constructing a system is partial and situated, necessarily reflecting one vision for the future over another (Cannon and Müller-Mahn, 2010; Tozzi, 2021). In our representation of the SES, nature and society seem to meet only at the end of the ES cascade while they interact well before that (e.g. in the joint production of the natural and anthropogenic capitals to supply ES). Our definition of resilience has a prescriptive attribute implying that resilience is desirable (Olsson et al., 2015) and that transformative change is needed to avoid the persistence of unsustainable practices.

From the conceptual part of the Navigate framework, we would have expected that the resilience concept having a system view would be the one that defines the ES concept. However, the opposite happened when the framework was operationalized. Indeed, the ES concept being more operational than the resilience one, the assessment of the system and its dynamic was mainly performed in the realm of the ES concept. This shows the gap between the theoretical and practical aspects: the implementation of the Navigate framework led to certain directorates.

2. Evaluation of the operational part of the Navigate framework

The implementation of the operational part of the Navigate framework to the municipal forest of Sivry-Rance is evaluated according to the 5-step valuation framework of IPBES (2022) (Termansen et al., 2023).

2.1 Step 1: Establishment of a legitimate process

This section reviews the legitimacy of the entire process (i.e. the fourth criteria used to select the methods in Chapter 2 6.2 Methods selection).

2.1.1 Importance of the stakeholder engagement

Stakeholder engagement is essential to have a comprehensive picture of the SES and its dynamics and to make legitimate and just decisions.

To truly perform an integrated assessment of the ES, stakeholder engagement is required to elicit the multiple values held by the various stakeholders and their trade-offs as well as to contribute to procedural justice (IPBES, 2022; Jacobs et al., 2018). Breyne et al. (2021) also demonstrated that understanding the socio-cultural values of the different stakeholders improves legitimacy and fosters consensus-building of decision-making in natural resource management. Because all the ES cannot be simultaneously maximized, the stakeholders need to be engaged to address their multiple needs and concerns and inform decision making (Swanson and Chapin, 2009).

To assess the social-ecological resilience, stakeholder engagement is crucial to understand the social aspects of the SES, its dynamics and interactions with the natural sub-system (Sellberg et al., 2021). Stakeholders bring in their local knowledge, their issues at stake, their perceptions and needs (Tengö et al., 2014) to make sure that the focus of the process is relevant, legitimate and addresses the real concerns of the people in the SES (Enfors-Kautsky et al., 2021). Furthermore, driving change toward sustainability requires deep engagement and long term commitment of the stakeholders (Miller and Wyborn, 2020; Walker et al., 2002). A fair and transparent process increases the prospect that the management decisions taken will actually lead to the desired changes and that the outcomes are perceived as legitimate and relevant (Enfors-Kautsky et al., 2021; Sellberg et al., 2021). Stakeholder engagement also builds capacity and connections between stakeholders to collectively find a way forward (Enfors-Kautsky et al., 2021).

The Navigate framework substantially gains from the involvement of the stakeholders. First, we broadened the understanding of ES and resilience by analysing the cultural ES that are still not enough taken into account in ES assessment (Cheng et al., 2019), the socio-cultural values of ES that are essential to interpret the outcomes of the ES assessment (Breyne et al., 2021), and the social uncertainty that is still rarely accounted for whereas it plays an important role in the SES dynamics (Seidl and

Lexer, 2013). Secondly, by informing and consulting the various stakeholders, the management plan of the municipal forest of Sivry-Rance became legitimate and transparent and fits better with the needs and expectations of the stakeholders. Thirdly, the relationships between the stakeholders were improved as the potential conflicts between them were detected and measures were taken to reduce them. Furthermore, the management plan is now a collective solution where the stakeholders understand better each other's stakes. Finally, for all these reasons, there is a better chance of implementation of this plan (Horcea-Milcu et al., 2020; Peter, 2020).

2.1.2 Points of attention in stakeholder engagement

There are several points of attention when engaging with stakeholders. Even with a stakeholder analysis, the risk of working only with particular people or organization that are interested in the topic and consider collaboration beneficial is still present (Lovens et al., 2014). There is also the risk of power imbalances (e.g. powerful organization, dominant personality) that can caused biased results (Hauck et al., 2016). Marginalized voices are more difficult to be heard because they do not have the power resources (e.g. access to relevant information or a voice loud enough to be heard) (Berk et al., 1999).

There is also the unclear role of the representatives of the stakeholders: do they represent their own stakes, the stakes of their organization or stakeholder group? (Hauck et al., 2016). The stakeholders might defend their own short-term interest, making more difficult to improve policies (Berk et al., 1999). There is still the potential dilemma between the interests of scientists and the interests of stakeholders who can have different expectations (Hauck et al., 2016). Finally, the participatory process can raise expectations that cannot be fulfilled (Berk et al., 1999).

Conflicts can be sparked during the participatory process when the facilitation is poor (Berk et al., 1999; Hauck et al., 2016). A risk is also the misuse of project results (e.g. a scientist who publishes sensitive findings or a policy maker who presents only selected outcomes or transforms the results to support her/his policy) (Hauck et al., 2016).

All these pitfalls have to be taken into account in the design of the process to limit them as much as possible (Kerkhof, 2001). They are discussed in the next section (Chapter 4 2.1.3 Reflections on the participatory methods).

2.1.3 Reflections on the participatory methods

How a participatory process is conducted including who is involved, in what way, and when are of utmost importance for the outcome (Enfors-Kautsky et al., 2021). Thus, these aspects are discussed in this section to highlight how the participatory methods influence the results, their advantages and drawbacks.

First, being a stakeholder of the municipal forest of Sivry-Rance, an unavoidable role in research action, I (and the other interviewers and facilitators) could have influenced the stakeholders in each step of the participatory process, even if we tried not to lead the stakeholders or take sides. Moreover, the results gathered from the participatory process can be biased by our perception (Lallemand and Gronier, 2018). A first bias (i.e. the confirmation bias) arises when the observer takes only the data and findings that are consistent with the assumptions or expectations without considering the ones that are inconsistent (Arnould, 2021). This bias mainly occurred in the participatory workshops (in the stakeholder analysis and the surveys, the predefined form minimizes this effect). A second bias (i.e. contrasting bias) arises when the observer tends to only note the salient facts in view of his/her previous experiences (Arnould, 2021). Two measures were taken to limit these two biases: (1) in the workshops, the findings were gathered by a diverse set of facilitators having different backgrounds to limit the individual bias, and (2) several measures (e.g. the presentation of the results of the different groups were recorded, the participants had to fill documents to synthesize their ideas) were taken to collect, as comprehensively as possible, the findings.

2.1.3.1 Stakeholder analysis

Lovens et al. (2014) discussed the advantages and the limits of the ecosystem services stakeholder matrix. The two main advantages are the stimulation of the stakeholders to think within the ES framework and the collection of information on the relations between ES and the stakeholders from the viewpoint of the respondents. They gave the two following limits: (1) time investment to conduct the interviews, and (2) the information is collected during interviews and is thus based on the perceptions and reality of the interviewees.

The resulting ecosystem services stakeholder matrix of the municipality of Sivry-Rance is almost complete: almost all the cells have a least one stakeholder and sometimes up to eleven different stakeholders in a cell. Most of the empty cells have truly no stakeholder (e.g. no stakeholder is negatively impacted by regulating ES). For some empty cells (influencer of some ES), information was missing from interviews (e.g. for the ES Hunting an influencer is the municipality of Sivry-Rance who designs the leasing contract) and the matrix was corrected correspondingly (**Table 3-1**). It is indeed more difficult for the interviewees to identify the influencers who are not directly visible.

The owner of the different ES was considered to be the municipality of Sivry-Rance by the different interviewees. In a sense, it is true because this municipality owns the forest and thus influences the ES it provides. On the other hand, if we strictly consider the owner of the ES, there is no real owner for the ES that everyone is free to use (i.e. most of the regulating and cultural ES).

This method based on the ES concept, which is central in the Navigate framework, allowed identifying the stakeholders related to the ES which provides a basis for the participatory workshops (i.e. we were able to invite the diversity of stakeholders and to better understand their stakes and how they interact with each other). We also identified the potential conflicts between the stakeholders (i.e. from the stakeholder analysis, we know that conflicts can arise between the stakeholders negatively impacted by an ES and its owner, manager or beneficiaries). Then, actions were designed to reduce these conflicts. For example, communication on the respect between the users and for nature as well as on the regulations is currently being improved (diversified communication means (e.g. information session, explanatory posters, articles, social media) adapted to the target audience) to help preventing the potential conflicts between the recreation users and the hunters. Another example is the design of different types of trails specifically adapted to different types of recreation users (e.g. bikers or horse riders).

On the other hand, we missed some stakeholders because this matrix only provides the stakeholders related to the ES of the municipality of Sivry-Rance. For example, this forest contributes to the sequestration of greenhouse gases which benefits people all over the world. So adding the resilience perspective in the stakeholder analysis would have broadened the identification of stakeholders to include the ones that are not directly interacting with the ES of the municipal forest of Sivry-Rance but that indirectly benefit from them or influence them (e.g. the evolution of societal demands all over the world). For example, Walker and Salt (2012a) provide guidance to identify the users of the system from the resilience perspective (what are the user groups (i.e. sectors) and what are their rights or entitlements?) and the governance (who controls resources use and regulations at each relevant scale? Are there problems in the relationships between the control agencies? Do the problems hinder or otherwise influence appropriate resource use?).

Finally, this matrix does not identify the persons but their hat (i.e. the way they are related to the ES). For example, a person can be a fisher, works at the municipality of Sivry-Rance and a hiker. This person is thus identified as three different stakeholders in the matrix. This allows understanding the different roles of a same person but at the same time reduces the person to these particular roles. Furthermore, when inviting a particular stakeholder to a participatory workshop, we could assume this person represents this particular stakeholder while each person of a same group of stakeholders can have different perceptions depending on his/her other hats and personal values. The analysis of the socio-cultural values in the surveys of the forest users indeed showed the variability in these values among a same stakeholder group. Thus, the different needs and expectations of a same group of stakeholders were considered in the Navigate framework. The variability inside a group of stakeholders was studied within the four surveys of the forest users (see Chapter 3 1.1.5.1 Surveys of the forest users). Moreover, the persons were not reduced to a certain group of stakeholders in the two participatory workshops. For instance, in the second participatory workshop, the persons were not grouped by stakeholders' type but rather on the basis of their needs and expectations regarding the ES.

Furthermore, this stakeholder analysis method did not reveal the marginalized groups such as persons with impaired vision or with reduced mobility. These marginalized groups may have a completely different vision of the forest and other needs that were not considered in our analysis. Other stakes, management scenarios and social preferences could have been raised.

2.1.3.2 Participatory workshops

Participatory workshops promote the active and explicit participation of the participants in the decision making process as well as their interactions, social learning, and capacity building leading to more informed decision making (Barker, 2005; Durham et al., 2014; Fish et al., 2011).

2.1.3.2.1 First participatory workshop

First, the representativeness is discussed. During the workshop, most of the groups of stakeholders were present. However, some groups of stakeholders were absent either because no representative of the group was invited (i.e. wood merchants, SWDE, CPAS and bee-keepers) or no representative came to the workshop (i.e. forest operator, nature association, river contract). Furthermore, some groups of stakeholders were overrepresented (i.e. hunters, recreation users) while others were under-represented (i.e. fishers, educational organization).

Thanks to the diversity of stakeholders attending the workshop, we gathered the knowledge and experience of the different stakeholders as well as their different sometimes conflicting views and values on the future of the area (Bohnet and Smith, 2007; Fish et al., 2011). Indeed, the stakes identified by the participants during the first part of the participatory workshop were diverse and highlighted the potential trade-offs between ES (e.g. Fauna and flora vs Recreation when there is too much travelling in the forest that could destroy some habitats), power relations (e.g. municipality vs the forest users) and social conflicts between stakeholders (e.g. walkers vs hunters). It allows broadening the stakes identified in the scientific literature (see Chapter 3 2 Step 2: Define the problem, the stakes and the goals). Furthermore, all the six scenarios designed by the six groups during the second part of the participative workshop acknowledge the multiplicity of ES as they were multifunctional and willing to find a balance between the different uses of the forest.

However, the overrepresentation or no representation of certain groups of stakeholders influenced the results. The importance given to certain stakes (e.g. the conflicts between the hunters and the recreation users) compared to others (e.g. soil or pollution) reveal the overrepresentation of the hunters and the recreation users. Some stakes might have been missed from the groups of stakeholders that were not present during the workshop (e.g. the wood sector and its stakes were not really discussed because no representative of this sector was invited). There is also the question of the stakeholders that do not have a direct representative (e.g. future generations, fauna and flora) even if some stakeholders can represent them (e.g. educational organization or naturalists). Some of their stakes (i.e. heritage, nature) were mentioned by some of the stakeholders and were considered in the scenarios. The overrepresentation of the old people may have limited the suitability of the scenarios to the younger and future generations who might have other needs. Moreover, some power relations between stakeholders not represented during the workshop may have been missed and hidden some inequities (Oteros-Rozas et al., 2015).

The representation of the different stakes is not only determined by the number of each stakeholders group present during the workshop but also by their behaviour. In some of the groups, some stakeholders led the discussion toward their stakes. For example, one group discussed a lot about tourism because of one representative of a tourism association guided the discussion toward this subject. In each group, the representative of the DNF framed the discussion by explaining what was and what was not possible to do in the forest.

The participative scenario planning method is potentially a powerful tool to engage a variety of stakeholders as the scenarios can be developed without much technical skills and can be easily understood by policy makers (Kok et al., 2007; Oteros-Rozas et al., 2015). This method is a knowledge sharing process to build common understanding of the SES, its dynamics and future management challenges, thus fostering learning about future planning of SES (Oteros-Rozas et al., 2015). It raises awareness of local management challenges and of the relevance of taking action in local planning (Oteros-Rozas et al., 2015). It increases stakeholders' awareness of the existence of local and global drivers of change and threats and the need for long-term planning to deal with such changes (Brown et al., 2016). Indeed, the first participatory workshop opened the mind of the participants to the needs and expectations of the others (they all agreed that the multifunctional forest was the ideal forest to fulfil the different needs of the stakeholders), to the drivers of change (e.g. climate change and pests that were mentioned by several participants) and the challenges of the management (e.g. the legal constraints, the balance to be found between the different functions of the forest).

Furthermore, participative scenario planning becomes a vehicle for consensus building (Wollenberg et al., 2000). It increases the dialogue and resolves conflicts (Oteros-Rozas et al., 2015). Indeed, the ideal forests designed by the participants are a consensus between their needs and expectations. Each group also stressed the respect between the different forest users.

Each choice is normative (Oteros-Rozas et al., 2015) and greatly influenced our results (e.g. the selection of the best pathway depends on the considered pathway, if we had designed another pathway, it could have changed the selected best pathway). This is why the scenarios were designed from a participatory workshop to better reflect the choices of the stakeholders and to decrease the normativity of the researchers' choices. Furthermore, the fact that one of the preferred pathway is the one designed by the stakeholders partly results from our methodological choices. It is quite logical that the scenario built from a consensus between the needs of the different stakeholders is the one that answers the best the multiple needs of the various stakeholders.

At the end of the workshop, we asked the participants to vote for their preferred ideal forest to determine their preferred future scenario, but they said that they liked all the scenarios and did not want to vote. It quite logical as the six groups designed more or less the same ideal forest.

We also asked their feedback on the workshop as an open question at the end of the workshop but nobody said anything, certainly because it was already late and maybe because they did not want to give their opinion in front of everybody. A short-written survey to be individually filled at the end of the workshop could be an alternative to have their feedback on the workshop. This idea was implemented at the end of the second participatory workshop and enabled to gather efficiently the feedbacks of the participants (see Chapter 4 2.1.3.2.2 Second participatory workshop).

2.1.3.2.2 Second participatory workshop

Only 19 persons participated in the second workshop. The fact that this workshop was held during the summer holidays and the covid-19 outbreak might explained this lower number of participants. Nevertheless, they represented a diversity of stakeholders, knowing that they can wear several hats (i.e. belong to several groups of stakeholders). Some groups were absent (i.e. forest operator, nature association, river contract). Most of the stakeholder groups were represented by 1 to 2 persons except the hunter, recreation users/association and municipality group who was overrepresented. Compared to the first participatory workshop, we have almost the same diversity of stakeholder groups but we have less different representatives of a same stakeholder group.

With this diversity of stakeholders, we were able to capture a variety of preferences concerning the ES as we obtained four contrasting groups of social preferences. These preferences depend highly on the values of the participants, other participants would have given other preferences. For instance, all the participants except the fisher gave a low weighting to the ES Fishing. If more fishers were present during the workshop, maybe this ES would have had a higher weighting. Another example is the overrepresentation of old people who can put aside the preferences of the young and future generations. Indeed, the preferences depend on who we ask (Fontana et al., 2013).

Stakeholder deliberation is an important part of the preference construction process (Tompkins et al., 2008). It is notably interesting to compare the individual preferences of each person of a group to the preferences of the entire group. We can only compare the opinion and the weighting because the individual table did not have the acceptable and satisfactory levels. For the four groups of social preferences, depending on the ES considered, the individual opinion and weighting can be considerably different than the one of the group. These differences are smaller for the group who prefers the cultural ES. They are also less marked for the preferred ES (e.g. for the group who prefers the regulating ES, the individual opinion and weighting of these regulating ES are quite consensual). These differences between the individual preferences and the ones of the group showed the influence of the group interactions on their preferences.

Moreover, in search of consensus between their individual preferences, the extreme values (very low or very high) were a bit blurred (i.e. the weighting of the group is less extreme than the one of some individuals). The preferences are thus a bit more homogenous than the individual ones.

Nevertheless, the four groups of social preferences are very distinct from each other. So, from the process of deliberation, new group preferences were constructed (Sagoff, 1998). This process helps them also to revise their preferences through interaction with other people (Kenter et al., 2015; Raymond et al., 2014).

Other problems can arise when eliciting the preferences by groups:

- Some individual's preferences may not be reflected by the group consensus;
- Some individual's preferences may not be heard within the group depending on the power relations;
- Some individuals may not be able to articulate their preferences in a group setting due to a lack of confidence or trust in the group. (Fischhoff, 2000)

These problems were limited during the second participatory workshop. Indeed, most of the participants felt satisfied by the group table, some said that the group discussion helped them better understanding the table, others appreciated the exchanges and the consensus building and to see that other persons shared their values. This reflects social learning (Saarikoski et al., 2019). During the group discussion, the floor was well shared among the members of the group except in one group where someone did not feel legitimate in face of the other members that had a higher expertise and, in another group, someone was a bit leading the discussion.

Some stakeholders also pointed some difficulties:

- To differentiate some ES (in Fontana et al. (2013), some stakeholders also expressed their difficulties to weight similar ES);
- To distinguish the acceptable and satisfactory levels;
- To fill the table because it was too complicated.

These difficulties influence the social preferences given by the participants (Fontana et al., 2013).

2.1.3.3 Surveys of the forest users

A critical analysis of the four surveys of the users of the municipal forest of Sivry-Rance is performed by discussing the following issues:

- The elements that influence the answers of the respondents (e.g. type of survey, formulation of the questions);
- The length of the surveys;
- The sample;
- The three economic methods (i.e. TCM, DCE and contingent valuation).

The way the respondents are interviewed has an influence on their answer (de Singly, 2016). For instance, it has been demonstrated that the respondents said more easily "I do not know" in internet survey than in face-to-face survey (de Singly, 2016). We used these two types of surveys in the municipal forest of Sivry-Rance. The face-to-face survey allows having a questionnaire filled until the end, reformulating the questions when they are not well understood and having additional information (some interviewees gave more information than just the answers to the questions asked). On the other hand, this method is time-consuming and resources demanding and the interviewer can influence the answers of the respondent. The internet survey is faster and demands fewer resources, there is no bias created by the interviewer, they can take their time to answer the questions and they can express more freely thanks to the relative anonymity. On the other hand, the questionnaire may not be filled until the end. The DCE questions are more adapted to the internet questionnaire because the respondent had more time to become thoroughly acquainted with the scenarios. We had a few questionnaires that were not filled until the end when the respondents answered it online. The use of the tablets in the face-to-face interview allowed us keeping some advantages of the internet survey: the answers can be directly exported in an Excel file (it is a time saving) and the survey is interactive (the next questions are displayed depending on the previous answers). (Brahic and Terreaux, 2009)

The **questions** have a strong influence on the answers of the respondents (de Singly, 2016). For instance, in the DCE questions, the pictogram of deadwood has mushrooms on it, so some respondents could prefer deadwood because they also saw the possibility to pick mushrooms. To limit this influence, de Singly (2016) gives the following guidelines: (1) asking a question in the most neutral way possible, (2) making the question understandable (e.g. avoiding (double) negation), (3) using opening words such as what do you think of, what would you say, and (4) using a logical sequence in the questions. These guidelines were followed in the four surveys (e.g. we used pictograms in the DCE to illustrate the different forest characteristics or the socio-economic questions were put at the end of the questionnaire) but the use of opening words could have been stronger.

Most of the questions were either closed questions or numerical questions (i.e. the answer is a number). These questions are easy to analyse and thus are less resources demanding (de Singly, 2016). However, the closed questions have a higher influence on the answers of the respondent because we select the information that the respondent can give (de Singly, 2016). de Singly (2016) gives also several guidelines to limit this influence: (1) to have a good balance between the positive and negative answers, (2) to accept multiple answers so the respondent feels less that he/she has to give to ‘correct’ answer, (3) to give the opportunity to answer “none” or “other”, and (4) to broaden the yes/no answers (e.g. yes, always; yes, in general; it depends; etc.). These guidelines were followed in the four surveys except the last one which could have been implemented in some questions (e.g. the contingent valuation questions). Concerning the third guideline, the test of the questionnaires allowed broadening the use of “none” or “other”. For instance, in the question “What other activities do you undertake in the municipal forest of Sivry-Rance” of the survey of the fishers, we added the answer “none” because several fishers told us they only came to this forest to fish. This guideline could have been implemented in more questions (e.g. the questions on the preferences for the tourism infrastructures did not propose “none option”, so we forced them to choose between the different alternatives proposed).

Some questions were open to capitalize their advantages: (1) there is not predefined category of answers, (2) the categories are built from the answers, and (3) several indicators can be assessed from a single answer (de Singly, 2016). They have the two following limitations: (1) there is a stronger bias from the effects of the interviewer (in the face-to-face interview), and (2) the answers can provide little useful information (de Singly, 2016). The last limitation was not observed in the four surveys as we gathered useful information from the open questions.

Biases also come **from the respondents**. They do not always give their exact answer for four reasons:

1. They give the awaited answer because they want to give the 'correct' answer (i.e. answering a survey is perceived as taking an examen);
2. They give the legitimate answer (e.g. the one that is socially acceptable);
3. They give an approximate value when they do not know the exact value;
4. They give an answer to influence the results in line with them. (de Singly, 2016)

The first two biases must have happened even if they are difficult to observe. The approximation bias could have been stronger in the numerical questions (e.g. for the number of annual visits, some respondents were not sure about the exact number of visits). The last bias is typical of the contingent valuation (Champ et al., 2017). For instance, a lot of respondents were against having additional taxes and did not give a WTP even if maybe they were willing to improve the infrastructures.

For the central thematises of the questionnaire, it is opportune to ask several questions on the same thematic to gather several indicators on the matter because of the imperfection of each question and because no single indicator is able to capture the full spectrum of the matter (de Singly, 2016). This technique was applied in the entire survey to gather the preferences of the forest users. Indeed, these preferences were estimated by three economic valuation methods (i.e. TCM, DCE and contingent valuation) and by several questions, some were closed (e.g. Why do you come in the municipal forest of Sivry-Rance?) and others were open (e.g. What are the characteristics of the municipal forest of Sivry-Rance that bother you?).

Concerning the **length of the questionnaire**, the four surveys were a bit long. In the face-to-face interview, some respondents expressed their fatigue to answer the questions and in the online questionnaire, some respondents did not answer all the questions. An effort was made to reduce them as much as possible to limit the respondent fatigue. For instance, the survey of the hunters was reduced after testing it (e.g. the questions on the preferences of the tourism infrastructures were removed) because it was too long. Some questions were also too long. For instance, in the DCE questions, some respondents saw no end. We could have reduced it by only asking four choice sets instead of six.

We will now discuss **the sample**. Its size was appropriate for most of the questions and analyses to gather the diversity of points of views. For the contingent valuation, because we had a lot of protesters, the sample was too small especially for the inhabitants harvesting firewood, the hunters and the fishers. We could have increased the sample of the fishers by doing some additional days of questionnaire administration around the fishing ponds. For the inhabitants harvesting firewood and the hunters, it would have been more difficult to increase the sample because they were all contacted. However, we could have increased their willingness to answer the questionnaire for example by offering a reward.

2.2 Step 2: Define the purpose of valuation

The underlying purpose of our valuation was to inform the management plan of the municipal forest of Sivry-Rance. This means that our valuation was profoundly influenced by the existing process of forest management plan design, the decision-making context of the municipal forest of Sivry-Rance and the forest management plan itself. These three influencing factors converge in the multifunctionality of the forest, ensuring that the two multifunctional management scenarios were the best ones.

2.3 Step 3: Establish the scope of valuation

The choose of the **ES concept** orientated the assessment toward the instrumental values of nature (see **Table 2-20** which shows that most of the methods elicit instrumental values). Nevertheless, the participatory process broadened the types of values considered (i.e. broad values were elicited during the first participatory workshop and specific values were assessed in the surveys) and demonstrated that the intrinsic and relational values are also important to the stakeholders. These two types of **specific values** should have been further evaluated.

The assessment of the intrinsic values was quite comprehensive as we combined nature-based valuation methods (i.e. four indicators derived from literature review, scientific paper and model) together with statement-based valuation methods (i.e. participatory workshops, surveys). The first group of methods assesses the intrinsic values by assessing nature irrespective of the importance to people while the second group assesses these values by assessing why people consider nature to be intrinsically important (IPBES, 2022). Nevertheless, other methods could have been used to broaden the inclusion of intrinsic values. For example, biodiversity inventory or remote sensing analysis could have been performed to derive biodiversity indicators (e.g. species diversity, functional diversity). Furthermore, the intrinsic values gathered from the participatory process were little used in the assessment of the pathways because we did not know how they could evolve in the different pathways. We could have asked the respondents, in the surveys, to assess how the values they attach to the forest would have changed in the different pathways.

The relational values were also assessed with different methods (i.e. participatory workshops, surveys and literature review). To further assess these relational values, the socio-cultural values could have been used, instead of the ES, to elicit the preferences of the stakeholders, in the second participatory workshop (i.e. five of the thirteen socio-cultural values are relational (see **Table 3-3**)). Furthermore, other methods could have been used to assess the two ES related to the relational values (i.e. nature observation, learning and inspiration, and natural heritage). For instance, some results of the surveys (notably depicting the attachment to the forest and how the forest promotes social interactions) could have been integrated into the ES assessment of the pathways by asking the respondents how these values would change in the different pathways.

Moreover, the **selection of the ES** influenced the results (Kull et al., 2015). Even if the list of the ES considered was quite large, the results of the ES assessment could have been different if the missing ES were assessed. A selection of the ES with the stakeholders could have been performed to legitimate the list of ES. Furthermore, in the second participatory workshop, we could have asked the participants the values they hold to the forest and their corresponding preferences without giving a predefined list.

The ES assessment also shows that in any pathway, some ES are not well provided. Swanson and Chapin (2009) also stated that it is unlikely that all these services can be maximized simultaneously. This reflects the trade-offs among ES (i.e. the provision of one ES is reduced as a consequence of increased use of another ES) arising from the management choices (Rodríguez et al., 2006). An assessment of multiple ES is thus essential for understanding the interactions among ES and the negative implications that a decision may have on key or important ES (Bennett et al., 2009; Rodríguez et al., 2006).

In the ES assessment, we have seen that different **indicators** of a given ES can have contrasting trends, showing the necessity for performing an integrated assessment that highlights different values of an ES. Jacobs et al. (2018) also demonstrated that no single valuation method can capture the full spectrum of values and that we need to select complementary valuation methods to cover all value dimensions. The different methods used to assess the ES (including the participatory methods) cover the three types of indicators defined in the values assessment typology of IPBES (2022). The biophysical perspective remains predominant, especially for the regulating ES which were only assessed by biophysical indicators. We should further diversify the methods notably by better integrating the results of the participatory methods in the ES assessment of the pathways (see above).

MCA allows treating complex and multidimensional decision-making, over long-term time horizons, involving multiple conflicting objectives, a diversity of possible outcomes, with incommensurable or uncertain effects, various stakeholders with different perceptions and values (Ananda and Herath, 2009; Martinez-Alier et al., 1998; Munda, 2004). In other terms, MCA allowed us testing different pathways, performing an integrated assessment of the ES including the different socio-cultural values of the stakeholders and analysing resilience. The different values of the ES were synthetised without reducing the assessment to a single metric to truly consider the diverse values and languages in decision-making (Jacobs et al., 2018). Indeed, multi-criteria analysis is consistent with value pluralism by acknowledging that it is difficult, if not impossible, to produce single right answer in complex decision-making situations involving multiple values and conflicting judgments (Saarikoski et al., 2016).

Indeed, MCA is particularly suited to perform an integrated assessment of the ES because it accommodates conflicting stakeholder perspectives and multiple indicators units including quantitative and qualitative ones to address trade-offs between ecological, social and economic values (Fontana et al., 2013; Langemeyer et al., 2015). Furthermore, because uncertainty and ignorance cannot be managed by means of one dimensional perspective and thus expressed in a single evaluating measure (Funtowicz and Ravetz, 1994), MCA attempts to deal with this inherent uncertainty by means of involving a plurality of legitimate perspectives and values as well as allowing it to be expressed in multiple metrics (Oikonomou et al., 2011). This is why we used MCA to study the resilience of the ES and social resilience.

Moreover, MCA elicits the trade-offs among multiple management objectives (Schwenk et al., 2012) to achieve compromise in decision-making (Cork and Proctor, 2005). With the MCA, we were able to demonstrate to the stakeholders that a balance needs to be found between the different ES and their needs and expectations because it was not possible to maximize all the ES at the same time. They could also understand how the increase of the supply of an ES important to them could decrease the supply of other ES and thus negatively impact other stakeholders.

However, this integrated assessment is not so easy to perform. Indeed, **diverse methods** need to be used, each method demanding certain resources (time, data, expertise, etc.) that can be restricted in practice (IPBES, 2022; Jacobs et al., 2018). Furthermore, in order to truly reveal the value pluralism, the ES assessment methods should be ontologically and epistemologically very different (Arias-Arévalo et al., 2018) and thus require various data and expertise. Even if several experts from different backgrounds (e.g. social and economic sciences) have been consulted throughout the assessment, the inclusion of various disciplines should go one step further by having a multidisciplinary team applying the Navigate framework. This will broaden the expertise and thus the methods used and the values they convey.

Moreover, a balance needs to be found between feasibility and relevance: the number of value types and elicitation methods should be sufficient to elicit the main value dimensions that exist in a system to obtain a meaningful understanding of the problem at stake, but should also be mindful not to overburden the process and resources with demanding methods (Jacobs et al., 2018). This is why we used some methods that are less accurate but low resources demanding to diversify the assessment methods without overburdening the assessment of the ES.

The combination of various methods also promotes the inclusion of the different voices and interests of the multiple stakeholders in decision-making (Martín-López and Montes, 2015; Menzel and Teng, 2009). This inclusion was further promoted using a combination of **participatory methods** in the Navigate framework. We could have engaged more the stakeholders by selecting the assessment methods or indicators with them.

We used various participatory methods, ranging from surveys to participatory workshops, in every step of the Navigate Framework. As each participatory method has its blind spots and yield different results (Jacobs et al., 2018), it is necessary to combine different participatory methods. From the different methods, we reached the various stakeholders (e.g. in the forest users' surveys, we went directly in the forest to interview the users during their activities while in the participatory workshops, we invited only some of the forest users but also other stakeholders such as representative of local associations). We also engaged them at different levels: we informed them with the public information session, we consulted them in the two participatory workshops and the surveys, and we involved them in the stakeholder analysis.

The second participatory workshop helps understanding the socio-cultural values, including self and other-regarding values, ethical judgements and relational values through which people attribute meaning and importance to ES (Kenter et al., 2015; Pascual et al., 2017; Vatn, 2009). These socio-cultural values are essential to interpret the values of the ES in terms of the needs and expectations of the stakeholders to foster transparency and legitimize the decision making process (Breyne et al., 2021). They improve the transparency and legitimacy of the decision-making process (Breyne et al., 2021) by selecting a pathway that (partly) fulfils the different needs and expectations of the various stakeholders. Furthermore, this integration of the socio-cultural values reinforces the integrated assessment of ES by underlining the various ways in which an ecosystem matters and making explicit other important ES (than the ones that are the scope of the research) (Breyne et al., 2021). During the second participatory workshop, we gave the stakeholders no chance to express their preferences regarding the ES or other values they hold for nature not considered in the analysis. This is an area of improvement to go one step further into a truly integrated assessment of ES.

Stakeholder preferences have a great influence on the final decision and, at the same time, bringing in some uncertainty into the decisions (Kodikara et al., 2010). Indeed, in the PROMETHEE ranking, we have seen that the best pathway depends on the social preferences.

This participatory workshop also reflects the existence of an irreducible plurality of standpoints that stems from the complex nature of the issues at the hand and of the necessity of living together on the same planet (van den Hove, 2006). An important consequence of this irreducible plurality of standpoints is that the existence of divergent interests must be recognized and decisions processes will have to deal with judgements that may be contradictory, without always hoping to reconcile them (van den Hove, 2006). By considering four distinct groups of social preferences, we acknowledged the irreducible plurality of standpoints, and we showed how these different social preferences influence the choice of the best pathway.

We were also able to capture **different points of view**. We gathered the individual points of view in the surveys, in the first part of the first participatory workshop and from the individual preferences obtained before the second participatory workshop.

We got shared values, that are fundamentally different from the sum of each individual value (Arias-Arévalo et al., 2018), from the first and second participatory workshops. Deliberative methods allow the participants to reflect on the values at stake and to share their knowledge, views and perceptions with other participants (Kenter et al., 2015). This learning and consensus building process was more pronounced in the first participatory workshop where the groups were heterogenous and where we asked them to reflect on desirable futures (see e.g. Reed et al. 2013). The second participatory workshop was more helpful to illustrate the value differences than reconciling them (see e.g. Saarikoski et al. 2019). We can place the different participatory methods on a continuum between consensus-oriented cooperation in the pursuit of common interest and compromise-oriented negotiation aiming at the adjustment of particular interests, defined by van den Hove (2006). The first participatory workshop was more a consensus-oriented cooperation where the different stakeholders had to balance their different needs and expectations while the second participatory workshop was in between as they had to find a consensus with people sharing more or less the same values and where conflicting interests were account for. As suggested by Van den Hove (2006), using different participatory methods, we were able to have both consensus-oriented cooperation and compromise-oriented negotiation.

Finally, we get a more complete understanding of the social part of the SES (i.e. from each participatory method, we got one piece of the puzzle and it is only by merging them that we obtained a fuller picture). Indeed, when we combine different participatory methods, we get a more complex picture of why and how people value ES (Arias-Arévalo et al., 2018). For instance, from the surveys, we understand how the people use the forest and what values they hold (i.e. the origin of the values they assign to the ES) while from the second participatory workshop, we gathered how they value the different ES (i.e. the values they assign to the ES).

In each participatory method, the ES concept was present. Some methods (i.e. stakeholder analysis, second participatory workshop and public information session) were based on this concept to acknowledge the many different values of the forest and to unite the different stakeholders around (Sellberg et al., 2021). In the other methods (i.e. surveys and first participatory workshop), the ES concept was not explicitly mentioned but was still present. From the surveys, we assessed the cultural ES and the socio-cultural values. In the first participatory workshop, the balance needed to be found between the different ES was one of the main findings.

The resilience concept was less present in the participatory process. It was not explicitly mentioned in any participatory method. Nevertheless, it was discussed in the first participatory workshop because we talked about the future of the forest. Indeed, this concept is more difficult to grasp (Brand and Jax, 2007) but remains essential to understand the dynamics of the system and to acknowledge change and uncertainty (Standish et al., 2014). The different participatory methods ultimately helped integrating resilience in the analysis. For instance, from the second participatory workshop, we were able to analyse the social uncertainty.

It is recommended to combine different methods to assess **resilience** as each method has its own strengths and weaknesses and captures only some aspects of resilience (Cantarello et al., 2017; Folke, 2016; Seidl et al., 2016). In the Navigate framework, we assessed two types of resilience (i.e. the resilience of ES and the social resilience) each one with one indicator using one method (i.e. the multi-criteria analysis) due to limited time, knowledge and resources. Indeed, the operationalization of resilience still lags behind, especially for the social-ecological resilience that lacks an integrated set of indicators to assess the different aspects of resilience (Nikinmaa et al., 2020). For the same reason, data to assess resilience were even more scarce.

To get a fuller picture of the resilience of the SES, other types of resilience (e.g. the resilience of the ecosystem) and other methods (e.g. models to assess how the ecosystem, the ES and the societal demands vary through time) should be used, which need more time and resources as well as further development (Nikinmaa et al., 2020). To assess the ecological resilience, we could have evaluated several indicators such as the extent of disturbance the forest is able to absorb without changing fundamentally (Gunderson, 2000; Walker et al., 2004) and the critical thresholds of regime shifts (Scheffer et al., 2012) from modelling (Biggs et al., 2009; Schlüter et al., 2019). We could also have used STM to understand the different states of the municipal forest of Sivry-Rance, the transitions between these states, the conditions inducing these transitions and the possible thresholds. From this model, the ES of the different states and their resilience can be assessed (e.g. Lavorel et al. 2015, Peri et al. 2017) as well as the ecological resilience (e.g. Peri et al. (2017) assessed a Forest Resilience Index, based on seedling recruitment under 2 years old and the trees growth or López et al. (2011) assessed the structural ecosystem change (vegetation and soil) and functional change to identify critical thresholds). By understanding the ecological resilience, we would have extended the analysis to not only consider what people get from nature but also what nature gets from the people (i.e. actions that can be done to improve the resilience of the ecosystem).

Finally, we only studied the social resilience from an ES perspective (i.e. the social preferences and the impacts of climate change on the ES and their respective stakeholders). To further study social resilience, we could have used agent-based models that depict the stakeholders and the rules of their decision process to explore the outcomes of various policy decisions when change occur (e.g. Dressler et al., 2018; Egli et al., 2018; Van Strien et al., 2019). These agent-based models would also have deepened the analysis of the vulnerability of the stakeholders to climate change.

2.4 Step 4: Choose and apply relevant valuation methods

All the valuation methods are evaluated according to the 3R of IPBES (2022) (**Table 4-1**). No method outperforms the others on all the criteria (no method considers the different factors affecting the ES, has a high accuracy, is assessed at the forest stand scale and is low resources demanding). Nevertheless, some methods fulfil most of the criteria. In addition to allow assessing indicators for which no other suitable method was found, the literature review is a good compromise between the precision of the method (several factors are considered, the accuracy of the method is medium) and the time and resources needed. However, we obtained qualitative values on 5 levels scale at the scale of the municipal forest of Sivry-Rance. Nevertheless, it is possible, with this method, to assess the values at the forest stand level and the qualitative values were enough to compare the different pathways. All in all, this method is suitable to perform an integrated assessment of the ES (medium precision with low resources) when different alternatives need to be compared. For these reasons, this method was sometimes chosen over quantitative indicators that only consider the land cover. For instance, to assess the Forest temperature buffering capacity, it was first decided to evaluate the difference of temperature between the one in the forest and the air temperature of the different forest stands based on the maps of Haesen et al. (2021) to have quantitative values. But this method was not very accurate: we crossed our actual forest stands map with the maps of the difference of temperature in the four seasons of Haesen et al. (2021) to calculate a mean difference of temperature for each forest stand knowing that the forest stand type is not the only explanatory factor of the forest buffering capacity. Furthermore, with this method, we were not able to capture the other factors influencing the forest buffering capacity such as climate change. We finally decided to assess this indicator with a literature review to capture other factors and have a better estimation.

The Wood indicators based on the Data of the forest management plan + IPRFW + expertise method, the Total carbon stock and PROMETHEE are also quite good: they are more resources demanding but they consider several factors with a high accuracy and are estimated with quantitative values. For the indicators of Wood, it was first decided to use the SIMREG model (i.e. tree-level distance-independent Walloon model simulating the forest dynamics and management) (Perin et al., 2021) to assess them. After, we realized using this model would be time consuming and resources demanding to have more precise values that we did not really need to compare the pathways and still have errors from the model. This is why we finally decided to combine the data of the forest management plan with the ones of the IPRFW and expertise that provide estimates accurate enough for our purpose.

Some methods such as the Water cycle indicators or the Water purification score are less accurate but are still needed to perform an integrated assessment of the ES to diversify the pool of methods used. These methods should be further improved to increase their accuracy. Several areas of improvement are discussed in Chapter 4 2.4.1.1 Factors considered in the method and Chapter 4 2.4.2 Robustness.

The participatory methods even if they are high resources demanding are needed to broaden the values assessed and to legitimize the valuation. The robustness of the TCM and the contingent valuation should be further improved (see Chapter 4 2.4.2 Robustness).

Table 4-1. Synthetic comparison of the different assessment methods/indicators according to the 3R of IPBES (2022). When forest stand is indicated in the column "Factors considered", it means that the land cover, the management and the ecological context are considered.

	Relevance		**Robustness**		**Time and resources needed**
Indicator/method	**Factors considered**	**Spatial scale**	**Accuracy**	**Type of value**	
Participative scenario planning	Forest stand, climate change	Forest stand	Medium	Qualitative	High
Participative preferences elicitation	/	Municipal forest of Sivry-Rance	Medium	Qualitative	High
Socio-cultural values (survey)	/		High	Qualitative	High
TCM (survey)	/		Medium	Quantitative	High
DCE (survey)	Land cover, management		High	Quantitative	High
Contingent valuation (survey)	Recreation infrastructures		Medium	Quantitative	High
Forest attendance (cameras traps)	/	Trails	High	Quantitative	High
Data of the forest management plan + IPRFW + expertise	Forest stand and climate change	Forest stand	High	Quantitative	Medium
Preferences of the forest users based on the surveys		Municipal forest of Sivry-Rance	Medium	Qualitative (5 levels)	High
Literature review					Low
Forest buffer width	Forest stand	Forest stand	Medium	Quantitative	Low
Water cycle	Land cover	Broad types of forest	Low	Quantitative	Low
Total carbon stock	Forest stand and climate change	Forest stand	High	Quantitative	Medium
Water purification score	Land cover and ecological context	Broad types of forest	Low	Qualitative (score)	Low
Pollinator abundance	Forest stand, wild bee populations	Forest stand (map)	Medium		High
Fine particles capture	Land cover	Broad types of forest	Medium	Quantitative	Low
PROMETHEE (MCA)	Management, climate change	Municipal forest of Sivry-Rance	High	Quantitative	Medium

2.4.1 Relevance

The relevance of the methods is evaluated regarding three criteria: (1) the factors considered in the method, (2) the spatial scale, and (3) the temporal scale. The relevance in terms of the values considered is discussed in the previous step (see Chapter 4 2.3 Step 3: Establish the scope of valuation).

2.4.1.1 Factors considered in the method

In this section, we reviewed the methods based on the plurality of sources of information used and the factors considered (e.g. land cover, ecological context, forest management, climate change).

The participatory methods are based on a single source of information (i.e. participatory workshop or survey) but combined the different knowledge of the stakeholders. Most of these methods (except participative scenario planning, DCE and contingent valuation) focused on the entire forest without asking the stakeholders how their responds would change in different forest stands (i.e. varying forest composition, ecological context, and management).

The forest attendance assessment is also based on a single method given the resources we had we could not test other relevant methods (e.g. “eco-compteurs”, passive Wi-Fi tracking and social media (Flickr)) that were highly demanding in terms of resources. However, it would have been interesting to compare the forest attendance results with other methods.

Some of the methods (i.e. Data of forest management + IPRFW + expertise, Preferences of the forest users and Literature review) were assessed based on several sources of information to obtain a detailed and comprehensive picture of the ES. By combining data of forest management with the IPRFW and the expertise of several forest experts, we assessed the growing stock, the annual volume of harvested timber and the annual profit from timber harvesting for the different forest stands depending on the site and considering their management and the impact of climate change. To elicit the preferences of the different forest users, we gathered information from different questions of the surveys (e.g. DCE, what they like and dislike?) considering the management of the concerned ES and the impact of climate change. From the literature review, we get the different factors influencing the indicator (at least the ones discussed in the scientific literature).

Nevertheless, some factors were not considered in the first two methods. From the Data of forest management + IPRFW and expertise, some other influencing factors were not considered such as the age of the even-aged stands (we only differentiated the young plantations from the rest of the stands) or the stand density. In the annual profit from timber harvesting, we directly included the harvesting costs but not the management costs. These management costs could include not just the forestry costs but also the other management costs (e.g. nature restoration costs, recreation infrastructures maintenance cost) and benefits (e.g. the rental of the fishing ponds or nature subsidies) to have a full picture of the net income of the forest. The preferences of the forest users could be influenced by other factors such as the mix of hardwood and softwood species or the ground vegetation (see Van Keymeulen (2022) who reviewed the forest characteristics that influence the preferences of the forest users) that were not taken into account. Furthermore, these preferences represent the main preferences of each forest user knowing that a minority of them had other preferences for some characteristics.

From the methods based on the data from a paper and existing models, we could only consider the factors integrated in the paper or in the model. Some indicators (i.e. Fine particles capture and the ones based on the Forest buffer width and the Water cycle) only depend on the land cover type. Furthermore, the indicators of Fine particle capture and the ones based on the Water cycle only differentiate the main forest type (hardwood, softwood or a mix of the two). The Forest buffer width only distinguished the forest stands that can be considered as a forest buffer (i.e. ideal riparian forest that performs correctly its functions) from the others. For the other indicators (i.e. Total carbon stock, Water purification score and Pollinator abundance), other factor(s) than the land cover were included. The Water purification score and the Pollinator abundance consider one additional factor that we did not change in the pathways: the slope for the Water purification score and the wild bees for the Pollinator abundance. The Total carbon stock indicator considers several additional factors (i.e. site, management and climate change that vary in the pathways as well as the soil and the humus that do not vary in the pathways). In the Water purification score, the land cover type only differentiates the three main forest types while for the two other indicators, the different forest stands are distinguished.

Land cover is not enough to assess the ES because they are other factors that influence them. The ecological context and the management are two important factors that need to be taken into account (Maebe et al., 2019). They were partially considered when the different forest stands could be differentiated because the definition of the forest stand integrates their management and the suitability of the species with the site. Other factors should also be included depending on the ES and the indicator considered. For example, the pollinator abundance depends on the floral resources that can vary inside a same land cover class (Monseu 2021) and the size of the habitat patch (Natural Capital Project, n.d.).

By varying the management and the rising temperature due to climate change, we were able to test the influence of these two factors on the ES provided by the municipal forest of Sivry-Rance and its resilience.

We selected six contrasting management scenarios based on the first participatory workshop to test the impacts of forest management on the ES and the resilience. Their respective impacts were highly visible (see Chapter 3 4.4 Assess the ES and Chapter 3 5 Step 5: Assess resilience). The making of heterogenous groups ensures that the multifunctional management scenarios are the best ones because they represent a consensus between the needs of the different stakeholders. Using participative scenario planning to develop these management scenarios ensures selecting scenarios that make sense for the stakeholders to improve their legitimacy, transparency and uptake (see Chapter 4 2.1.3.2.1 First participatory workshop that discusses in detail the advantages of engaging the stakeholders in scenario development). To go one step further in the participatory design of the scenarios, we could have validated the management scenarios with the stakeholders as suggested by Carlsen et al. (2013).

Climate change was directly integrated in the pathways by testing two contrasting climate change scenarios from IPCC (2022). Surprisingly, our analysis showed a limited impact of climate change on ES while it has been demonstrated that climate change could have a significant impact on ES (Mooney et al., 2009; Runting et al., 2017). Indeed, climate change actually has a low impact on some indicators of ES. For instance, for the indicator of Recreation supply, climate change does not change drastically the availability of recreation infrastructure and the visual characteristics of the forest in both our climate change scenarios. Furthermore, the large differences between the management scenarios could blur the distinct effects of the two climate change scenarios. If we had fully considered all the aspects of the two IPCC climate change scenarios (i.e. societal drivers) and not only the effects of rising temperature, the effects of climate change could have been stronger. Finally, for some ES, the impacts were not clearly evident due to limitations of the methods. Most of the methods (i.e. those using data from a paper, existing models, or the surveys of the forest users) did not directly integrate climate change. The impacts of climate change were only investigated in terms of land cover changes (i.e. the composition of forest species). Furthermore, among these methods, some of them discriminate only main forest stand types (e.g. hardwood vs softwood) so that the impact of species composition changes within a certain forest type is not able to be considered. From the literature review, we evaluated the influence that climate change could have on the SES but generally, trends were uncertain (e.g. for the ES “Picking”, the fungal distribution is positively correlated with a warmer climate, but the increase of droughts has a negative impact (Olah et al., 2020; Tomao et al., 2017)). Even if the impacts of climate change on ES is broadly studied (Runting et al., 2017), climate change is not sufficiently integrated into existing ES assessment methods, especially in the simple and fast methods needed to perform an integrated assessment (e.g. none of the three models that we used to assess ES incorporates climate change).

To also account for social uncertainties, the varying social demand was studied in PROMETHEE. This varying social demand was not directly included in the pathways but was studied when assessing the resilience. We have seen that societal demand has an impact on the selection of the best pathways. If we had not considered the different social preferences, we could have chosen a wrong pathway and not met possible future needs of the stakeholders. Furthermore, varying social demand allows accounting for societal and cultural values in the future diversifying the pool of values considered when analysing the outcomes of the scenarios which are rarely taken into account (IPBES, 2022). We also indirectly addressed distributional justice by highlighting the winners and the losers of each pathway (i.e. for a pathway, the winners are the social preferences groups for which the pathway has a positive Φ while the losers are the social preferences groups for which the pathway has a negative Φ) while distributional justice in scenarios is still too rarely considered (IPBES, 2022).

Other drivers could have been considered to deepen the resilience analysis. In particular, the pests and diseases including non-native species could have been studied because they were identified as an important driver of the municipal forest of Sivry-Rance (see Chapter 3 1.2 Define the system dynamics). Other socio-economic drivers such as technical innovations or political changes (e.g. by considering the political aspects of the SSP scenarios) could also have been considered.

This inclusion of other drivers would have allowed better understanding the changes that can occur in the municipal forest of Sivry-Rance and which measures can be taken to still provide the ES expected by the stakeholders. Moreover, we could have deepened the understanding of the co-production processes between natural and anthropogenic capital that supply the ES. Although, this joint production was a bit studied in the ES assessment (e.g. the habitat quality for game indicator considers anthropogenic factors (e.g. human infrastructures) and the interactions between natural and anthropogenic capital (e.g. the forest cover)), we did not specifically examine this co-production.

However, each new driver introduced in the scenarios multiplies the number of scenarios. Thus, a balance needs to be found between the number of drivers considered and the number of scenarios to be analysed. We could have reduced the number of management scenarios to include one or two additional drivers (pests and diseases and another socio-economic driver such as the wood market) but we were particularly interested in the impacts of the management on ES and resilience.

2.4.1.2 Spatial scale

The spatial scale of the different methods ranges from the entire municipal forest of Sivry-Rance to the forest stand. For the qualitative indicators, a mean level was given for the entire municipal forest of Sivry-Rance. It is technically possible to give a level at a finer scale. For instance, for the indicators of the Suitability level of the forest with the preferences of the different forest users, a level could be attributed to each forest stand considering the infrastructures around and its management. It was not done because we were interested in the global differences between the pathways. The same goes for the participatory methods, we could have asked the participants to give their preferences for different forest stands in place of the entire forest.

For the quantitative indicators, we obtained the values at the forest stand level. Only the indicators of the Growing stock, the Annual volume of harvested timber, the Annual profit from timber harvesting, the Forest buffer width, the Pollinator abundance and the Total carbon stock are truly at the stand level because all the different forest stands were distinguished while for the other quantitative indicators, only the broad forest types were differentiated.

Only one indicator (i.e. Pollinator abundance) was directly spatialized because the InVEST model considers the movement of the wild bees. All the other indicators can be spatialized depending on the land cover and possibly other factors that influence them (e.g. infrastructures, objective area). With the maps of the pollinator abundance in the different pathways, we have seen that even if the mean pollinator abundance of the municipal forest of Sivry-Rance is similar between two pathways, the spatial distribution can vary greatly if the repartition of the forest stands varies accordingly. Mapping the indicators thus shows the possible spatial variation between two pathways that are not always visible when comparing their mean value for the entire municipal forest of Sivry-Rance.

The inclusion of other drivers in the pathways design would have deepened the analysis of the scales and their interactions with the forest. Indeed, the central spatial scale of the pathways is the municipal forest of Sivry-Rance. Finer scales were used to delineate the objective series and the forest stands but larger scales were not directly considered except the interactions of the forest with the world scale thanks to the two climate change scenarios. We could have considered the impacts of other processes occurring at larger scales. For instance, we could have changed the population density, the road network around the municipal forest of Sivry-Rance and the public transportation in different scenarios to study their impacts on the ES Recreation and the others. This means also extending the scale of the pathways to a larger scale than the municipal forest of Sivry-Rance and integrating other influencing factors that can vary in the pathways. To continue the previous example, when assessing the indicator of the Recreation supply of the ES Recreation, we could have considered other factors such as the accessibility of the forest by car and public transport.

2.4.1.3 Temporal scale

Some of the methods (i.e. socio-cultural values, TCM, contingent valuation and forest attendance) were only assessed for the actual state of the municipal forest of Sivry-Rance because we did not have the data to assess how their corresponding indicator would evolve in the pathways. To gather these data, in the surveys, we could have asked the respondents how their socio-cultural values, travelling, preferences and their WTP would have changed in the different pathways, but it would have increased the length of the questionnaire. For the forest attendance assessment, the camera traps method does not allow assessing how the forest attendance would evolve in the future. In the surveys, we could have asked the respondents if they would go less or more in the forest in the different pathways.

The other methods allowed assessing the evolution of the indicator in the different pathways. The **time frame** of 65 years in our pathways was a good compromise. It was not too far away to ensure that the stakeholders could visualize the future of the municipal forest of Sivry-Rance and it was long enough to focus on long-term planning issues associated with global changes as suggested by Carlsen et al. (2013). However, this time frame should be further extended to better assess the long-term effects of the pathways. For instance, the Profitability management scenario is not tenable in the long-term in terms of wood production as all the valuable trees would be eventually harvested.

This time frame strongly influences the results as the forest and the ES it provides continuously evolve. If we take the example of the indicator of Growing stock for the ES Wood in the Biodiversity management scenario, the growing stock increases progressively as almost no wood is cut until the forest reaches its natural equilibrium. Furthermore, events such as drought or storms would reduce temporarily the growing stock.

From the **participative scenario planning** method, we only gathered the future ideal forest in 2085 of the participants because we did not ask them to think about the continuous evolution of the forest from now to 2085. Scenarios are not static snapshots of future events, but rather include a logical sequence of images of the future and drivers of change (Rotmans et al., 2000). We could have asked the participants to divide their scenario in different times intervals (see Kok et al. 2008) to create a sequence of images of the evolution of the forest (Palomo et al., 2011).

To consider the variation of the **ES** and the **resilience** from now to 65 years, we could have studied the temporal variation of ES over time to understand how the ES, their interactions and their resilience vary through time and how disturbances affect them. We could have either taken snapshots of the municipal forest of Sivry-Rance at regular intervals or modelled its dynamics. The first solution is rather simple. For instance, every 5 years in each pathway, the forest stands are mapped based on how they evolve over 5 years and then the ES are assessed based on these maps to have their values in 2025, 2030, 2035, …, 2065. The second solution is more complex as a model suitable for the municipal forest of Sivry-Rance and to assess the different ES must be found or built and then run. Several models exist or are being developed in Wallonia to model forest dynamics at different scales (e.g. Samsara2 (Courbaud et al., 2015) at the stand level scale or SIMREG (Perin et al., 2021) at the regional scale). Their use at the forest massif scale is currently developed as well as their potentialities to assess several ES (e.g. global climate regulation). An example of the assessment of the resilience of the ES can be found in Cantarello et al. (2017) who assessed the resilience of nine ES using a spatially explicit model of forest dynamics. By modelling the forest dynamics, we could have also studied the ecological resilience of the SES that is currently missing in our analysis. However, these models need further development to integrate a diversity of ES and especially their various values to perform an integrated assessment of the ES.

We did not implement one of these two solutions to assess the changes in ES and resilience over time because we did not have the time and the resources needed, especially for the modelling. We preferred to perform an integrated assessment of the ES and to engage with the stakeholders, which are also both time consuming and resources demanding. However, we are aware that is an important limitation of our current methodology and that this limits the assessment of resilience.

2.4.2 Robustness

The robustness is discussed in terms of the accuracy of the methods and compared the qualitative and quantitative methods. The legitimacy was discussed in Chapter 4 2.1 Step 1: Establishment of a legitimate process.

Participative scenario planning facilitates discussions regarding the future effects of the drivers of change on human well-being, ES and their trade-offs, biodiversity, or other social-ecological components across multiple spatial, temporal or institutional scales (Oteros-Rozas et al., 2015). It enables the participants to deal with problems that involve high uncertainty and complexity, helps them structuring their choices by revealing their possible long-term consequences and the possible solutions (Carlsen et al., 2013; Fish et al., 2011). Indeed, the resilience of the forest, its degradation and the possible solutions (e.g. diversity of forest species adapted to the site) were discussed during the workshop. However, some participants felt powerless in the face of the actual disturbances (e.g. pests and diseases) and did not know what solutions to offer (they felt that they did not have the knowledge). Moreover, the focus was more on balancing the different functions of the forest and the respect between the users than on the future changes and uncertainties.

Having heterogenous groups helps widening the exposure of viewpoints held by the participants and increases the opportunities for learning and capacity building (Bohnet and Smith, 2007). On the other hand, in search of a consensus between the different needs and expectations of the heterogenous members of the group, each group reaches similar ideal forest. This shows that it is possible to find a scenario that answers the various needs of the stakeholders. We could not directly used these six ideal forests to design the six management scenarios as they were too similar while scenario planning is most powerful when a small set of scenarios explore clear and striking differences (Carpenter et al., 2006). We, thus, considered their six ideal forests as one management scenario, the other ones were built based on the stakes of a particular group of stakeholders except the one based on the forest management plan. To directly use the scenarios from the participatory workshop, we could have formed a heterogenous group to obtain a consensus scenario and five homogenous groups to get distinct scenarios representing the stakes of a certain group of stakeholders.

The unavoidable trade-off between the accuracy requested by the science base, which includes high complexity of scientific information, versus the social relevance of the process (Oteros-Rozas et al., 2015) was experienced during the workshop. At first, it was asked the participants to map their ideal forest based on several existing maps (i.e. maps of the forest stands, the sites, the infrastructures and the legal constraints) to obtain quantitative scenarios. However, most of the participants did not feel comfortable with the maps and their information (e.g. the forest species, the sites). It was instead asked to only provide the storyline of their ideal forest. From this qualitative information, we quantified and mapped the scenarios (see Chapter 2 5.1 Six management scenarios).

This participative element of scenario planning improves the quality of the scenarios and also contributes to their acceptance among the users (van der Heijden, 2011). We built the scenarios from the stakeholders' own concerns, which makes them more relevant and increases the likelihood that the findings are used (Carlsen et al., 2013). Thus, the policies designed based on these scenarios are better suited to serve the needs of the stakeholders (Patel et al., 2007). They are more legitimate and equitable (Oteros-Rozas et al., 2015). Indeed, our analysis showed that the best pathway is the one designed by the stakeholders during the workshop, so the one that answers the best their different needs and expectations.

The **people's preferences** are not fixed but are context and information dependent (Tompkins et al., 2008). The methodology, the documents, presentations, etc. that we used during the workshop influenced the preferences given by the stakeholders. For instance, we asked them to work on the ES and not the indicators of the ES to have a reasonable number of items. We thus have the same preferences parameters for all the indicators of an ES while the stakeholders could have different preferences for the different indicators of an ES. A group did not want to fill the acceptable and satisfactory levels of the ES because they said that these levels depend on the indicator considered. The list of ES we gave to the participants strongly influenced the results because they could only give their preferences regarding these particular ES and in the frame of the ES concept. To limit this bias, we could have asked the values they hold to the forest and the preferences regarding these values. Subsequently, we would have related these preferences to the corresponding ES.

The composition of the groups also had an influence on the preferences gathered. If we had formed heterogeneous groups, the preferences gathered may have been completely different (they would have certainly been more consensual). As suggested above, we could have used a mix of heterogeneous and homogeneous groups to gather both contrasted and consensual preferences.

The degree of familiarity of the stakeholder with a certain ES or the awareness of a ES in society influences its weighting (Fontana et al., 2013). Indeed, people have to be aware of an ES to be able to appreciate and request it (Costanza, 2001; Sen, 1995). For instance, all the participants gave a high weighting to the ES Fauna and flora reflecting the importance they all give to the natural aspect of the municipal forest of Sivry-Rance as it was reflected in the surveys of the forest users.

The **socio-cultural values**, gathered in the surveys, are robust. We forced the respondents to make choices between the different values as we asked them to distribute 100 points among the different values. However, this question was not easy to answer (i.e. it is hard to put numbers on intangible values and at the end, sum the points to reach 100).

The **TCM** estimates the direct use value of a recreational site based on the visits that are done in this site. However, the economic value of a recreational site is not restricted to the visits that are done in it but also to other non-use values (e.g. existing or heritage value) (Mayer and Woltering, 2018). This is why we used two other economic methods (i.e. DCE and contingent valuation) to broaden the values taken into account (Brahic and Terreaux, 2009).

Another limitation of TCM is that the relationship between the travel cost and the value of the recreational site is not true for individuals that live nearby the site that can give a high value to the site even if their travel cost is very low (Parsons, 2003). This is why we had to remove the inhabitants harvesting firewood from the analysis because this method was not suited to estimate their economic value as they live nearby the forest. Furthermore, some people choose where they live based in part on the nearness to recreation sites (Champ et al., 2017). These two limitations tend to underestimate the WTP (Champ et al., 2017). We obtained a rather low WTP for a visit (i.e. 8€) compared to other studies. The Agreta project estimated a WTP of 17€ to go to the Ardennes and of 28€ to go to the Natural Parcs of PNDO and PNHF (Abildtrup et al., 2021). These WTP are higher as the respondents travel on average higher distance (i.e. on average 97km to go to the Ardennes and 91km to go to one of the two Natural Parcs) than the distance travelled by the users of the municipal forest of Sivry-Rance (i.e. on average 20km).

An advantage of the TCM is that it is based on the real behaviour of the respondents and not an hypothetical one as in the contingent valuation and DCE (Brahic and Terreaux, 2009). Moreover, this method is little sensitive to the collection of data compared to the two other methods where the formulation of the questions greatly influences the WTP (Champ et al., 2017; Haab and McConnell, 2002). Indeed, in our **contingent valuation** analysis, the price ranges had a high impact on the WTP: the higher it was, the higher was the WTP. Furthermore, we had a high number of protesters (31% of the respondents) and almost half of them were protesters because they already pay enough taxes. This shows the aversion of many people to increase taxes, which leads to a downward bias in value estimates (Champ et al., 2017). We simply removed the protesters from our analysis but Grammatikopoulou and Olsen (2013) demonstrated that removing the protesters led to an underestimation of the WTP. Indeed, it is likely that protesters would state genuinely positive WTP under different circumstances (Grammatikopoulou and Olsen, 2013). Our WTP is thus likely underestimated and represents a conservative value. Other studies also showed the influence of the frequency of payments (e.g. monthly or annual, one time or extend over some other period of time) on the WTP (Champ et al., 2017).

The contingent valuation method has received a significant amount of criticism (Champ et al., 2017; Grammatikopoulou and Olsen, 2013). This method is hypothetical as the people do not actually make a monetary payment (Champ et al., 2017). However, a large number of studies found evidence to support the conclusion that well-conducted contingent valuation studies produce reasonably reliable estimates even if the method still needs to be strengthened (Champ et al., 2017). From these criticisms and given the strong influence of the way the question is asked, the procedure of our contingent valuation was well documented and checks for robustness were performed (i.e. test of the influence of the price range on the WTP, comparison of different methods to estimate the WTP). To test the influence of the question formulation on the WTP, we could have asked twice the question with two different formulations (e.g. adding a dichotomous question in addition to the price range) as it was done by Durand and Point (2000) who found an influence on the question formulation on the WTP. Furthermore, the positive relationship between the WTP and the income found in our analysis supports the positive income sensitivity assumption found in many contingent valuation studies (Champ et al., 2017).

Finally, the influence of certain variables (e.g. respondent environmentalism, distance) on the WTP can be interpreted as proxies either for preferences or for differences in individual circumstances, demonstrating that the contingent valuation studies tap into economic preferences and hence, that the method is adequately construct valid (Carson et al., 2001; Champ et al., 2017). We indeed found the WTP being influenced by several variables (i.e. forest users type, being an inhabitant of the municipality of Sivry-Rance, and to a lesser extent by the number of annual visits).

We aggregated all the respondents in our contingent valuation while the question was adapted to each forest users type (i.e. the improvement of the cultural ES concerns the one for which the respondent was interviewed (e.g. for the hunters, the improvement concerns the hunting infrastructures)). This could introduce a bias as we did not exactly ask the same thing to each respondent. Nevertheless, the influence of the forest type was considered in our analysis (as a variable in the interval regression). Moreover, we could not have performed four different analyses (i.e. one for each user type) as the number of non-protesters respondents was too low for the inhabitants harvesting firewood, the hunters and the fishers.

DCE has the advantage compared to the contingent valuation method to value different attributes and their trade-offs as well as situational change and captures thus more information from each respondent (Adamowicz et al., 1998; Rodríguez et al., 2001). Furthermore, it reduces the potential biases of the contingent valuation methods (Rodríguez et al., 2001), notably the protesting behaviour (Hanley et al., 2001) because the WTP is indirectly determined (Brahic and Terreaux, 2009). Indeed, we only had 4% of protesters in the DCE compared to the 31% in the contingent valuation. To conclude, DCE seems to be ideally suited to inform the choice and design of multidimensional policies (Hanley et al., 2001). We in fact used the results of the DCE to define several indicators of ES and ultimately assessed the different pathways, and to propose several management measures (e.g. increasing deadwood).

However, DCE also has limitations. It requires from the respondents a cognitive effort due to the choice-task complexity (Hoyos, 2010). The choice-set construction affects the results (Adamowicz and Deshazo, 2006). It was thus carefully designed and tested several times. To embrace model uncertainty, we tested several models and chose the best one as advised by Hoyos (2010). The answers of the respondents are hypothetical, and they do not always take into account all the variables (Hoyos, 2010). Indeed, 30% of the respondents said not having considered all the variables in their choice, especially the distance. However, we have demonstrated that it did not significantly influence our results.

Depending on the **method used to assess the ES**, we either get qualitative or quantitative values. All the qualitative values are based on the same ranking scale (i.e. scale of 5 levels ranging from very low to very high) that was used in the second participatory workshop. We chose to have 5 levels to facilitate the assignment of the acceptable and satisfactory levels by the stakeholders. With these 5 levels, we were not able to differentiate close pathways. The assignment of these levels is subjective even if it is based on the levels of the factors influencing the indicator.

The indicators of **Pollinator abundance** and the **Water purification score** are a numerical value, but they are based on qualitative indices, so it is rather qualitative. The Pollinator abundance index is based on a quite complex model from InVEST. Still, there are five limitations of this model discussed by Natural Capital Project (n.d.):

1. The use of central place foraging in the model's pollinator abundance index has yet to be tested empirically;
2. The model does not include the dynamics of bee populations over time and does not account for the order of seasons or the dependence of pollinator abundance in one season on the resources available in the previous season;
3. Some of the factors that influence the bee populations, like habitat disturbances and typical population fluctuations, are not captured;
4. The model does not account for the sizes of habitat patches;
5. The model does not consider the variation in the pollination efficacity of different wild bee species as well as the fact that some bee species could only pollinate some plant species.

They advise to verify empirically the model which was not possible to do due to time and resources limitations. The input data and the results of the model could have been reviewed by experts to improve the quality of the estimations. Several of them were contacted but none of them had the time to provide such expertise.

The Water purification score gives a quite rough estimate but that is sufficient to differentiate the different forest stands and thus compare the twelve pathways. Winn et al. (2015) discussed the following biases of this score: (1) the slope class categories are too broad and simplistic, (2) the movement of water is not modelled, and (3) the width of the habitat patch should be accounted for. A hydrological model established for the Walloon forests still needs to be developed to have better estimations of the ES Water quality & quantity and Control soil erosion and flooding.

For the quantitative values, their accuracy depends on the method used. From the methods of **Data of forest management plan + IPRFW + expertise** and **Total carbon stock,** we got quite good estimations that were enough accurate to differentiate the different forest stands and thus the various pathways. These methods do not provide an estimate of the errors. To assess the errors of the method Data of forest management plan + IRFW + expertise, the estimations could be compared to data obtained from the field but currently, we only have a forest inventory of a few stands. For the Total carbon stock, Latte et al. (2013) compared their estimations with other studies to highlight the possible biases. Their main conclusions were the need to increase the precision of horizon bulk density for soil, of wood basic density and of biomass factor (ratio belowground/aboveground) for living biomass. Furthermore, the use of the harvested timber is not considered while it has a strong influence on the carbon balance (e.g. firewood quickly releases the stored carbon compared to lumber).

From the indicator of the **Fine particles capture**, we got quite rough estimations. The two following biases are discussed by Pairon et al. (2022): (1) for some land covers (i.e. mixed hardwood softwood forest, water body), the deposition rate is uncertain, and (2) the resuspension constant is highly variable in the literature (from 0 to 75%), so the most commonly used constant was considered (i.e. 50%). Thus, field experiment should be conducted to assess more precisely the deposition rate and verify the resuspension constant.

From the **Forest buffer width** and the **Water cycle** methods, we obtained a range of values (a minimal and maximal values) which accounts for the variability in the estimation. Indeed, the literature review performed by Broadmeadow and Nisbet (2004) for the forest buffer width and by Bansept (2013) for the Water Cycle showed a high variability in the values from one paper to another depending notably on the local context of the study (e.g. climatic conditions, management). To have a more accurate estimation of the indicators of the Water Cycle, measures in the field of the evapotranspiration, the precipitation interception and infiltration in different forest stands in Wallonia should be performed. For the forest buffer width, some similar values were found for Wallonia (Leboeuf et al., 2003).

Furthermore, some indicators (i.e. the Growing stock, the Annual volume of harvested timber, the Annual profit from timber harvesting, the Suitability level of the forest with the preferences of the forest users, the Mean annual profit from hunting leases) were designed for the municipal forest of Sivry-Rance. They reflect the local context of this forest. Some other indicators (i.e. the Total carbon stock, the Fine particles capture and the Cultural ES supply) were designed for Wallonia. They are still adapted to this forest, but they do not consider its particularities. The other indicators were not specifically designed for Wallonia (or even Belgium). They have still to be verified for Belgium except for the forest buffer width. For the pollinator abundance, even if the InVEST model was not designed specifically for Wallonia, some input data came for Walloon datasets.

We are not interested in the absolute values of the indicators but rather on the differences between the pathways. So, we do not need very accurate methods, only methods that reveal the differences between the pathways which is the case for most of the indicators except the maximal percentage of evapotranspiration. This indicator has the same value for the softwood and hardwood stands. In general, the indicators that are only based on broad types of land cover were less able to differentiate the pathways.

MCA remains subjective as it relies on the judgement of the decision-making team to define the alternative and criteria and to estimate the evaluation parameters of the criteria (Brander and van Beukering, 2015). The subjectivity of the alternatives selection and the criteria assessment is already discussed respectively in Chapter 4 2.1.3.2.2 Second participatory workshop and Chapter 4 2.3 Step 3: Establish the scope of valuation.

To limit the subjectivity of the evaluation parameters, they were determined by the stakeholders during the second participatory workshop. Furthermore, four evaluation parameters (i.e. four groups of social preferences) were tested in PROMETHEE to see how they influenced the ranking of the pathways. We have seen that the ranking is indeed influenced by the evaluation parameters even if the main trends remain the same.

We also made choices when translating the social preferences into the evaluation parameters that were introduced in the PROMETHEE software. First, the evaluation parameters were defined by the stakeholders on the criteria (i.e. the twelve ES) and not on the indicators. Therefore, we used the same evaluation parameters for each indicator of an ES. We tested two ways of translating the weighting of the ES into the weight of the indicators of the ES and two ways to define the five intervals of the quantitative indicators (see Chapter 2 7.2 Application of the MCA on the municipal forest of Sivry-Rance). They gave similar results demonstrating the low influence of the way the evaluation parameters are translated from the preferences of the stakeholders.

Finally, from all the MCA methods and software, we selected the outranking method and the PROMETHEE software (see Chapter 2 7.1 Selection of the MCA method for a justification of this choice). We could have tested other methods and softwares to study their influence on the rankings of the pathways as suggested by Ananda and Herath (2009). It was not done due to time and resources limitations.

For instance, another outranking method could have been tested such as NAIADE. This tool allows for two types of complementary evaluation: (1) the MCA, where the alternatives are compared based on their performance on the selected criteria, and (2) the social analysis, where the alternatives are compared based on the stakeholders' value judgments (Oikonomou et al., 2011). With this second evaluation, we could have better understood the distributional justice and the potential conflicts between the stakeholders. Furthermore, this method allows using fuzzy sets for the indicators (i.e. a fuzzy set is a class with un-sharp boundaries) (Ananda and Herath, 2009). Instead of assigning a single impact value, the border between positive and negative impacts is not sharp and considers degrees of positive or negative possibility (Phillis and Andriantiatsaholiniaina, 2001). This approach is thus useful to deal with uncertainties (Ananda and Herath, 2009). This would have deepened the resilience analysis by introducing uncertainties in the values of the ES indicators. However, this method was not selected because it does not explicitly take into account the weighting of the indicators (Munda, 2008), reducing its transparency (Saarikoski et al., 2016). Furthermore, the results are more difficult to communicate (Saarikoski et al., 2019).

Another example is kerDST, which is an online tool offering a multi-stakeholder multi-criteria deliberation framework that can be applied to any situation of social choice or debate (Chamaret et al., 2009). Its main outcome is a deliberation matrix that represents, in a transparent way, the process and outcomes of judgements offered by each category of stakeholders, for each scenario across a spectrum of governance or performance issues (Chamaret et al., 2009). This tool could have been directly used during the second participatory workshop by the participants to judge (e.g. satisfactory, poor, intolerable) each scenario in relation to each of the performance issues (i.e. each ES or indicators of ES). This tool was not used because it would have complexified the second participatory workshop: the stakeholders would have first got acquainted with this tool before being able to use it.

2.4.3 Resources efficiency

Stakeholder engagement is time-consuming (Kerkhof, 2001), especially when combining different participatory methods. It is time-consuming for the researchers but also for the stakeholders that were engaged several times which could lead to stakeholder fatigue. However, this engagement is essential to make informed, transparent and legitimate decisions. It needs to be pursued to inform the stakeholders on the progress of the forest management plan and to continuously adapt this plan to their evolving needs and expectations.

Participatory workshops are expensive in terms of time and energy consumption (Oteros-Rozas et al., 2015). The design of the workshop, its organization and its follow-up were time consuming and resources demanding (e.g. two interns where needed for the all process). From the participants, it was also a time and energy investment to come after their daily work to reflect about the future of the municipal forest of Sivry-Rance or the preferences for different ES for more than three hours. The two workshops were quite long for most of the participants.

The **surveys** were also highly resources demanding to design the surveys, to conduct them and to analyse the results (e.g. six interns over 3 years, two tablets).

The time needed to assess the **ES indicators** ranges from a few hours to several months. The resources needed are also highly variable from one indicator to another.

Some indicators (i.e. Water cycle and Fine particles capture) required low resources (the input data were the maps of the forest stands and an Excel file was enough to link each forest stand to its corresponding value) and were rapidly assessed (in a few hours). The indicators of the Forest buffer width and the Water purification score were a bit more demanding because another input data was needed (i.e. the buffer around the river network for the Forest buffer width and the slope map for the Water purification score) and necessitated an expertise in a GIS software.

The literature review can be easily and quite fast performed for anyone who is familiar with this process. Generally, a few papers are enough to gather the information needed because we used review papers that synthetized the findings of the field. When the factors influencing the indicator are collected from the literature review, the levels for each pathway are easily assigned.

For the indicators of the Growing stock, the Annual volume of harvested timber, the Annual profit from timber harvesting and the Total carbon stock, several input data were gathered in addition to the land cover data (e.g. annual growth of the different forest stands on the different sites collected from the data of the forest management plan and the IPRFW modulated by the expertise of several forest experts for the indicator of the Annual volume of harvested timber). These data were then linked to the different forest stands in an Excel file to assess the corresponding indicator. The assessment of these indicators thus necessitated some expertise and time.

The InVEST model of pollinator abundance was time consuming (i.e. several months) and resources demanding (e.g. an intern, several datasets needed, InVEST software) in order to gather all the inputs needed to run the model. This software required to have some expertise in natural sciences and in GIS.

For the method of the suitability of the forest with the preferences of the forest users, the surveys were demanding in terms of time (i.e. over a year) and resources (e.g. several interns, two tablets to administrate them, expertise in the R software for the analyses) to first design the four surveys, then administrate them and finally analyse them, especially for the DCE analysis.

The **PROMETHEE** software is quite easy to use and provides relatively quickly the results (several days of work).

2.5 Step 5: Articulate and communicate valuation outcomes to inform decisions

The implementation of the Navigate framework on the municipal forest of Sivry-Rance allowed improving its management plan in a number of respects. The four typical functions of the forest analysed in forest management plan (i.e. economic, social, ecological, and hunting) were decompartmentalized. The ES integrated assessment showed that each ES has different values that need to be acknowledged and how a measure designed to improve one of the four functions has impact on the three others. This analysis also highlighted the importance of the social function which is generally little studied in forest management plan.

Indeed, the main added value of this framework to the forest management plan is the comprehensive analysis of the socio-cultural aspects. The comprehensive assessment of the cultural ES objectified their supply, use and demand to assess how well the actual forest and its socio-cultural infrastructures answer the needs of the various stakeholders. Measures are taken in the forest management plan to improve the forest and its infrastructures in this direction (e.g. design of new trails, increasing the amount of deadwood). The needs and expectations of the stakeholders were revealed. This has an impact on the stakeholders: they understood the stakes of the other stakeholders and the possible negative impacts of their needs and the corresponding actions they want to take in the forest on the other stakeholders. This highlight the necessary and appropriate compromise between the needs of the different stakeholders: it is not possible to answer, at a maximal level, all the needs of the different stakeholders but it is possible to answer, at an acceptable level, their various needs. The stakeholders also understood the constraints of forest management (e.g. legal constraints) and why some of their suggestions were not feasible. The owner and manager of the forest better understood the different stakeholders (their needs, expectations, values) and correspondingly, designed a forest management plan suited to them. To continue the dialogue with the stakeholders, appropriate communication (e.g. outreach, critical mind, openness) on the management of the forest should be pursued.

Nevertheless, stakeholder engagement remains consultative because the municipality of Sivry-Rance is the decision maker and values this role. Moreover, the closed procedure of forest management plan limits stakeholder engagement in a consultative role.

3. Implications for forest management

Based on the results of the ES and resilience assessments as well as management measures recommended in the scientific literature, measures to improve respectively the ES, the resilience including the resilience of ES of the municipal forest of Sivry-Rance are discussed. Then, a synthesis of the recommended measures is provided.

3.1 Measures to improve the ES

It is tricky to provide general recommendations for ES management as it is highly dependent on the results of ES assessment. Still, some broad guidelines can be followed such as the maintenance or restoration of the proper functioning of ecosystems because it forms the basis for ES supply (Bouma and Van Beukering, 2015; Chapin, 2009).

Based on the ES assessment in the current state and in the twelve pathways, specific recommendations are given to improve each ES separately. The synergies and trade-offs of these measures on the ES are then discussed.

Concerning the **ES Wood**, the best management scenario for all the indicators is the Users' Forest where high quality wood is produced and where some areas are dedicated to wood production to obtain the highest income (see Chapter 3 3.6.2 for a more detailed description of the silviculture of this scenario). This scenario has the highest income compared to the annual volume of timber harvested and promotes other ES. The annual growth is harvested each year to ensure a regular income on the long-term as it is done now in the municipal forest of Sivry-Rance and proposed in the forest management plan.

The wood market was not considered in the pathways, but some general recommendations can be given: (1) the use of timber should be promoted by advertising it, and (2) its local valorisation should be improved by developing and diversifying the selling methods, the transformation and local valorisation tools. In the municipal forest of Sivry-Rance, the most common selling method is the public tender along with the auction for the firewood to the inhabitants and a private sale for the local sawmills. These two last selling methods could be further developed, and new methods could be tested such as the logyard or the supply contract. (SPW Environnement, 2023)

To limit the harvesting impacts, a permanent exploitation network is currently being designed in the municipal forest of Sivry-Rance. Hauling horses is also used for the thinning timber on the sensitive soils (e.g. wet soil, slope).

For the **ES Hunting**, it is not possible to maximize all the four indicators because the improvement of some factors for an indicator decreases another indicator. For instance, to increase the mean annual profit from hunting and the level of satisfaction of the hunters, hunting is promoted but it decreases the habitat quality for game and the deer impact mitigation because the game is more disturbed. Hunting from a hide or tracking could be promoted to decrease the disturbance on the game even if these two methods might be less appreciated by the hunters. Nevertheless, some common ground can be found for all the indicators: (1) well-developed ground vegetation, shrubs and bushes, (2) a heterogenous forest cover (with open areas and dense forest), (3) a mix of forest species mainly hardwood species with some softwood ones, (4) a network of ponds, (5) natural edges, and (6) a restriction of the recreation activities. To limit the conflicts between the hunters and the recreation users, an awareness campaign should be designed to explain the role of hunting and why it is important for the sustainability of the forest.

For the **ES picking**, both the indicators are maximized in the Biodiversity management scenario because timber harvesting is very limited and it promotes (1) forest species diversity, (2) a diversity of ages, (3) shrubs and bushes, and (4) deadwood in all its forms. To further improve this ES, some additional measures can be taken: increasing (1) the spatial heterogeneity of the forest cover, (2) the landscape heterogeneity, and (3) landscape connectivity by diversifying the silvicultural methods and by promoting hedges and bands of trees in the open areas.

For the **ES fishing**, we only assessed the suitability level of the forest with the preferences of the fishers. The indicator is maximized in the Recreation management scenario because the forest is a hardwood forest with some natural open areas and where deadwood is promoted and where the fishing infrastructures are well maintained. To further improve this indicator, the other recreation activities, during the fishing season, could be restricted to preserve the calm and quiet. Based on ES assessment, we cannot offer other recommendations. Nevertheless, the forest management plan of Sivry-Rance suggests some management measures for the fishes (e.g. laissez-faire on the banks of the Vivier pond so the natural vegetation can grow)

(Colson and Baix, 2021)) but it does not impact the supply of the ES Fishing because the restoration measures are taking place where fishing is not permitted.

The Recreation, Biodiversity and Multifunctional forest management scenarios maximize the ES **Water quality and quantity** because they promote a riparian forest composed of native hardwood forest species with a well-developed root system and with a light cover (e.g. birch, alder, oak), with a diversity of ages and forest covers (some open areas), with a well-developed ground vegetation and old trees (Broadmeadow and Nisbet, 2004). The management of the riparian forest with selective thinning is essential to avoid overshading (50% of the river must be lit) (Broadmeadow and Nisbet, 2004). From the two other indicators, we only know that hardwood should be promoted.

For the ES **Control of soil erosion and flooding**, the riparian forest should also be promoted. In the rest of the forest, a mixed of hardwood and softwood species is recommended. The measures taken to limit soil compaction (i.e. permanent exploitation network and hauling horses) will be beneficial to this ES. Leaving the forest residues from harvesting is also recommended to limit run-off (Broadmeadow and Nisbet, 2004).

For the ES **Fauna and flora**, the riparian forest should also be promoted. From the three other indicators, some recommendations can be given: (1) promoting forest species, genotypic and ages diversity, (2) protecting and restoring the natural habitats, (3) developing the natural open areas, (4) promoting deadwood, (5) developing the ground vegetation, and (6) increasing landscape heterogeneity notably by diversifying the silvicultural methods. In general, management for biodiversity, especially functional diversity, likely improves the other ES but the relationships between biodiversity and ES are complex and non-linear (here are some examples of research that studied the links between ES and biodiversity: Balvanera et al. 2006, Bullock et al. 2011, Brockerhoff et al. 2017, Girardello et al. 2019, Slade et al. 2019) (Bouma and Van Beukering, 2015; Daily, 1999; Diaz et al., 2011). Indeed, the Biodiversity management scenario does not maximize all the ES, especially some indicators of provisioning ES. Even for the ES Fauna and flora itself, this scenario does not maximize all the indicators because some measures can promote some species and be detrimental to others (e.g. wild bees like old stands with deadwood while the old stands decrease the forest undesirable species regulation).

For the ES **Climate regulation and air purification**, for the Fine particles capture, softwood should be promoted. It is also interesting to promote softwood to increase the buffering capacity of the forest in winter or even in summer with a higher forest cover and density (De Frenne et al., 2021, 2019; Frey et al., 2016; Haesen et al., 2021; Zellweger et al., 2019). However, these softwood stands should be managed under the principles of continuous cover forestry to increase their structural complexity, the height of the stand, and to maintain their cover over time. Thanks to their higher density, softwood stands stock also more carbon especially if they are managed under the principles of continuous cover forestry.

For all the **cultural ES**, unsurprisingly, the best management scenario is the Recreation one because it promotes a continuous uneven aged hardwood forest or with natural open areas, with deadwood, a high forest species diversity, numerous water bodies and with a high biodiversity. The recreation infrastructures are enough developed and well maintained. The historic and cultural elements are promoted. A standard information system is in place and local products are available. However, the calm and quiet could decrease with an increase of the recreation users. Measures to improve recreation are proposed in the forest management plan: (1) development of new trails, (2) maintenance and improvement of the signposting, (3) maintenance of the recreation infrastructures, and (4) improvement of communication. To decrease the conflicts between the different recreation users, some trails are designed for a specific recreation user (e.g. biking trail and equestrian trail).

We developed the management measures for each ES separately. However, the interactions between ES need also to be considered: in ES bundles, the management of some key ES is sufficient to maintain other synergetic ES while the inevitable trade-offs between ES should be incorporated in the management decisions (Chapin, 2009). We also must consider the social dimension to promote the ES needed by the stakeholders. From the ranking of the pathways, we have seen that the best management scenarios are the Multifunctional Forest and the Users' Forest. Therefore, the forest management plan of the municipal forest of Sivry-Rance is already beneficial to supply the ES needed and should be followed.

However, some additional measures should be implemented to further improve the ES supply (some of these measures come from the Users' Forest management scenario):

- Increasing the forest cover heterogeneity and landscape heterogeneity by diversifying the silvicultural methods (i.e. some areas should be dedicated to wood production with the plantation of productive species and an objective tree silviculture, others should be multifunctional following the principles of continuous cover forestry, the areas dedicated to nature conservation and restoration should be a bit increased as well as the ones dedicated to recreation) and by promoting mixed hardwood and softwood stands in the productive areas;
- Increasing the amount of deadwood;
- To limit the conflicts between the users, some areas could be dedicated to a specific recreation activities (e.g. in the recreation areas, hunting is performed from a hide or by tracking early in the morning or late in the night during the week when no cultural or sportive event is organized while in the hunting/fishing areas, the other recreation activities are restricted during the hunting/fishing season).

It is also essential to improve communication to limit the conflicts between the users and to inform on the management. Stakeholder engagement should also be pursued to ensure regular social commitment (Swanson and Chapin, 2009) and to adapt the management plan to the evolving needs of the stakeholders.

3.2 Measures to improve resilience

General measures to improve resilience are first given. Then, their implementation in the municipal forest of Sivry-Rance is discussed.

Managing for resilience focuses on enhancing or maintaining the resilience of the desirable attributes of the system rather than implementing one or several restrictive management options (Chapin et al., 2009a; Walker et al., 2002). In that sense, general principles have been developed:

1. Recognizing change and uncertainties and the continuously evolving nature of the system (Chapin et al., 2009a; Seidl, 2014);
2. Encouraging some disturbances to reduce the vulnerabilities to other disturbance at larger scales (Chapin et al., 2009a; Seidl, 2014);
3. Accounting for the trade-offs between the short and long terms solutions (Maru et al., 2014; Rist and Moen, 2013);
4. Integrating the social and ecological dimensions by engaging the stakeholders (Swanson and Chapin, 2009) and by recognizing the human role in disturbances (Ruhl and Chapin, 2014);
5. Diversifying the management options (Chapin et al., 2010; Seidl, 2014) as well as enhancing biological (Elmqvist et al., 2003; Perrings and Kinzig, 2018) and socio-economic diversity (Chapin et al., 2009c) to sow the seeds of future options (Swanson and Chapin, 2009);
6. Keeping the doors open and guaranteeing flexibility (Chapin et al., 2009a; Folke, 2016);
7. Learning continuously (Ballard and Belsky, 2010) and using the past as a laboratory for innovations (Redman, 2014);
8. Recognizing cross-scale effects (Folke, 2016; Walker and Salt, 2012a);
9. Sequencing the interventions (Walker and Salt, 2012a);
10. Identifying pragmatic solutions that increase the probability of beneficial results and reduce adverse results, and balancing the benefits and the costs of management solutions (e.g. actions can increase resilience of some parts and reduce resilience of other parts) (Folke, 2016; Walker et al., 2002).

All these general principles must be applied with caution depending on the context and the advances in research. For example, the relationships between resilience and biodiversity are still being debated in the literature (e.g. De Boeck et al., 2018; Newton, 2016; Norgrove and Beck, 2016; Oliver et al., 2015). Depending on which property of resilience is targeted (i.e. reducing risk, adapting or transforming), these general principles should be applied differently and some may be more relevant than others. First, reducing risk means identifying them and lowering their magnitude, the exposure and sensitivity to them (Chapin et al., 2009c). Diversifying and broadening the range of opportunities reduce, in general, the vulnerability of the system to stress (Chapin et al., 2009c). Then, to adapt, the adaptive capacity should be enhanced thanks to the socio-economic and biological diversity, learning and flexibility (Chapin et al., 2009a; Walker et al., 2002). Finally, to transform, actions are undertaken to reconfigure the system by introducing a new set of dynamics that operates within specified desirable values over the long term (Redman, 2014). Three ingredients are necessary for transformation according to Walker et Salt (2012a): (1) preparedness for change, (2) having the options for change, and (3) having the capacity to change. Careful planning with the stakeholders is needed to assess the risks of good and bad results, the transparent navigation into the transformational processes and to ensure answering societal goals (see Folke et al. (2009) for detailed strategies to navigate the transformation).

Some of these general principles are an integral part of the Navigate framework: this framework recognizes changes and uncertainty (principle 1) and the interactions between the scales (principles 3 and 8) and integrates the social and ecological dimension by engaging with the stakeholders (principle 4). The interactions between the scales should be further analysed. The analysis of the changes over time of the forest, its ES and its resilience proposed in Chapter 4 2.4.1.3 Temporal scale would help understanding the trade-offs between the short and the long term solutions as well as the cross-scale effects. These cross-scale effects can be further studied by extending the spatial scale of the analysis as proposed in Chapter 4 2.4.1.2 Spatial scale.

Others general principles are applied in the forest management plan. This plan promotes biodiversity with several measures (e.g. designation of wilderness areas, restoration actions) and enhances socio-economic diversity thanks to its multifunctionality to provide a diversity of ES. To further enhance biodiversity, the areas dedicated to biodiversity conservation and restoration should be increased as suggested in Chapter 4 3.1 Measures to improve the ES. To further increase the socio-economic diversity, economic instruments and business models promoting regulating and cultural ES could be promoted with consistent policies as suggested by Hernández-Morcillo et al. (2022). This forest management plan sequences the interventions (principle 9) and identified pragmatic solutions balancing the benefits and the costs (principle 10) from the analysis of the ES and the resilience. As discussed in Chapter 4 2.3 Step 3: Establish the scope of valuation, the assessment of resilience should be improved to better understand the impacts of a management decision on the resilience of the different parts of the system.

The monitoring established in the forest management plan and in the Navigate framework will help keeping the doors open and guaranteeing flexibility (principle 6) as well as promoting learning (principle 7). This monitoring should engage the stakeholders to understand their evolving needs and to continuously communicate as suggested in Chapter 4 3.1 Measures to improve the ES.

The diversifying of the management options (principle 5) has been suggested in Chapter 4 3.1 Measures to improve the ES in addition to the continuous cover forestry proposed in the forest management plan.

Finally, the principle 2 is currently little implemented and is not really discussed in the forest management plan. Therefore, some disturbances should be encouraged in the municipal forest of Sivry-Rance.

The current forest of Sivry-Rance already provides a diversity of ES that answer partly the needs of the stakeholders. The forest management plan and the other measures proposed in Chapter 4 3 Implications for forest management are thus more adaptive measures that improve the supply of the ES and its resilience than transformative measures.

3.3 Measures to improve the resilience of ES

General measures to improve the resilience of ES are given below. Their implementation in the municipal forest of Sivry-Rance is also discussed.

Seven principles to improve the resilience of ES are given by Biggs et al. (2015, 2012):

1. Maintaining diversity and redundancy;
2. Managing connectivity;
3. Managing slow variables and feedbacks;
4. Fostering an understanding of the SES as complex adaptive systems;
5. Encouraging learning and experimentation: the capacity for innovating and understanding change in the SES;
6. Broadening participation to build trust and a shared understanding in order to make decisions;
7. Promoting polycentric governance systems.

Four of these principles (principles 1, 2, 5 and 6) have already been discussed in the previous sections (see Chapter 4 3.1 Measures to improve the ES and Chapter 4 3.2 Measures to improve resilience). The principle 4 is an integral part of the Navigate framework. The other principles need to be further integrated in the Navigate framework. The management of the slow variables and the feedbacks is conducted by understanding and monitoring the slow variables, the feedbacks and the regime shifts. To improve the resilience assessment, we proposed to conduct such an assessment (see Chapter 4 2.3 Step 3: Establish the scope of valuation). The maintenance and restoration of the regulating ES which are linked to the slow variables is also a way forward to implement this principle. The forest management plan and some of the additional measures to improve ES (see Chapter 4 3.1 Measures to improve the ES) and resilience (see Chapter 4 3.2 Measures to improve resilience) will further improve the regulating ES. Finally, the principle 7 is already a bit in place as the forest is managed by the municipality and the DNF. The continuous engagement of the stakeholders proposed earlier (see Chapter 4 3.1 Measures to improve the ES) will also broaden the governance system.

Hernández-Morcillo et al. (2022) propose fourteen solutions to sustain the ES provided by the European forests in response to 9 challenges. Only the solutions of the challenges facing the municipal forest of Sivry-Rance are listed below (one solution was already mentioned in Chapter 4 3.1 Measures to improve the ES and is not discussed here):

1. Promoting climate-smart forestry management;
2. Improving the integration of regulating ES in local and regional planning;
3. Coordinating strategic regional forestry stakeholders to join forces against biological and environmental threats;
4. Developing adaptive strategies to sustain multiple ES based on regional scenarios;
5. Ensuring diversity at different levels (genetic, species, and forest);
6. Establishing regional observatories for capturing societal ES demand and supply;
7. Fostering investments into ES oriented forest management to increase resilience (prevention and adaptation) towards natural hazards;
8. Increasing availability, volume, and accessibility of financial instruments to cover losses from natural hazards.

The first solution proposed by Hernández-Morcillo et al. (2022) is a large-scale strategy, with three main lines of action: (1) the enhancement of natural regeneration and avoidance of deforestation, (2) active forest management, and (3) adaptive forest management to build resilient forests (Nabuurs et al., 2018; Verkerk et al., 2020). The two first lines of actions are proposed in the forest management plan while the last one is part of the measures to improve resilience (see Chapter 4 3.2 Measures to improve resilience).

Most of the other solutions (solutions 2 to 6) are already implemented or suggested. The assessment of ES improves the integration of the regulating ES in local planning (solution 2). Stakeholders were engaged in this study and recommendations are given to continue their engagement (solution 3) and to understand their evolving needs (solution 6). Different scenarios have been analysed in this study to develop adaptive strategies (solution 4). Diversity is promoted in the forest management plan and as an additional measure to improve the ES and resilience (solution 5).

The last two solutions (solutions 7 and 8) should be further developed.

3.4 Synthesis

For all the measures discussed in the three previous sections, a synthesis of the recommended measures to manage the municipal forest of Sivry-Rance to improve the ES, the resilience and/or the resilience of ES is given in **Table 4-2**. We selected the measures that improve the ES, the resilience and/or the resilience of ES and that do not have a significant adverse effect on other ES, the resilience and/or the resilience of ES.

Table 4-2. Synthesis of the recommended measures to improve ES, resilience and/or the resilience of ES of the municipal forest of Sivry-Rance with information on whether they are already part of the forest management plan, their feasibility, scale and where they come from.

Measures	**To improve**	**In the forest management plan**	**Feasibility**	**Scale**	**Information sou[222]rce**
Continuous cover forestry	ES Resilience Resilience of ES	Yes	High	Forest stand	ES asssessment 5th general principle of resilience Hernández-Morcillo et al. 2022 (solution 1)
Diversify silvicultural methods	ES Resilience Resilience of ES	Additional measure	Medium (need to revise the management of some areas)	Forest	ES assessment 5th general principle of resilience Biggs et al. 2012, 2015 (principle 1) Hernández-Morcillo et al. 2022 (solution 5)
Diversify selling methods	ES (Wood) Resilience	Additional measure	Medium	Wood market	ES assessment 5th general principle of resilience
Mix of hardwood and softwood in productive areas	ES Resilience of ES	Yes but need to go further	High	Forest stand	ES assessment Hernández-Morcillo et al. 2022 (solution 5)
Permanent exploitation network + hauling horses + leaving forest residues from harvesting	Regulating ES Resilience of ES	Yes	High	Forest	ES assessment Biggs et al. 2012, 2015 (principle 3)
Zoning of the recreation activities	Cultural ES Resilience	Yes but need to go further	Medium (need to consult the stakeholders to design the zoning)	Forest and its surroundings	ES assessment 5th general principle of resilience
Conservation and restoration actions	ES Resilience Resilience of ES	Yes but need to go further	High	Habitat	ES assessment 5th general principle of resilience Biggs et al. 2012, 2015 (principle 1) Hernández-Morcillo et al. 2022 (solution 5)

Promote deadwood	ES	Yes but need to go further	High	Tree	ES assessment
Manage connectivity	ES Resilience of ES	Additional measure	Low (measures need to be taken outside the municipal forest of Sivry-Rance)	Forest and its surroundings	ES assessment Biggs et al. 2012, 2015 (principle 2)
Recognize changes and uncertainty	Resilience	Navigate framework	High	Forest	1st general principle of resilience
Assess resilience with time series	Resilience Resilience of ES	Additional measure	Medium	Forest stand	3rd and 8th general principles of resilience Biggs et al. 2012, 2015 (principle 3)
Encourage some disturbances	Resilience	Additional measure	Medium	Forest	2nd general principle of resilience
Monitor	Resilience Resilience of ES	Yes but need to go further	Medium	Forest stand	6th and 7th general principles of resilience Biggs et al. 2012, 2015 (principle 5)
Improve communication	ES Resilience Resilience of ES	Yes but need to go further	Medium (means and skills needed to better communicate)	Municipality and DNF	ES assessment 4th general principle of resilience Biggs et al. 2012, 2015 (principle 6) Hernández-Morcillo et al. 2022 (solution 3)
Stakeholder engagement	ES Resilience Resilience of ES	Navigate framework but need to be pursued	Medium	Forest and its surroundings	ES assessment 4th general principle of resilience Biggs et al. 2012, 2015 (principle 6) Hernández-Morcillo et al. 2022 (solution 6)
Promote polycentric governance	Resilience of ES	Additional measure	Medium	Municipality and DNF	Biggs et al. 2012, 2015 (principle 7)
Economic instruments and business models to promote ES and to cover losses of natural hazards	ES Resilience Resilience of ES	Additional measure	Low	Wood market	ES assessment 5th general principle of resilience Hernández-Morcillo et al. 2022 (solutions 7-8)

The measures to improve the ES and the resilience of the forest concern multiple spatial scales ranging from the tree to the forest and its surroundings. Some measures need to be taken at a certain social scale (i.e. municipality, DNF and wood market).

The actual forest management plan of the municipal forest of Sivry-Rance promotes land sharing (i.e. promotion of the supply of multiple ES on the same land (Maskell et al., 2013)) because most of the forest is multifunctional. It allows providing a diversity of ES on a same area. However, this management tends to homogenise the forest stands and can create conflicts between the forest users. Furthermore, on the forest scale, the ES tend to be better supply in the Users' Forest management scenario where some areas are dedicated to production, others to biodiversity, etc. Maebe et al. (2019) also demonstrated that a combination of land sharing and land sparing (i.e. spatial segregation of land dedicated to production from areas prioritised for other ES (Maskell et al., 2013)) is beneficial to improve the ES supply. They advised to have productive forests to maximize wood production on the good soils and to dedicate the wet and peat soils to nature restoration and conservation to maximize regulating and cultural ES. In the remaining areas, where all the ES can be well provided, land sharing was proposed. The triad forest management (i.e. landscape management regime composed of three parts: (1) intensive plantation management, (2) ecological forest reserves, and (3) a matrix of forests managed for multiple uses following the principles of ecological forestry (Himes et al., 2022)) also proposed to combine land sharing with land sparing to improve ES supply and biodiversity. The intensive plantation management provides the timber needed on a smaller area to dedicate other areas to forest reserves needed for some species (Himes et al., 2022). The rest of the forest is open to a plethora of silvicultural approaches that ensure the multifunctionality of the forest by maintaining the ecosystem structures, processes and diversity (Himes et al., 2022).

Therefore, we propose to combine land sharing with multifunctional areas with land sparing where some areas are dedicated to the supply of one or several specific ES without having an adverse effect on the other ES. Several measures proposed in **Table 4-2** (i.e. diversifying silvicultural methods, designing productive areas where a mix of hardwood and softwood species are managed, increasing the areas dedicated to nature restoration and protection, zoning the different recreation activities) are in line with land sparing. The areas dedicated to production on one hand and to nature conservation and restoration on the other hand are given on the map of the objective areas of the Users' Forest management scenario (**Figure 3-62**). For the zoning of the recreation activities, a participatory workshop should be organized with the different recreation users to define the zoning with them. Based on the forest attendance assessment, we can pre-identify the most frequented areas respectively by the hikers, the bikers, and the horse riders to inform the discussion of the workshop.

This combination of land sparing and land sharing also increases landscape heterogeneity which is beneficial for the ES and resilience (e.g. the vulnerability of the hunters to climate change can be reduced by increasing tree diversity to limit the degradation of the habitat quality for game). Furthermore, by diversifying management, this combination can help avoid catastrophic system collapse and loss of biodiversity (Aplet and Mckinley, 2017).

The allocation of the different objective areas should be flexible to account for shits in demand for the ES while a diversity of ES should be maintained (e.g. even if the demand for timber increases, enough areas must still be dedicated to the other ES and biodiversity) (Himes et al., 2022). Furthermore, the wilderness areas may need some managements in the future in response to disturbances (e.g. climate change, invasive pest and disease) creating novel threats (Himes et al., 2022). Finally, monitoring the performance of different silvicultural approaches is recommended to have a more adaptive and resilient forest where empirical data complement the experience and intuition of foresters (Himes et al., 2022).

All these measures by promoting resilience and the ES guarantee the sustainability of the forest by ensuring that the forest functions properly (i.e. provides the different ES) and answers the actual and future needs of the stakeholders.

Chapter 5

Conclusion and future perspective

The Navigate framework validates our central hypothesis: **coupling ES and resilience** is valuable in the quest toward sustainability. Indeed, these two concepts mutually reinforce each other (first assumption of this doctoral research). ES operationalize resilience and give a direction (i.e. which ES we want to maintain for whom) while resilience offers a dynamic and system perspective to take sustainable actions.

Their pairing should not be limited to incorporate one concept in the frame of the other but rather coupling them. Adaptations of existing concepts remain largely framed within the limits of the concept and its frame (Breyne, 2021). As Malmborg (2021) stated we should acknowledge the limitations of the ES concept to expand nature valuations with other concepts or tools. This doctoral research showed how the ES concept limited the inclusion of the different forms of human-nature interactions by focusing mostly on the instrumental values of nature. This concept does not fundamentally change the dominant human-nature relationships: it stays within and reinforces the dominant existing frames of human-nature relationships that organize western societies (Breyne, 2021). Several concepts and tools were used in this doctoral research to expand the ES concept: (1) resilience, (2) the socio-cultural values, (3) survey, (4) participatory workshop, and (5) MCA. Resilience forces us to take a step back and look at a larger scale than the forest and its ES. Stakeholder engagement allowed studying various forms of human-nature interactions by eliciting the broad values and specific values of the stakeholders regarding the forest and not only its ES. MCA offered an integration of all these concepts and tools without occulting the different values of nature.

Nevertheless, this doctoral research used the ES concept as a starting point which limited the true pairing of ES and resilience and the inclusion of all the forms of human-nature interactions. Resilience was mainly framed according to the ES (in its definition and assessment). The resilience concept should be further integrated in the framework notably by assessing its different forms (e.g. ecological resilience). The valuation of the human-nature interactions should also be further broadened, for instance, by following the guide on value assessment of IPBES (2022) and its corresponding 5-step valuation framework.

The second assumption (i.e. various methods including stakeholder engagement are needed to capture the multiple dimensions of ES and resilience) was also validated. The Navigate framework shows the importance of using **a variety of methods** to assess both ES and resilience to acknowledge value pluralism. This framework provides a quite simple operational tool with a set of complementary methods to assess ES and resilience to get a fuller picture of the SES and its dynamics. However, this integrated assessment of ES and resilience remains a complex exercise because of the need to use several complementary methods and because the resilience concept remains difficult to translate into practice. Because of this complexity, the joint assessment of ES and resilience is time consuming, resources demanding, and face several gaps.

Indeed, simple and fast ES assessment methods needed to perform an integrated assessment still not enough consider other factors influencing the supply of ES than the land cover. Furthermore, the land cover is too often reduced to broad classes while finer classes are needed to better discriminate ES supply and demand. We have demonstrated that ES assessment methods should at least consider the ecological context and the management that greatly influence ES supply (Maebe et al., 2019). Furthermore, the drivers of change such as climate change should also be integrated into ES assessment methods. There is still a lack of Walloon data (e.g. quantity of fine particles captured by the vegetation) and models (e.g. hydrological model for the Walloon forests) to verify the results of our ES assessment.

The gaps are even more pronounced in the resilience assessment where data and methods are even more scarce. We have no really data on the resilience of forests, of their ES and of their stakeholders in Wallonia. Models of the dynamics of the Walloon forests are being developed but they need to be broadened to understand the dynamics of the ES and human society. This is why the assessment of resilience in the Navigate framework is the prior area of improvement to broaden the methods to assess resilience (e.g. modelling, STM).

We also demonstrated the importance of having a **social perspective** which is still insufficiently considered in social-ecological research (Bretagnolle et al., 2019). We need to include the stakeholders in a participatory process to be sure that the chosen pathway fits with the different needs of the stakeholders and to have the multiple skills needed to navigate in these turbulent waters. The Navigate framework facilitates stakeholder engagement by schematizing and illustrating concepts that may at first sound complicated and vague and by providing guidelines and examples of participatory methods.

Several outcomes regarding forest management came out from the implementation of the Navigate framework and validated the third assumption of this doctoral research (i.e. one-fits-all solution does not exist: multiple solutions and compromises are the way forward).

First, some **management guidelines** aiming at better providing the ES also increase resilience and vice versa (i.e. continuous cover forestry, conservation and restoration actions, improving communication, stakeholder engagement, and economic instruments and business models to promote ES and to cover losses of natural hazards). These guidelines should be first and foremost implemented because they are the most beneficial ones.

Secondly, **land sharing and land sparing** should be combined to ensure the supply of a diversity of ES. With land sparing antagonist ES can be provided on different areas while synergetic ES can be supplied in the land sharing areas. This combination of land sharing and land sparing is also beneficial for resilience by increasing landscape heterogeneity and the diversity of management interventions and ES.

Finally, there is **no single best solution**. No management strategy provides all the ES needed by the different stakeholders. Therefore, compromise oriented negotiations are the only feasible alternative in the face of the irreducible plurality of values (Saarikoski et al., 2016). Furthermore, considering uncertainties and the changes the SES undergoes, multiple solutions should be implemented and constantly adapted to the changes (e.g. evolving demand for ES or climate change) (Chapin et al., 2010, 2009a).

The **agile design** of the Navigate framework allowed us to adapt continuously our framework to the scientific advances (gathered from the literature review and the interviews with leading experts on the concepts of ES and resilience) to have an up-to-date framework. As science continues to advance, the Navigate framework should be adapted after each use. For instance, the results from IPBES (2022) (e.g. values assessment typology, 3R to assess the assessment methods) should be further integrated in the Navigate framework. They were included in this doctoral research but not directly in the design of the Navigate framework.

The high flexibility and responsiveness of our framework development to the case study strengthened its capacity to respond effectively to the realities on the ground (notably to the ones of the stakeholders). On the other hand, the case study influenced the Navigate framework making it less adaptable to different application contexts. The conceptual part of the Navigate framework and the six-steps procedure of the operational part of the Navigate framework are broad enough to be easily implemented in other contexts. On the contrary, the methods and their results were profoundly influenced by our case study. They can be easily adapted to other forests, but they need a significant revision for other ecosystems. In particular, other drivers should be considered; the list of ES and their corresponding stakeholders should be reviewed; some assessment methods (e.g. forest buffer width, carbon stock) cannot be applied and other methods to assess these ES need to be found. The framework should be applied to other contexts (e.g. other ecosystems, regions) to see if some adjustments must be made.

We have seen that other frameworks pairing more or less closely the ES and resilience concepts have been developed in the last years (e.g. Wayfinder by Enfors-Kautsky et al., (2021), the analytical framework for resilience in regional management of Li et al. (2020), or the conceptual framework illustrating the linkages between scenarios, models and relationships among ES for informing decision-making by Ikematsu and Quintanilha (2020)). Each framework has its own strengths and limitations. To answer the actual complex and intertwined sustainability problems, we believe that each framework can contribute. Our framework does not intend to supplant the others but rather work together with them to find better solutions. In our opinion, all these frameworks are part of the solution, and we should select the best one depending on our context, knowing that in another context, other frameworks could be more appropriate. To help selecting the best framework(s), further research should be done on analyzing the existing frameworks based on several criteria (e.g. problems answered by the framework, resources needed to implement it (e.g.

knowledge and skills, time, money), its user friendliness) and giving guidance on which framework(s) used in which situation.

With the Navigate framework, we propose a **decision-support tool** to explore different management strategies to find the best solutions regarding the local context and the increasing uncertainty.

This framework provides evidence on the multiple benefits of the forest (i.e. its multiple ES, relational, intrinsic and instrumental values) and on how a decision designed to maximize one particular ES or value can have impacts on the other ES and values and their corresponding stakeholders as well as on resilience (of the forest, of its ES and of the stakeholders). This evidence combined with stakeholder engagement can trigger change in the political sphere.

However, it has been showed that so far the ES concept has not lead to transformative change of human-nature relationships (Muradian and Gómez-Baggethun, 2021). Indeed, the application of this concept tends to reinforce the existing frames and regimes of social organization and do not fundamentally question current human-nature relationships in view of the required changes (Breyne, 2021). Furthermore, in view of the needed transformative change, it would be wise not to bet on the very same frame for providing all solutions (Breyne, 2021). Thanks to stakeholder engagement, we were able to broaden the forms of human-nature relationships considered. The resilience concept also widened the analysis and demonstrated the need for transformative change.

This transformative change was not needed in the municipal forest of Sivry-Rance where an adaptation of the actual management is enough (according to our analysis) but is needed in the design of forest management plan to better integrate the multiple human-nature interactions and their future developments. In the actual separate analysis of four functions (i.e. economic, hunting, ecological and social), the forest is mainly seen in a utilitarian way where profitability (from wood harvesting and hunting) is at the core of forest management. Our analysis demonstrated that the instrumental value, mainly considered in forest management plan, was not often the main value hold by the stakeholders: the relational and/or intrinsic values were important for most of the stakeholders. Together, they also want a diversity of ES: forests must not be limited to wood production and hunting. Further communication should be performed to disseminate these results. For instance, a presentation to the DNF together with the person in charge of the forest management plan of the municipal forest of Sivry-Rance is envisaged.

However, this evidence-based knowledge is not alone sufficient to induce the required changes because of other lock-ins that impede such changes (Blicharska et al., 2020). Changes require agency (i.e. capacity to act in an independent way and to make free choices (Waeber et al., 2021)), advocacy (i.e. activities that aim to influence decision-making processes) combined with other impulses to overcome these lock-ins (Breyne, 2021). Stakeholder engagement gives agency and advocacy to the stakeholders to induce such changes. Indeed, the municipality of Sivry-Rance and the

DNF decided to adapt the forest management plan to answer certain expectations of the stakeholders.

Moreover, the person in charge of the forest management plan of Sivry-Rance saw a real added value of the Navigate framework especially in the integration and objectivation of the social aspects. She is willing to apply this framework on other case studies. The Navigate framework is currently applied on another forest management plan in a master thesis. To expand the implementation of the Navigate framework to forest management plans, resources (persons and skills) are needed. In its present state, the Navigate framework is extremely resource intensive.

To facilitate its uptake, a handbook should be made with three versions of the Navigate framework (i.e. a light, medium and extended version) depending on the size of the project. The three versions would follow the six steps of the Navigate framework but the extend of the methods is adapted to the resources at hand. In the light version, the system is defined (step 1) and the problem, stakes and goals are identified (step 2) based on a quick review of the existing literature completed by the knowledge of the project team. This analysis should highlight the most predominant drivers to design the pathways (step 3). The assessment of the ES (and other forms of human-nature interactions) (step 4) should be based on stakeholder engagement (e.g. a survey or a participatory workshop) to select the list of ES (a small list of the most important ES) and understand the preferences of the stakeholders. To assess the ES and resilience (steps 4-5), several existing low resources demanding tools should be used to assess different values. In the medium version, stakeholder engagement should be deepened to support the steps 1 (analysis of the stakeholders), 2 and 3. In steps 4 and 5, the methods to assess ES and resilience should be expanded to medium resources demanding tools.

In the extended version, the current version of the Navigate framework should be used together with the proposed improvements (e.g. values assessment guide of IPBES (2022), models to assess resilience). This extended version is not directly applicable by the DNF for their forest management plan design because its implementation is time consuming and resources demanding. Therefore, it is only applicable for researches or projects that have significant resources and managed by a transdisciplinary team, including researchers of different disciplines and the stakeholders, to have the different skills needed to improve the current version.

On the contrary, the light or medium version of the Navigate framework could be directly followed to design forest management plan depending on the resources at hand. Indeed, in current forest management plans, the steps 1,2 and 6 are already carried out. Small adjustments are needed to perform these three steps in the frame of the Navigate framework (e.g. deepen the analysis of the system dynamics, interactions and scales in step 1, include stakeholders in steps 1 and 2 in the medium version, propose measures that improve ES and resilience in step 6). Steps 3 and 4 are only lightly touched in current forest management plans. Currently, one pathway is designed, others should be added to test different management strategies and include the most predominant drivers. The assessment of ES should be broadened to include the diverse values and even extended to other forms of human-nature interactions. Finally, the assessment of resilience (i.e. step 5) is a completely new step to be added to forest management plan design.

To facilitate the integration of the Navigate framework in forest management plan design, an analysis of the current barriers that impede the implementation of this framework should be undertaken. To overcome some of these barriers (e.g. legislation, lack of relevance or feasibility), the integration of the Navigate framework in forest management plan should be co-designed with the DNF. Communication is also crucial to overcome other barriers (e.g. training or a user-friendly handbook to give the necessary knowledge to the DNF).

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Annexes

Annex 1. Individual table filled by the participants of the second participatory workshop to give their opinion and weighting of the ES provided by the municipal forest of Sivry-Rance.

	SERVICES OFFERTS PAR LA FORÊT		Entourez votre OPINION	IMPORTANCE : Distribuez les 100 points
1		Sol de qualité protégé de l'érosion et des inondations	↗ ↘ 😐	
2		Protection de la faune et de la flore	↗ ↘ 😐	
3		Emblème d'un patrimoine culturel collectif (identité régionale à travers des espèces ou paysages emblématiques...)	↗ ↘ 😐	
4		Chasse d'animaux sauvages	↗ ↘ 😐	
5		Récolte de plantes (jonquilles, ail des ours...), champignons (chanterelles...), animaux (insectes, plumes...)	↗ ↘ 😐	
6		Environnement naturel à proximité de lieux de vie (école, bureau, domicile)	↗ ↘ 😐	
7		Observation de la nature, activités de découvertes (classes vertes...) et de recherche, source d'inspiration (film...)	↗ ↘ 😐	
8		Eau de qualité en quantité suffisante	↗ ↘ 😐	
9		Limitation du changement climatique, climat local (la forêt garde une atmosphère plus fraîche l'été...) et air pur	↗ ↘ 😐	
10		Pêche (poissons et crustacés)	↗ ↘ 😐	
11		Activités quotidiennes et de loisirs de plein air (course à pied, promenade...)	↗ ↘ 😐	
12		Bois d'œuvre (ameublement, charpente…), d'industrie (papier…) et de chauffage	↗ ↘ 😐	

Annex 2. Collective table filled by the four groups of the second participatory workshop to give their opinion, weighting, acceptable and satisfactory levels of the ES provided by the municipal forest of Sivry-Rance.

	SERVICES OFFERTS PAR LA FORÊT	Entourez votre OPINION	IMPORTANCE : Distribuez les 100 points	Pour vous, le service rendu est					
1	Chasse d'animaux sauvages	↗ ↘ 😐		Acceptable à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
				Satisfaisant à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
2	Récolte de plantes (jonquilles, ail des ours...), champignons (chanterelles...), animaux (insectes, plumes...)	↗ ↘ 😐		Acceptable à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
				Satisfaisant à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
3	Pêche (poissons et crustacés)	↗ ↘ 😐		Acceptable à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
				Satisfaisant à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
4	Bois d'œuvre (ameublement, charpente…), d'industrie (papier…) et de chauffage	↗ ↘ 😐		Acceptable à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
				Satisfaisant à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
5	Eau de qualité en quantité suffisante	↗ ↘ 😐		Acceptable à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
				Satisfaisant à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
6	Sol de qualité protégé de l'érosion et des inondations	↗ ↘ 😐		Acceptable à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
				Satisfaisant à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
7	Protection de la faune et de la flore	↗ ↘ 😐		Acceptable à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
				Satisfaisant à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
8	Limitation du changement climatique, climat local (la forêt garde une atmosphère plus fraîche l'été...) et air pur	↗ ↘ 😐		Acceptable à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
				Satisfaisant à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
9	Environnement naturel à proximité de lieux de vie (école, bureau, domicile)	↗ ↘ 😐		Acceptable à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
				Satisfaisant à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
10	Activités quotidiennes et de loisirs de plein air (course à pied, promenade...)	↗ ↘ 😐		Acceptable à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
				Satisfaisant à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
11	Observation de la nature, activités de découvertes (classes vertes...) et de recherche, source d'inspiration (film...)	↗ ↘ 😐		Acceptable à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
				Satisfaisant à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
12	Emblème d'un patrimoine culturel collectif (identité régionale à travers des espèces ou paysages emblématiques...)	↗ ↘ 😐		Acceptable à partir de	Très bas	Bas	Moyen	Elevé	Très élevé
				Satisfaisant à partir de	Très bas	Bas	Moyen	Elevé	Très élevé

Annex 3. Question about the socio-cultural values asked in the second participatory workshop and in the surveys of the forest users.

Les valeurs que vous accordez à la forêt de Sivry-Rance :

Imaginez que vous ayez 100 points et que vous puissiez les attribuer librement aux valeurs listées ci-dessous selon leur importance respective. Il est possible d'attribuer tous les points à une même valeur, ou de les répartir autrement, mais la somme des points doit être égale à 100.

La forêt de Sivry-Rance est importante pour moi…

… car elle m'inspire et est un lieu **d'enchantement** qui me fait me **sentir mieux**, physiquement ou mentalement. ☐

… car elle fournit des **produits économiques** comme du bois, du gibier, des champignons, … ☐

… dans la **lutte contre le changement climatique** et car elle maintient mon cadre de vie sain en aidant à produire, préserver, renouveler l'air, le sol et l'eau. ☐

… car elle fait partie d'un **patrimoine culturel** au même titre que les villages, châteaux, abbayes et participent à l'histoire de la région. ☐

… car elle me fournit un espace pour mes **activités récréatives** comme le quad, 4x4, pistes et concours VTT, trail de masse, … ☐

… car elle m'offre un lieu où je peux tisser/**renforcer des liens sociaux** (sorties en famille, entre amis, environnement de travail, …) ☐

Je ne me sens **pas à l'aise** en me promenant ou en pensant à la forêt de Sivry-Rance car elle génère des **peurs** (peur de me perdre, peur de me retrouver seul, lieux noirs et sombres, …) ☐

… car elle **crée des emplois** par sa mise en **valeur touristique**, ce dont je peux bénéficier en tant qu'usager ou acteur de la filière touristique. ☐

… car elle me fournit un espace pour mes **activités d'extérieur** comme la randonnée, les circuits vélo/VTT, l'observation de la faune et de la flore, … ☐

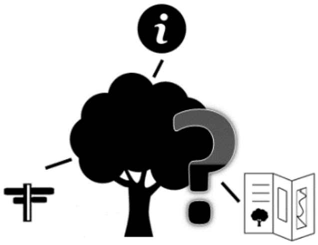
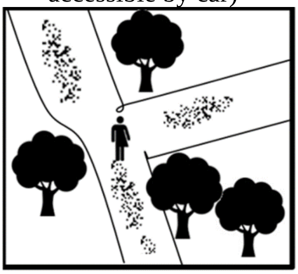
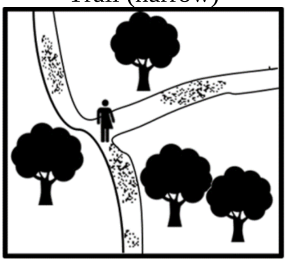
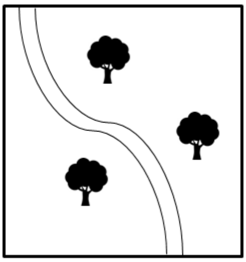
La forêt communale de Sivry-Rance peut, selon moi, avoir aussi un **impact négatif sur le quotidien** (moins de place pour les terrains agricoles ou l'urbanisation, dégâts causés par des animaux sauvages, …) ☐

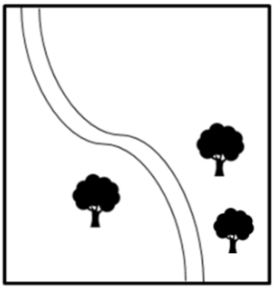
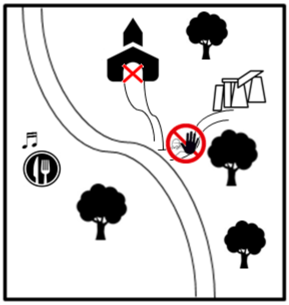
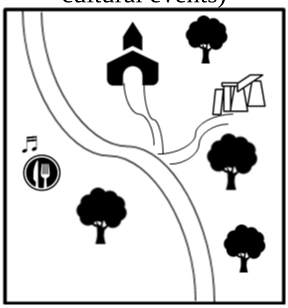
… car je peux y **profiter des paysages, des vues, des sons, des odeurs**… ☐

… car elle abrite des **animaux** sauvages ainsi qu'une grande variété de **plantes**, de micro-**organismes**, … ☐

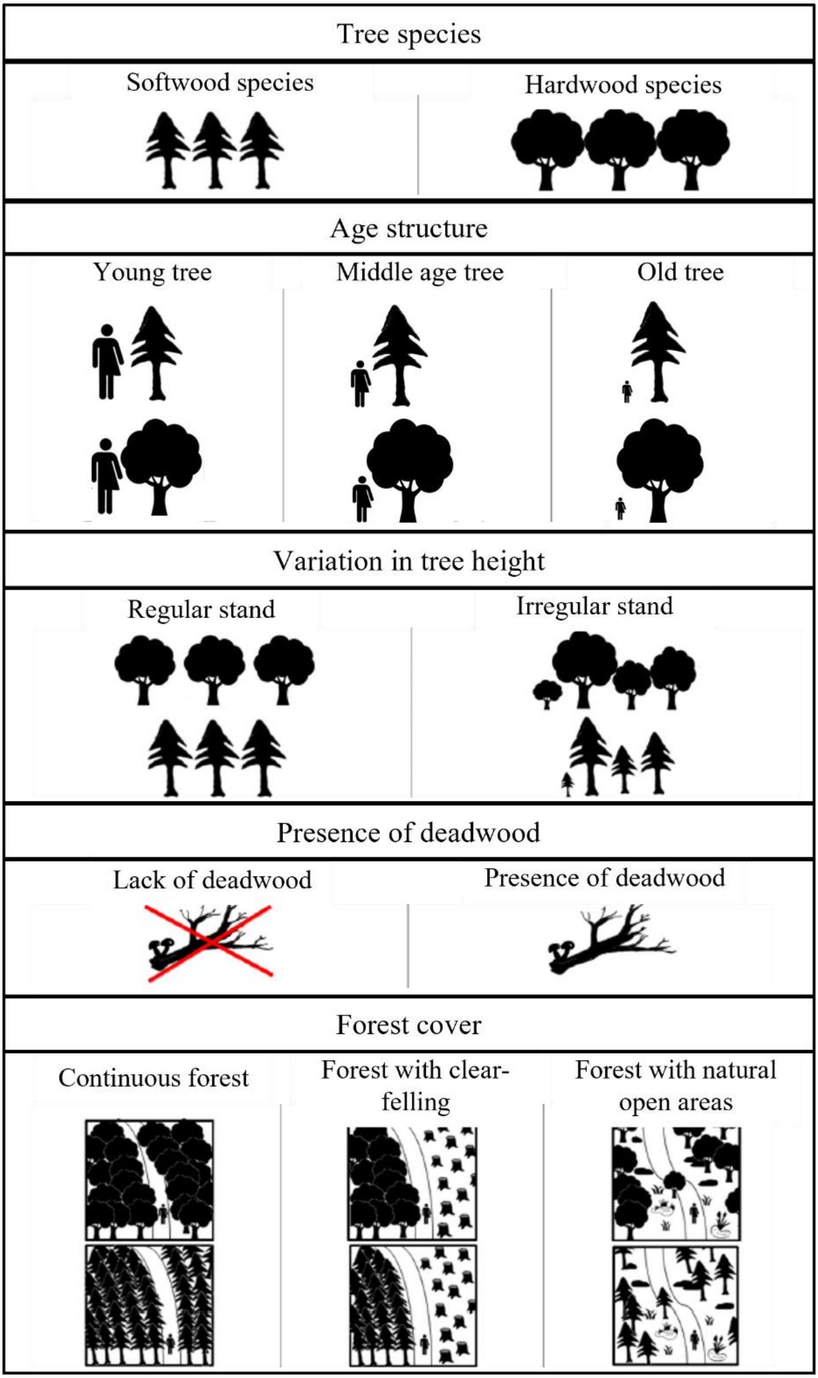
… car elle permettra aux **futures générations** de connaître et de vivre des expériences en forêt. ☐

Annex 4. The tourism infrastructures attributes used in the surveys of the inhabitants harvesting firewood, the fishers and recreation users, adapted from Breyne et al. (2021).

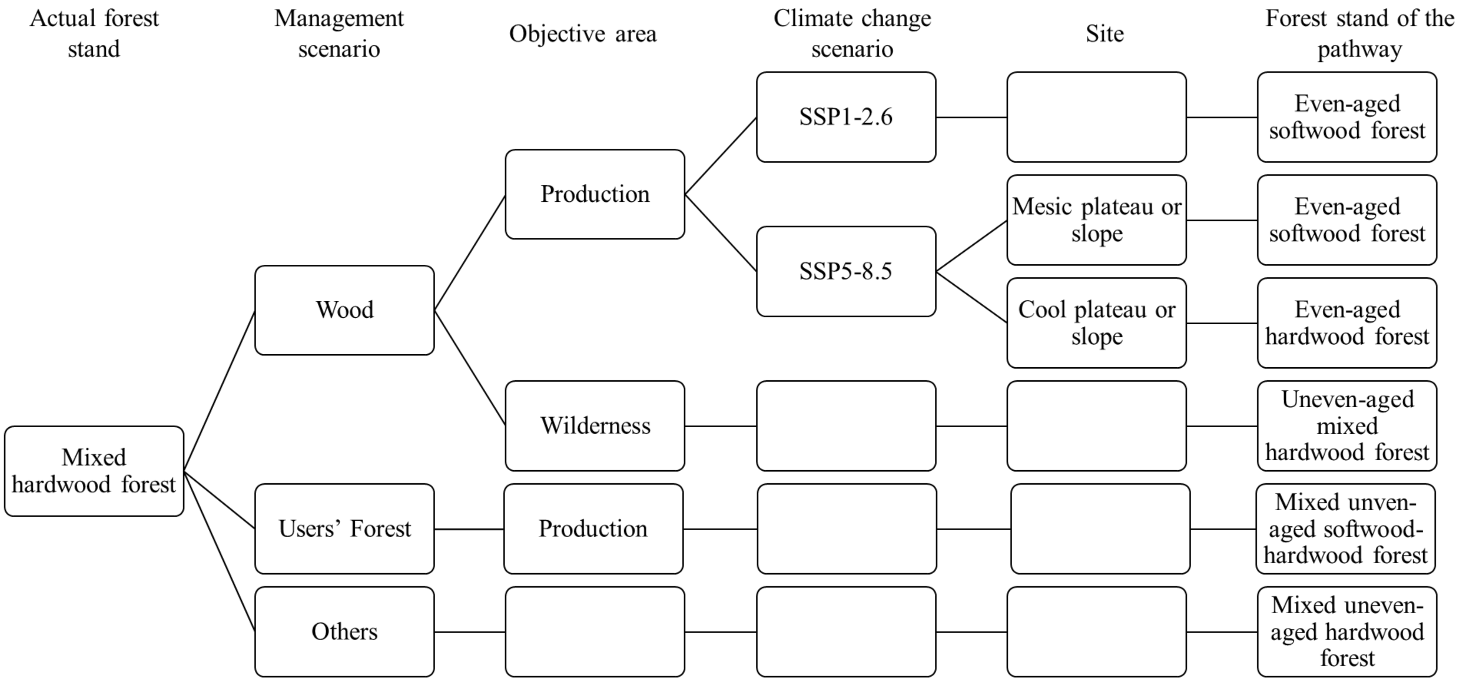
Information service		
No information service 	Standard information service (brochure, signposting, tourist office) 	Large information service (apps, tourist reception, didactic information on the services provided) 
Path type		
Road (wide enough to be accessible by car) 	Trail (narrow) 	
Tourism infrastructure		
No tourism infrastructure except hiking paths 	Basic tourism infrastructure (benches, picnic tables) 	Diversified tourism infrastructure (benches, watchtower, bivouac area) 

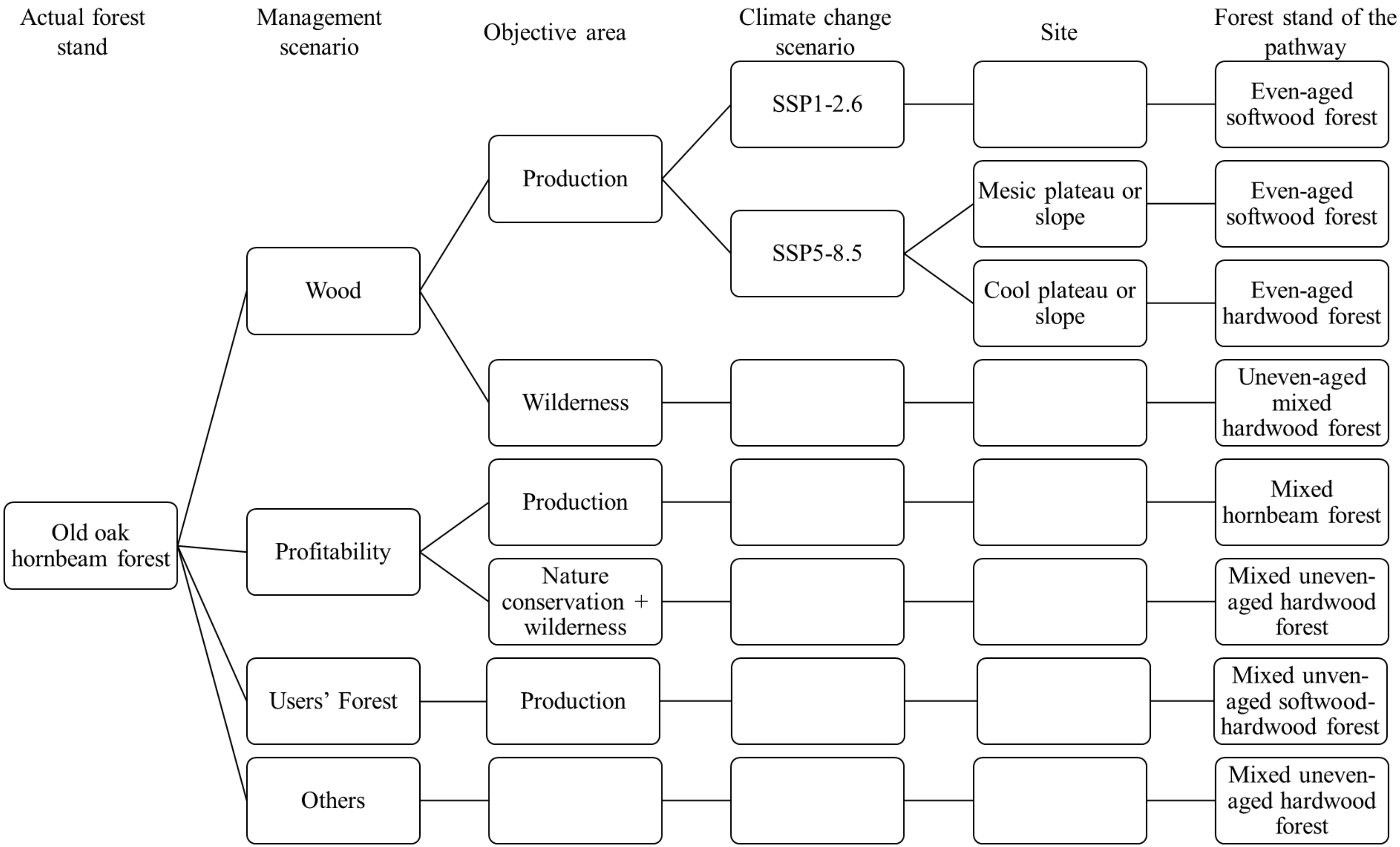
Availability of local products		
No local product	Purchase/intake of local products	Local products production or transformation workshop (including to pick yourself products in the forest)
		
Elements of cultural heritage (chapels, monuments, typical houses, etc.)		
No element of cultural heritage	Elements of cultural heritage not accessible or not well promoted	Elements of cultural heritage well promoted (restoration of historical elements, accessible, cultural events)
		

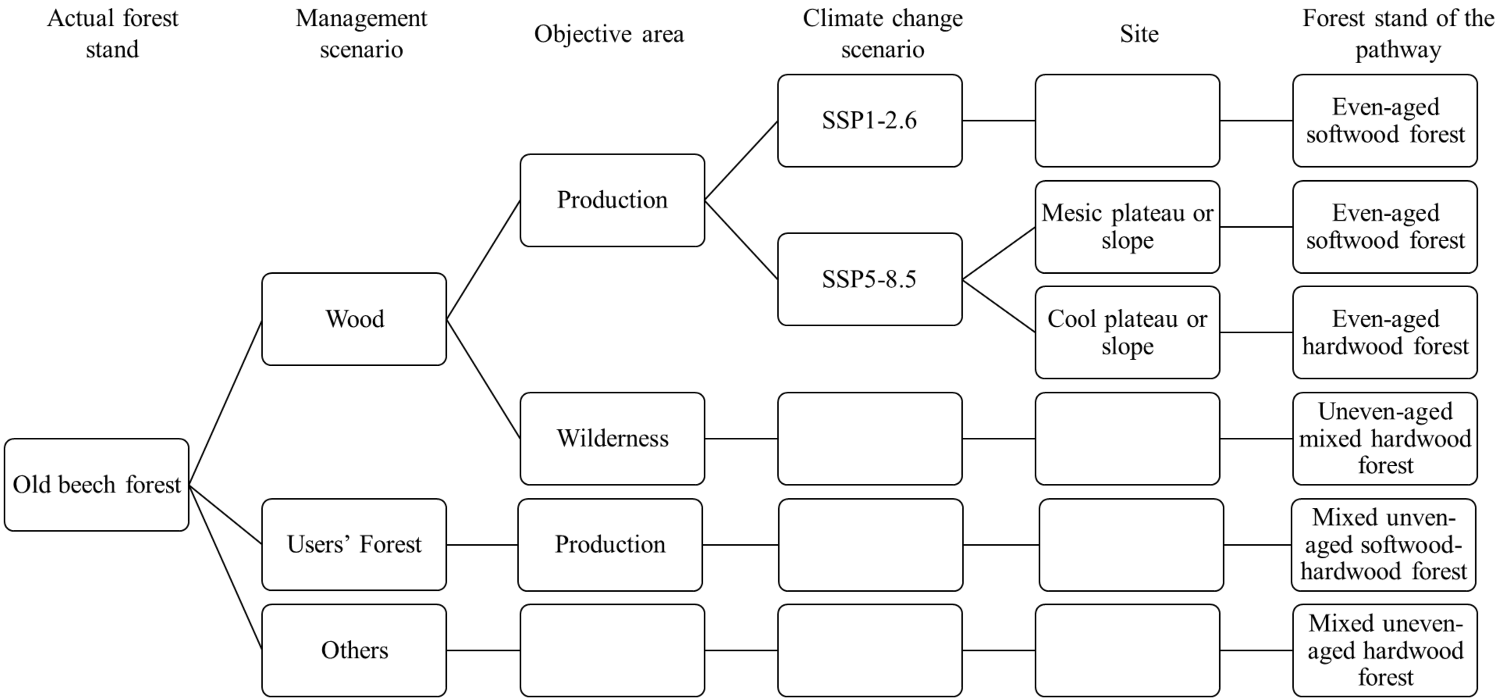
Annex 5. The forest structural attributes used in the DCE in the four surveys, adapted from Breyne et al. (2021).

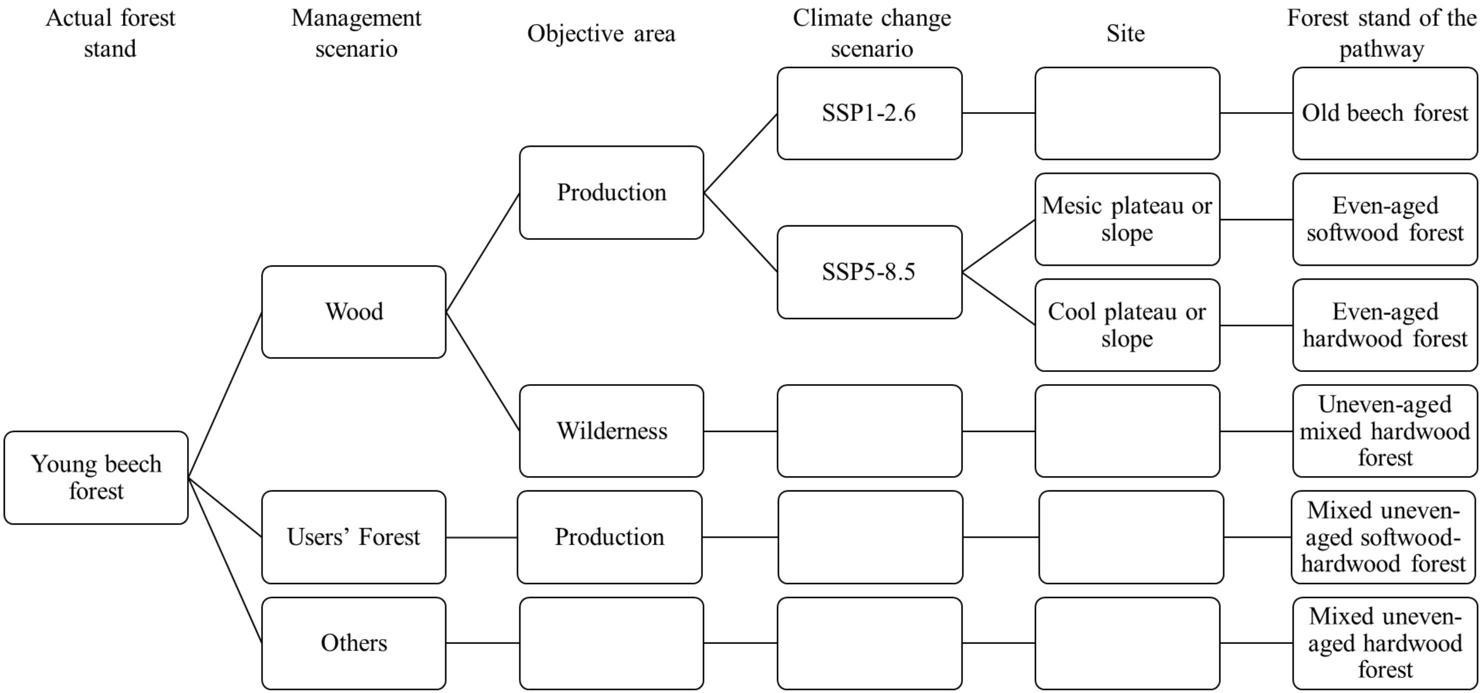


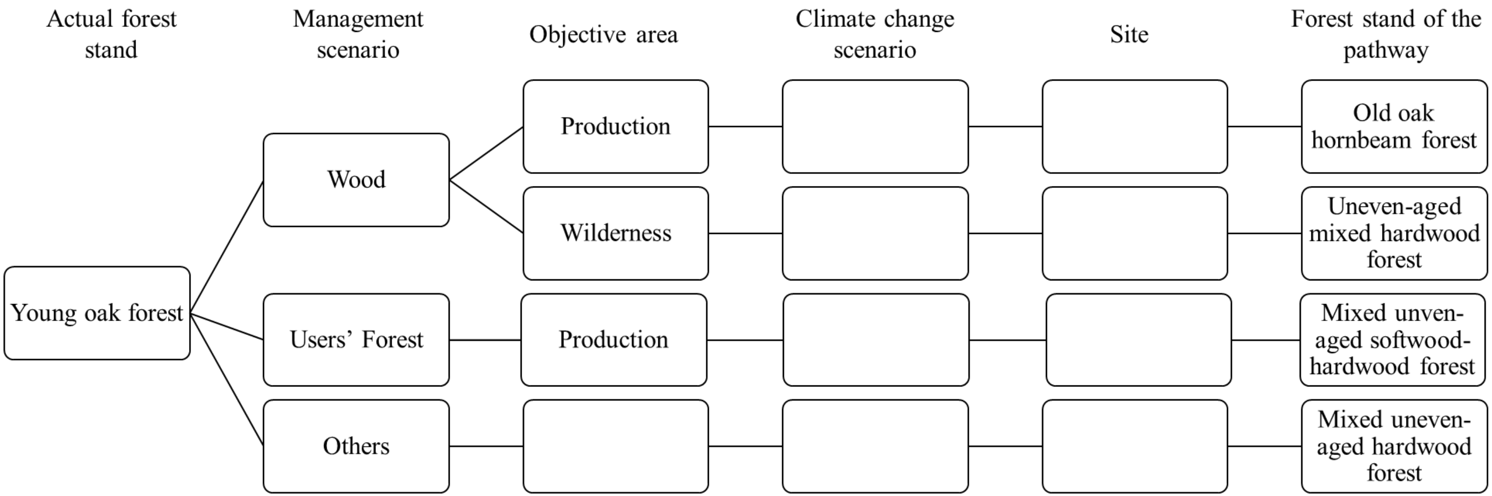
Annex 6. Definition of the different forest stands in the twelve pathways depending on the actual forest stand, the management scenario, the objective area, the climate change scenario, and the site.

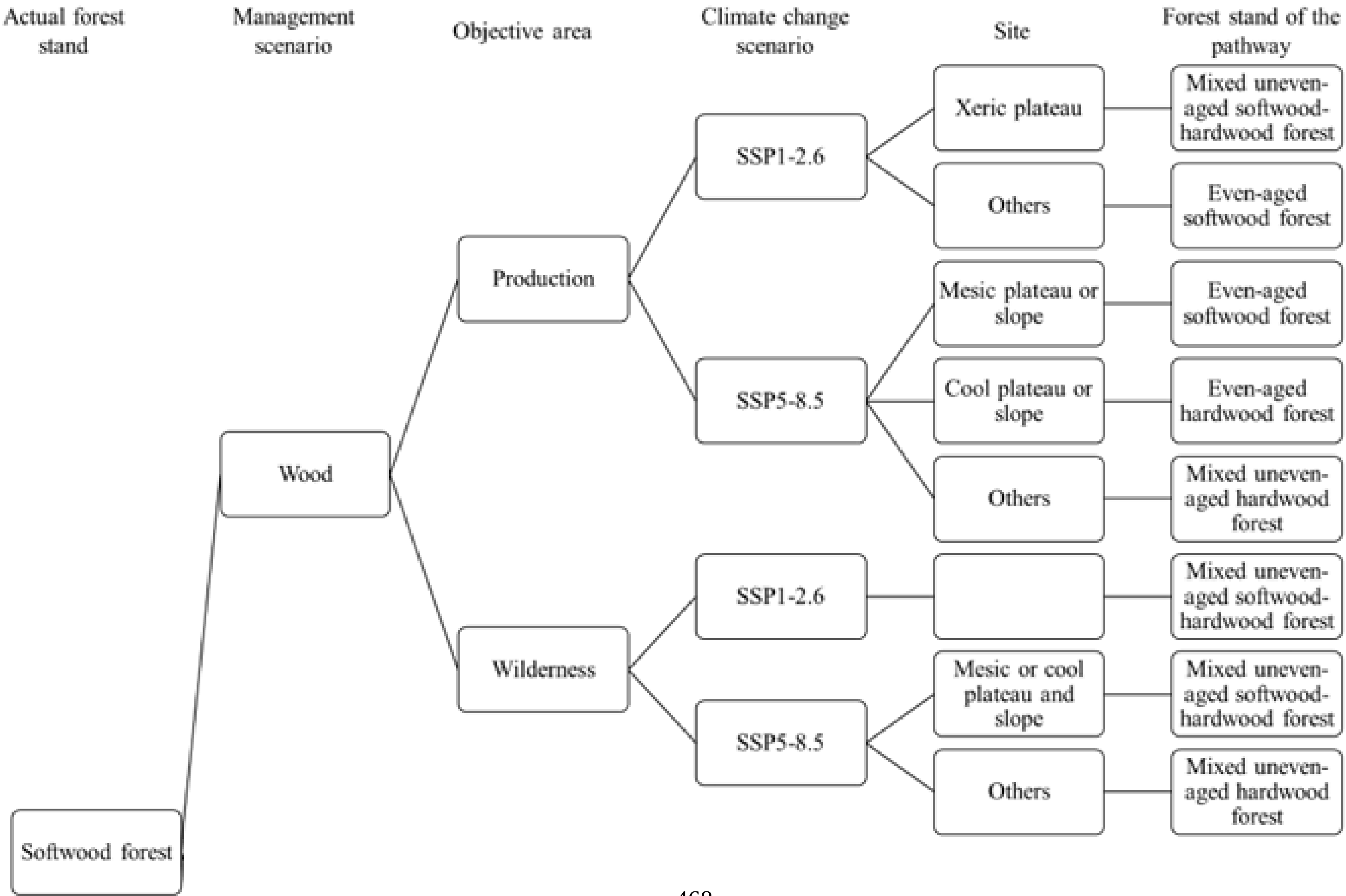


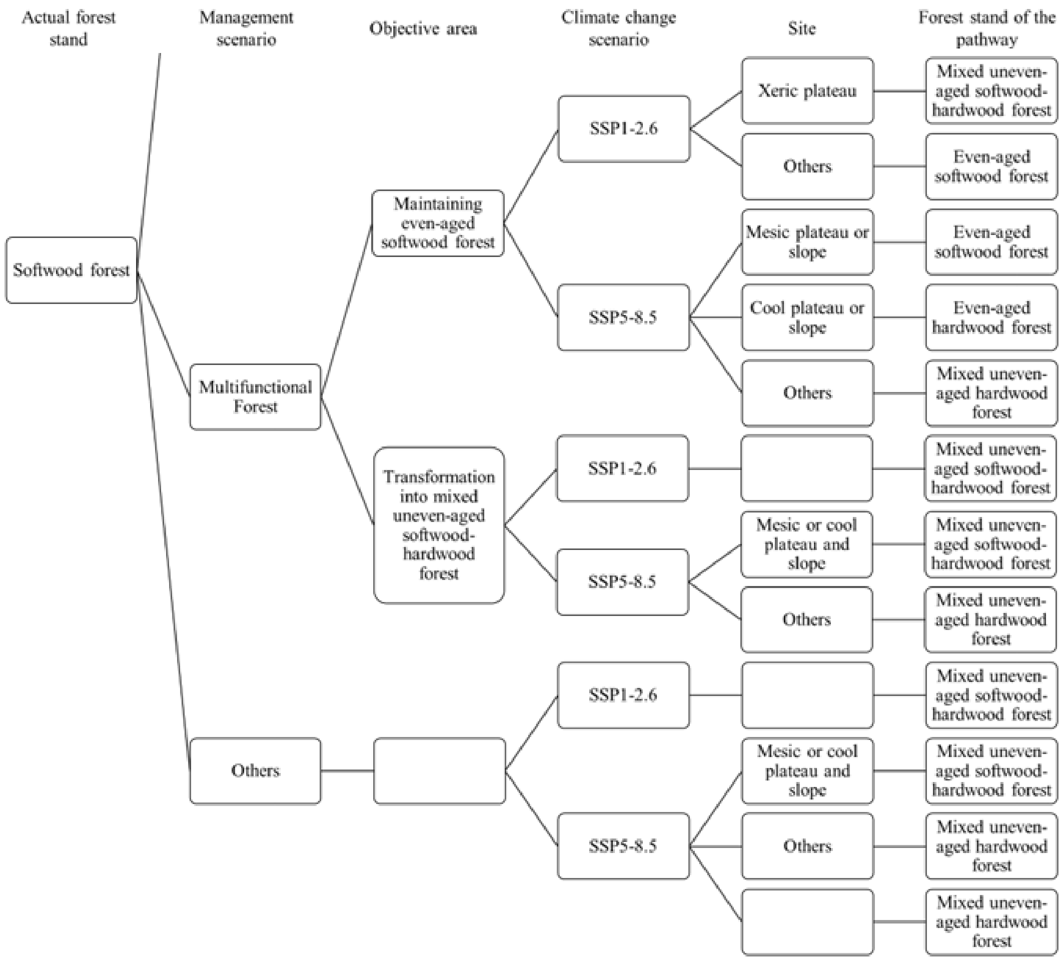

Actual forest stand
Management scenario
Objective area
Climate change scenario
Site
Forest stand of the pathway
Old oak hornbeam forest
Wood
Profitability
Users' Forest
Others
Production
Wilderness
Production
Nature conservation + wilderness
Production
SSP1-2.6
SSP5-8.5
Mesic plateau or slope
Cool plateau or slope
Even-aged softwood forest
Even-aged softwood forest
Even-aged hardwood forest
Uneven-aged mixed hardwood forest
Mixed hornbeam forest
Mixed uneven-aged hardwood forest
Mixed uneven-aged softwood-hardwood forest
Mixed uneven-aged hardwood forest

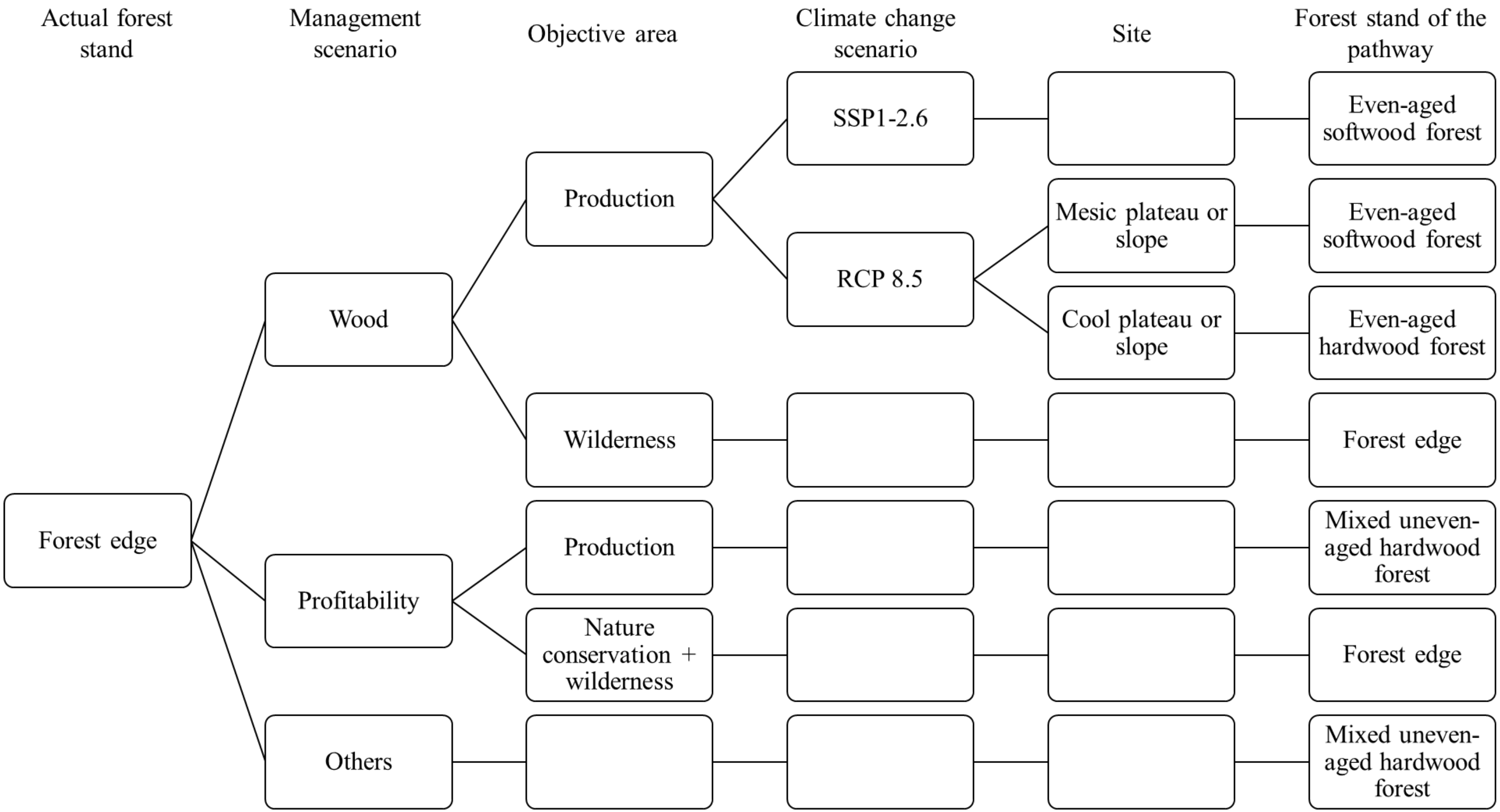

Actual forest stand
Management scenario
Objective area
Climate change scenario
Site
Forest stand of the pathway
Old beech forest
Wood
Users' Forest
Others
Production
Wilderness
Production
SSP1-2.6
SSP5-8.5
Mesic plateau or slope
Cool plateau or slope
Even-aged softwood forest
Even-aged softwood forest
Even-aged hardwood forest
Uneven-aged mixed hardwood forest
Mixed uneven-aged softwood-hardwood forest
Mixed uneven-aged hardwood forest

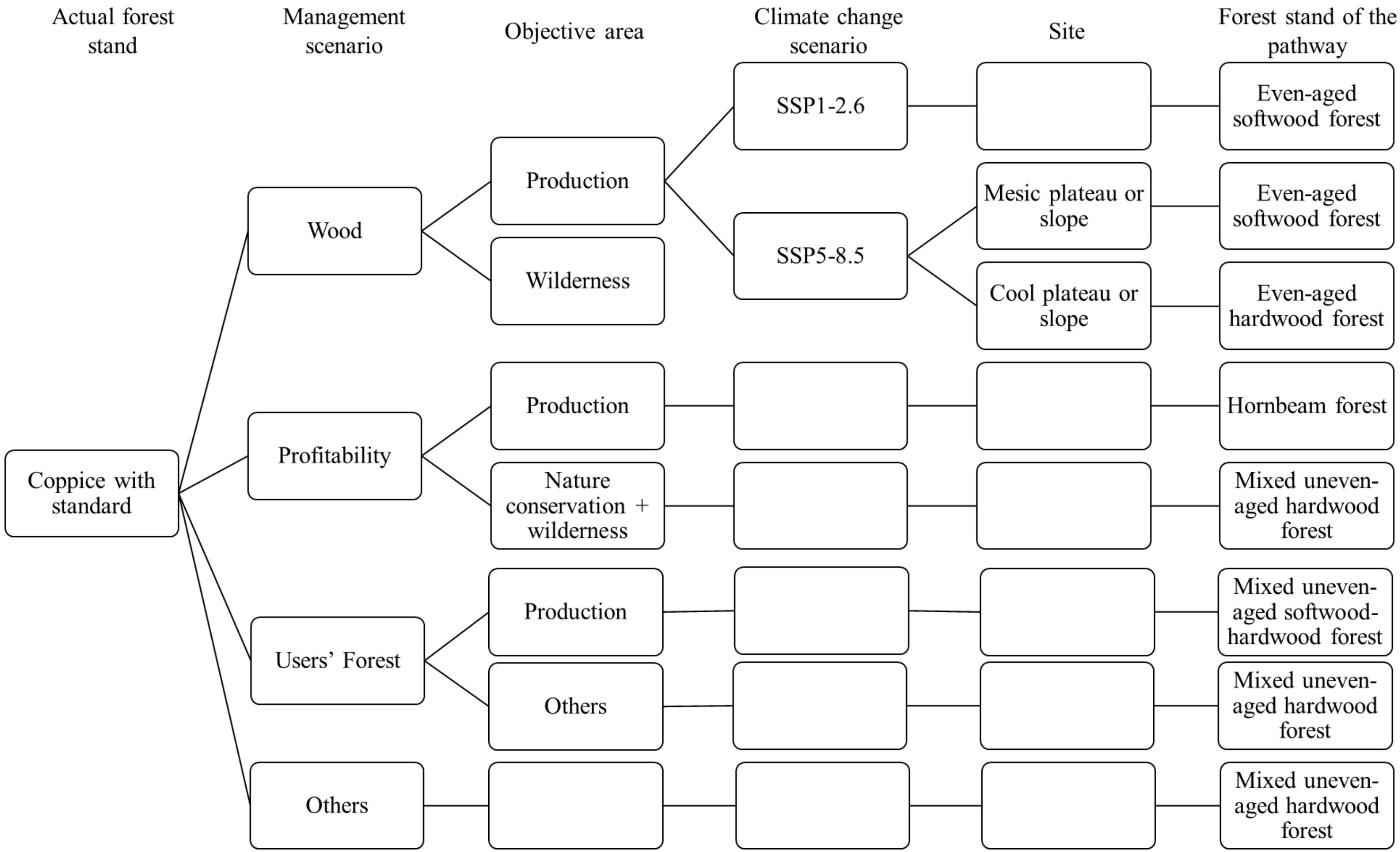

Actual forest stand
Management scenario
Objective area
Climate change scenario
Site
Forest stand of the pathway
Young beech forest
Wood
Users' Forest
Others
Production
Wilderness
Production
SSP1-2.6
SSP5-8.5
Mesic plateau or slope
Cool plateau or slope
Old beech forest
Even-aged softwood forest
Even-aged hardwood forest
Uneven-aged mixed hardwood forest
Mixed uneven-aged softwood-hardwood forest
Mixed uneven-aged hardwood forest

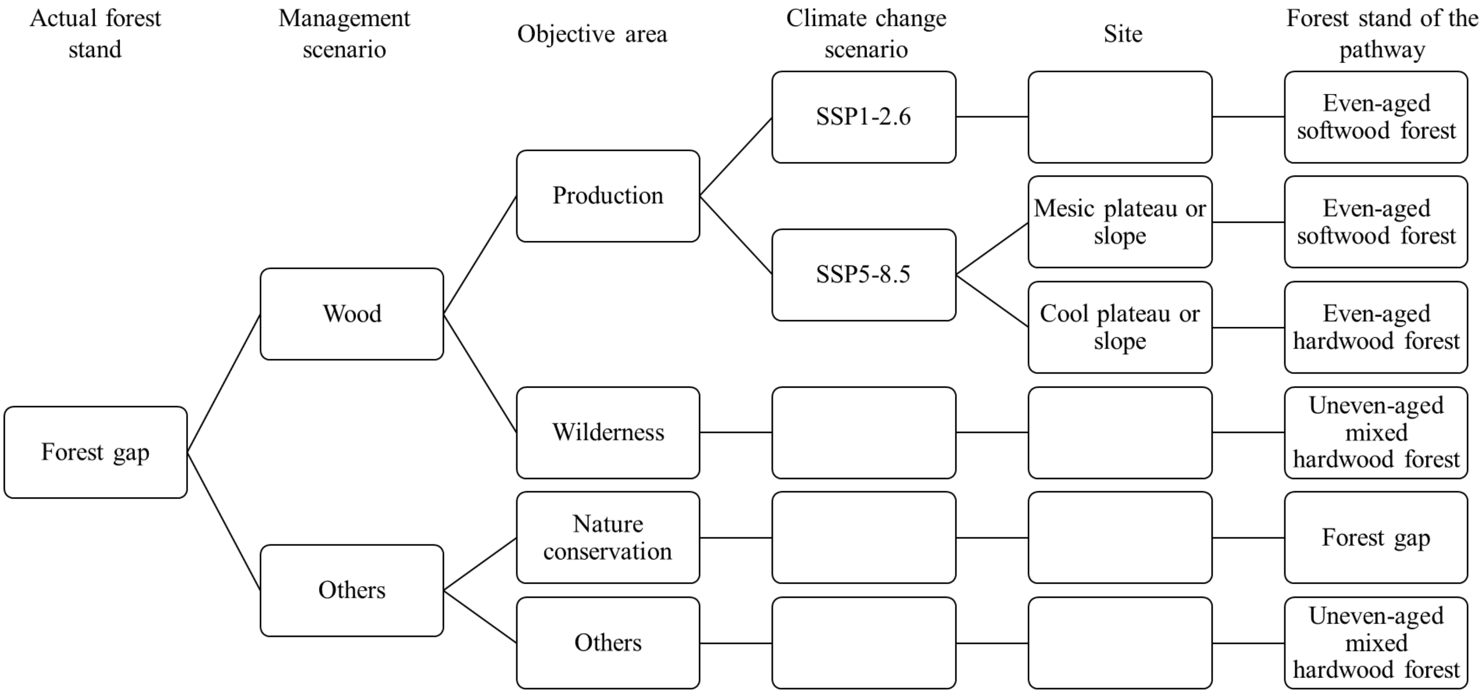

Actual forest stand
Management scenario
Objective area
Climate change scenario
Site
Forest stand of the pathway
Young oak forest
Wood
Users' Forest
Others
Production
Wilderness
Production
Old oak hornbeam forest
Uneven-aged mixed hardwood forest
Mixed unven-aged softwood-hardwood forest
Mixed uneven-aged hardwood forest

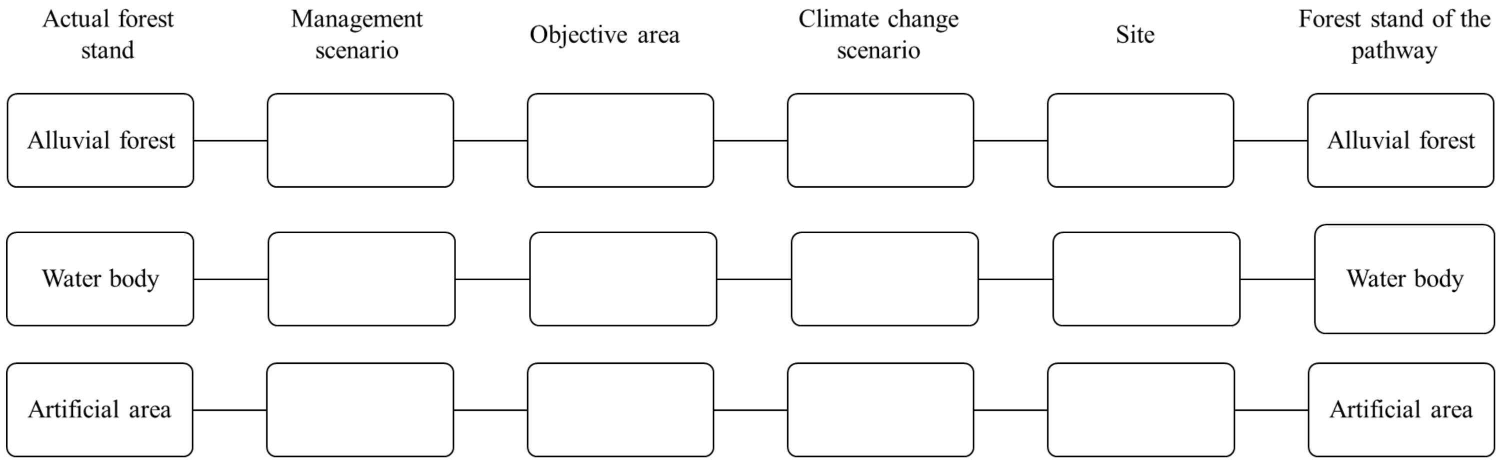

Actual forest stand
Management scenario
Objective area
Climate change scenario
Site
Forest stand of the pathway
Softwood forest
Wood
Production
Wilderness
SSP1-2.6
SSP5-8.5
SSP1-2.6
SSP5-8.5
Xeric plateau
Others
Mesic plateau or slope
Cool plateau or slope
Others
Mesic or cool plateau and slope
Others
Mixed uneven-aged softwood-hardwood forest
Even-aged softwood forest
Even-aged softwood forest
Even-aged hardwood forest
Mixed uneven-aged hardwood forest
Mixed uneven-aged softwood-hardwood forest
Mixed uneven-aged softwood-hardwood forest
Mixed uneven-aged hardwood forest


Actual forest stand
Management scenario
Objective area
Climate change scenario
Site
Forest stand of the pathway
Softwood forest
Multifunctional Forest
Others
Maintaining even-aged softwood forest
Transformation into mixed uneven-aged softwood-hardwood forest
SSP1-2.6
SSP5-8.5
SSP1-2.6
SSP5-8.5
SSP1-2.6
SSP5-8.5
Xeric plateau
Others
Mesic plateau or slope
Cool plateau or slope
Others
Mesic or cool plateau and slope
Others
Mesic or cool plateau and slope
Others
Mixed uneven-aged softwood-hardwood forest
Even-aged softwood forest
Even-aged softwood forest
Even-aged hardwood forest
Mixed uneven-aged hardwood forest
Mixed uneven-aged softwood-hardwood forest
Mixed uneven-aged softwood-hardwood forest
Mixed uneven-aged hardwood forest
Mixed uneven-aged softwood-hardwood forest
Mixed uneven-aged softwood-hardwood forest
Mixed uneven-aged hardwood forest
Mixed uneven-aged hardwood forest


Actual forest stand
Management scenario
Objective area
Climate change scenario
Site
Forest stand of the pathway
Forest edge
Wood
Profitability
Others
Production
Wilderness
Production
Nature conservation + wilderness
SSP1-2.6
RCP 8.5
Mesic plateau or slope
Cool plateau or slope
Even-aged softwood forest
Even-aged softwood forest
Even-aged hardwood forest
Forest edge
Mixed uneven-aged hardwood forest
Forest edge
Mixed uneven-aged hardwood forest


Actual forest stand
Management scenario
Objective area
Climate change scenario
Site
Forest stand of the pathway
SSP1-2.6
Even-aged softwood forest
Production
Wood
Mesic plateau or slope
Even-aged softwood forest
SSP5-8.5
Wilderness
Cool plateau or slope
Even-aged hardwood forest
Production
Hornbeam forest
Profitability
Coppice with standard
Nature conservation + wilderness
Mixed uneven-aged hardwood forest
Production
Mixed uneven-aged softwood-hardwood forest
Users' Forest
Others
Mixed uneven-aged hardwood forest
Others
Mixed uneven-aged hardwood forest


Actual forest stand
Management scenario
Objective area
Climate change scenario
Site
Forest stand of the pathway
Forest gap
Wood
Others
Production
Wilderness
Nature conservation
Others
SSP1-2.6
SSP5-8.5
Mesic plateau or slope
Cool plateau or slope
Even-aged softwood forest
Even-aged softwood forest
Even-aged hardwood forest
Uneven-aged mixed hardwood forest
Forest gap
Uneven-aged mixed hardwood forest


Actual forest stand
Management scenario
Objective area
Climate change scenario
Site
Forest stand of the pathway
Alluvial forest
Alluvial forest
Water body
Water body
Artificial area
Artificial area

Annex 7. The values of the ES in the current state and in the twelve pathways. For each ES, the indicators and methods used to assess it are given. The values of each indicator is divided in five color classes ranging from dark green (i.e. the highest values) to dark red (i.e. the lowest values). SSP1-2.6: shift toward sustainability and a rising of the global temperature of 1.8°C by 2100 and SSP5-8.5: global economy growth fueled by exploiting fossil fuels and energy-intensive lifestyles and a rising of global temperature of 4.4°C by 2100.

Ecosystem services			Current state	Pathways											
				Wood Production		Profitability		Recreation		Biodiversity		Multifunctional Forest		Users' Forest	
				SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
Wood	Growing stock (m³/ha)	Data of forest management + IPRFW + expertise	191	368	326	191	191	234	219	438	412	198	186	212	194
	Annual volume of harvested timber (m³/ha*year)		3.3	6.0	4.7	6.9	6.1	3.9	4.2	0.8	0.8	4.2	3.9	4.4	3.9
	Annual profit from timber harvesting (€/ha*year)		152	197	196	334	298	171	171	33	32	180	161	211	174
	Suitability level of the forest with the preferences of the inhabitants harvesting firewood	Survey of the inhabitants harvesting firewood	High	Very low	Very low	Very low	Very low	Medium	Medium	Low	Low	Very high	Very high	Very high	Very high
Hunting	Habitat quality for game	Literature review	High	Medium	Medium	High	Medium	High	High	Very high	Very high	High	Medium	High	Medium
	Deer damage mitigation	Literature review	High	Very low	Very low	Very low	Very low	High	Medium	Very high	High	High	Medium	High	Medium

Hunting	Mean annual profit from hunting leases	Data of forest management + literature review	Medium	Low	Low	Very high	High	Very low	Very low	Low	Low	High	Medium	High	Medium
	Suitability level of the forest with the preferences of the hunters	Survey of the hunters	High	Low	Medium	Very high	Very high	Medium	Medium	Medium	Medium	Very high	Very high	Very high	Very high
Picking	Fungal potential distribution	Literature review	Medium	Very low	Low	Low	Low	High	High	Very high	Very high	Medium	Medium	Medium	Medium
	Suitability level of the forest with the preferences of the pickers	Survey of the pickers	High	Very low	Low	Very low	Very low	Very high	Very high	Very high	Very high	High	High	Very high	Very high
Fishing	Suitability level of the forest with the preferences of the fishers	Survey of the fishers	High	Low	Medium	Medium	Medium	Very high	Very high	Very low	Very low	High	Very high	High	Very high
Water quality and quantity	% of riparian woodland in the minimal buffer width for water purification	Broadmeadow and Nisbet (2004)	93	94	94	95	95	100	100	100	100	100	100	98	98
	% of riparian woodland in the ideal buffer width for water purification	Broadmeadow and Nisbet (2004)	54	48	48	62	63	100	100	100	100	100	100	89	89
	Water purification capacity score	EcoServ-GIS	53	47	51	54	54	54	54	54	54	54	54	53	53

Water quality and quantity	Minimal % of evapotranspiration	Bansept (2013)	47.8	43.8	46.2	47.8	47.8	47.8	47.8	47.8	47.8	47.8	47.8	47.5	47.5
	Maximal % of evapotranspiration	Bansept (2013)	71.7	71.8	71.8	71.8	71.8	71.7	71.8	71.8	71.8	71.7	71.7	71.7	71.7
Control of soil erosion and flooding	% of riparian woodland in the minimal buffer width for soil erosion and flooding control	Broadmeadow and Nisbet (2004)	83	86	86	87	87	100	100	100	100	100	100	96	96
	% of riparian woodland in the ideal buffer width for soil erosion and flooding control	Broadmeadow and Nisbet (2004)	54	48	48	62	63	100	100	100	100	100	100	89	89
	Minimal % of precipitation interception	Bansept (2013)	14.9	18.3	16.3	15.0	15.0	14.9	14.9	15.0	15.0	14.9	14.9	15.2	15.2
	Maximal % of precipitation interception	Bansept (2013)	44.8	51.6	47.7	44.9	44.9	44.8	44.8	44.9	44.9	44.8	44.8	45.3	45.3
	Minimal % of precipitation infiltration	Bansept (2013)	32.0	22.0	27.9	32.1	32.1	32.0	32.0	32.1	32.1	32.0	32.0	31.3	31.3
	Maximal % of precipitation infiltration	Bansept (2013)	55.7	45.9	51.8	56.0	56.0	55.9	55.9	56.0	56.0	55.9	55.9	55.2	55.2

Fauna and flora	% of riparian woodland in the minimal buffer width for water habitat quality	Broadmeadow and Nisbet (2004)	93	94	94	95	95	100	100	100	100	100	100	98	98
	% of riparian woodland in the ideal buffer width for water habitat quality	Broadmeadow and Nisbet (2004)	60	58	58	68	68	100	100	100	100	100	100	90	90
	Habitat biological quality	Literature review	High	Low	Very low	Low	Very low	High	Medium	Very high	High	High	Medium	High	Medium
	Forest undesirable species regulation capacity	Literature review	Very high	Very low	Low	Low	Very low	High	High	High	High	Medium	Medium	High	High
	Mean pollinator abundance	InVEST Crop pollination	0.22	0.16	0.17	0.17	0.17	0.22	0.22	0.21	0.22	0.22	0.22	0.21	0.21
Climate regulation and air purification	Fine particles capture (kg/year)	Nature Value Explorer	38,338	48,716	42,628	38,370	38,367	38,325	38,306	38,347	38,341	38,331	38,308	39,032	39,027
	Forest temperature buffering capacity	Literature review	Medium	Medium	Low	Low	Very low	High	High	Very high	Very high	Medium	Medium	High	High
	Total carbon stock (Mg C/ha)	Latte et al. (2013)	148	188	177	151	152	157	157	232	224	156	152	168	158
Natural surroundings	% of visible valued forest	Surveys of the forest users	3.2	1.0	1.0	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.0	3.0

Recreation	Suitability level of the forest with the preferences of the recreation users	Surveys of the recreation users	Medium	Very low	Low	Very low	Very low	Very high	Very high	High	Very high	High	Very high	High	Very high
	Recreation supply	Literature review	High	Very low	Low	Very low	Very low	Very high	Very high	High	High	Very high	Very High	Very High	Very High
Nature watching, learning and inspiration	Suitability level of the forest with the preferences of the nature watchers or in search of inspiration	Surveys of the nature watchers or in search of inspiration	Medium	Very low	Low	Very low	Very low	Very high	Very high	High	Very high	High	Very high	High	Very high
	Supply of nature watching, learning and inspiration areas	Literature review	High	Very low	Low	Very low	Very low	Very high	Very high	High	High	Very High	Very High	Very High	Very High
Natural heritage	Supply of natural heritage areas	Literature review	High	Very low	Very low	Low	Low	Very high	Very high	Very high	Very high	Very high	Very high	Very high	Very high

Annex 8. Opinion and weighting for the 12 ES of the group who finds all the ES important and individual opinion and weighting of each person of this group.

	Group		Person 1		Person 2		Person 3		Person 4	
ES	**Opinion**	**Weighting**	**Opinion**	**Weighting**	**Opinion**	**Weighting**	**Opinion**	**Weighting**	**Opinion**	**Weighting**
Wood	Maximize	11	Identical	4	Maximize	12	Identical	6	Maximize	13
Hunting	Identical	8	Identical	6	Identical	1	Identical	3	Identical	6
Picking	Minimize	8	Identical	2	Minimize	12	Identical	6	Maximize	6
Fishing	Identical	5	Identical	6	Maximize	9	Identical	3	Maximize	6
Water quality & quantity	Maximize	13	Maximize	18	Maximize	10	Identical	12	Maximize	13
Control of soil erosion & flooding	Identical	9	Maximize	10	Identical	1	Identical	7	Maximize	13
Fauna and flora	Maximize	9	Maximize	18	Maximize	12	Maximize	12	Maximize	9
Climate regulation and air purification	Identical	9	Maximize	12	Identical	1	Identical	12	Maximize	13
Natural surroundings	Identical	9	Identical	4	Maximize	12	Maximize	9	Minimize	2
Recreation	Minimize	9	Identical	6	Minimize	12	Identical	9	Maximize	12
Nature observation, learning and inspiration	Identical	5	Identical	6	Minimize	12	Maximize	12	Identical	6
Natural heritage	Maximize	5	Maximize	8	Maximize	6	Maximize	9	Identical	1

Annex 9. Opinion and weighting for the 12 ES of the group who prefers the provisioning ES and individual opinion and weighting of each person of this group.

	Group		**Person 1**		**Person 2**		**Person 3**		**Person 4**	
ES	**Opinion**	**Weighting**	**Opinion**	**Weighting**	**Opinion**	**Weighting**	**Opinion**	**Weighting**	**Opinion**	**Weighting**
Wood	Maximize	14	Maximize	23	Minimize	27	Maximize	14	Maximize	7
Hunting	Maximize	27	Maximize	17	Maximize	37	Maximize	27	Maximize	7
Picking	Minimize	1	Minimize	1	Identical	1	Minimize	1	Minimize	1
Fishing	Minimize	7	/	6	Identical	1	Identical	7	Maximize	2
Water quality & quantity	Maximize	7	Maximize	11	Identical	1	Maximize	7	Maximize	4
Control of soil erosion & flooding	Maximize	7	Maximize	11	Maximize	27	Identical	7	Identical	1
Fauna and flora	Maximize	14	Maximize	11	Identical	1	Maximize	14	Maximize	69
Climate regulation and air purification	Identical	1	/	1	Maximize	1	Maximize	1	Maximize	4
Natural surroundings	Maximize	7	/	6	Identical	1	Maximize	7	Identical	1
Recreation	Maximize	7	/	6	Minimize	1	Minimize	7	Minimize	1
Nature observation, learning and inspiration	Maximize	7	/	6	Identical	1	Identical	7	Identical	2
Natural heritage	Identical	1	Minimize	1	Identical	1	Maximize	1	Identical	1

Annex 10. Opinion and weighting for the 12 ES of the group who prefers the regulating ES and individual opinion and weighting of each person of this group.

	Group		**Person 1**		**Person 2**		**Person 3**	
ES	**Opinion**	**Weighting**	**Opinion**	**Weighting**	**Opinion**	**Weighting**	**Opinion**	**Weighting**
Wood	Identical	3	Maximize	10	/	16	Maximize	19
Hunting	Identical	3	Maximize	8	/	11	Identical	1
Picking	Minimize	3	Minimize	1	/	10	Minimize	6
Fishing	Identical	9	Maximize	1	/	11	Identical	1
Water quality & quantity	Identical	16	Maximize	11	/	11	Maximize	19
Control of soil erosion & flooding	Maximize	16	Maximize	10	/	1	Maximize	18
Fauna and flora	Maximize	16	Maximize	11	/	11	Maximize	13
Climate regulation and air purification	Maximize	3	Maximize	10	/	1	Maximize	7
Natural surroundings	Maximize	12	Maximize	8	/	5	Maximize	13
Recreation	Identical	4	Maximize	8	/	11	Minimize	1
Nature observation, learning and inspiration	Identical	6	Maximize	11	/	11	Identical	1
Natural heritage	Maximize	7	Maximize	11	/	1	Maximize	1

Annex 11. Opinion and weighting for the 12 ES of the group who prefers the cultural ES and individual opinion and weighting of each person of this group.

	Group		Person 1		Person 2		Person 3		Person 4	
ES	**Opinion**	**Weighting**	**Opinion**	**Weighting**	**Opinion**	**Weighting**	**Opinion**	**Weighting**	**Opinion**	**Weighting**
Wood	Maximize	6	Maximize	2	Minimize	4	Maximize	8	Maximize	2
Hunting	Minimize	1	Minimize	16	Minimize	4	Minimize	1	Minimize	16
Picking	Maximize	11	Maximize	16	Maximize	6	Maximize	12	Maximize	16
Fishing	Maximize	6	Maximize	5	Identical	4	Identical	6	Maximize	5
Water quality & quantity	Maximize	8	Maximize	5	Maximize	9	Maximize	8	Maximize	5
Control of soil erosion & flooding	Maximize	6	Maximize	2	Maximize	12	Maximize	8	Maximize	2
Fauna and flora	Maximize	13	Maximize	16	Maximize	13	Maximize	11	Maximize	16
Climate regulation and air purification	Maximize	6	Maximize	5	Maximize	8	Maximize	6	Maximize	5
Natural surroundings	Maximize	8	Maximize	5	Maximize	12	Maximize	8	Maximize	5
Recreation	Maximize	17	Maximize	21	Maximize	10	Maximize	8	Maximize	21
Nature observation, learning and inspiration	Maximize	9	Maximize	5	Maximize	9	Maximize	12	Maximize	5
Natural heritage	Maximize	11	Maximize	2	Maximize	9	Maximize	12	Maximize	2