Full Length Article

The Navigate framework: How the ecosystem services and resilience concepts can help us navigate in the current crises

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ABSTRACT

In the last decades, humanity has considerably altered the functioning of Earth, resulting in global and interrelated social, economic, and environmental crises. To address these crises, the concepts of 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 the 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.

1. Introduction

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. poly-crisis) 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 ecosystem services (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). From the multiple definitions of the ES concept, we choose the one of Daily (1997):"the conditions and processes through which natural ecosystems, and the species that make them up sustain and fulfill human life". They represent the output, the external perceptions of the social-ecological system (SES) (i.e. inter-twined system of humans and nature where people and the biosphere are interconnected and mutually interdependent (Brown, 2021)) driven by the societal demand (Kull et al., 2015). ES emphasize the strong interrelationships between nature and society to highlight the impacts of human activities on human well-being (Biggs et al., 2015; Ruhl and Chapin, 2014). This concept also reveals the balance that needs to be found between the different ES (e.g. the balance between the maximization of provisioning ES for individual interests and the regulating or cultural ES, generally related to collective interests) by highlighting the hidden costs and multiple contradictory benefits of a decision (Howe et al., 2014).

Resilience focuses on the functioning of the system and its transformational dynamics (Holling and Gunderson, 2002; Walker et al., 2006) to prepare us for cascading impacts of actions and to move the system out of undesirable states (Anderies et al., 2013; Folke et al., 2010; Redman, 2014). From its multiple conceptualizations (Brand and Jax, 2007; Fuller and Quine, 2016), we choose the social-ecological 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., 2009a). 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 (i.e. the system does not change fundamentally), (2) adaptation (i.e. gradual change of the system on the current trajectory), and (3) transformation (i.e. form of change in which the system embarks on a new, substantively different trajectory) (Enfors-Kautsky et al., 2021; Li et al., 2020).

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. Biggs et al., 2015; Field and Parrott, 2017; Ruhl and Chapin, 2014). 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. 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 paper is thus to propose the Navigate framework which pairs the concepts of ES and resilience 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) yet 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 helping us understand 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 and to reveal the interactions between society and nature (MA, 2005), numerous frameworks and guides currently exist (see for example Baral et al. (2016) for ES assessment framework, IPBES (2022) or Barton et al. (2017) for guides).

We propose the inclusion of resilience to bring a 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)).

The resulting Navigate framework is divided into two parts. The first part is conceptual to explain the interconnections between the ES and resilience concepts and how they perform in the SES in the face of increasing global changes. The second part is operational by providing a step-by-step procedure for the joint implementation of ES and resilience. After describing how the framework was designed, the two parts of the framework are explained in detail. Then, its implementation is demonstrated with a case study to show how it can be implemented in the field and the challenges faced. Finally, the advantages and limits of this framework are discussed, and some guidelines are given on how best to implement it. We conclude with some future perspectives.

2. Methods

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 (see Appendix A that regroups these 61 papers by thematic). 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 concepts (see Appendix B for a synthesis of these 26 papers). Most of the existing frameworks are conceptual and not easily applicable.

Furthermore, only few of them really 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 (see Appendix B that synthesizes how these 26 frameworks have inspired the Navigate framework).

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, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Program on Ecosystem Change & Society (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. We selected the municipal forest of Sivry-Rance for several reasons. First, we chose to study a forest because of the increasing known and unknown threats caused by human activities (e.g. climate change, novel pests and diseases) it is facing (Millar et al., 2007; Rist and Moen, 2013) while the demand increases for the numerous ES it provides (Aerts and Honnay, 2011; Thom and Seidl, 2016). We opted for this particular forest because it is a good example of a multifunctional forest with a diversity of stakeholders coping with multiple pressures. Finally, this forest of about 2200 ha provides an optimal scale of analysis: sufficiently small to consider the local specificities while large enough to include the social stakes and the interactions associated with larger scales.

The municipal forest of Sivry-Rance is owned by the municipality of Sivry-Rance (Belgium) and managed by the Public Department of Nature and Forest (DNF) (Fig. 1). The area, culminating at 250 m high, is characterized by a temperate climate (i.e., relatively cool and wet summer and relatively mild and rainy winter) and is gouged by numerous streams. This forest is mainly composed of hardwoods, mostly oak and hornbeam, accompanied by beech and other deciduous trees (e. g. maple, birch, alder) in uneven-aged stands. This forest is managed under the principles of continuous cover forestry (e.g. natural regeneration, selective thinning) (Pommerening and Murphy, 2004). Because most of the forest is part of the Natura 2000 network, biodiversity restoration actions are carried out (e.g. excavation of ponds, conservation of deadwood, designation of wilderness areas). This forest is also socially important for the local community for the different activities it offers (e.g. walking, biking, mushroom picking, hunting). These multiple societal demands along with climate change (e.g. several summer droughts and storms in the last few years have caused high tree mortality), pests (e.g. ash dieback caused by a fungal pathogen), among others have put a lot of pressure on this forest (Colson and Baix, 2021).

3. The Navigate framework

First, the conceptual part of the Navigate framework is described. Then, the operational part is discussed. Finally, its implementation to the municipal forest of Sivry-Rance is presented.

3.1. Conceptual part of the Navigate framework

The conceptual part of the Navigate framework, illustrated in Fig. 2, synthesizes 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.

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) (Fig. 2A). This representation is fundamental to understanding the influence of humans on an ecosystem, 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., 2009a; Lauerburg et al., 2020) (Fig. 2B). For instance, a change in the ecosystem results in changes in ecosystem functioning and consequently 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
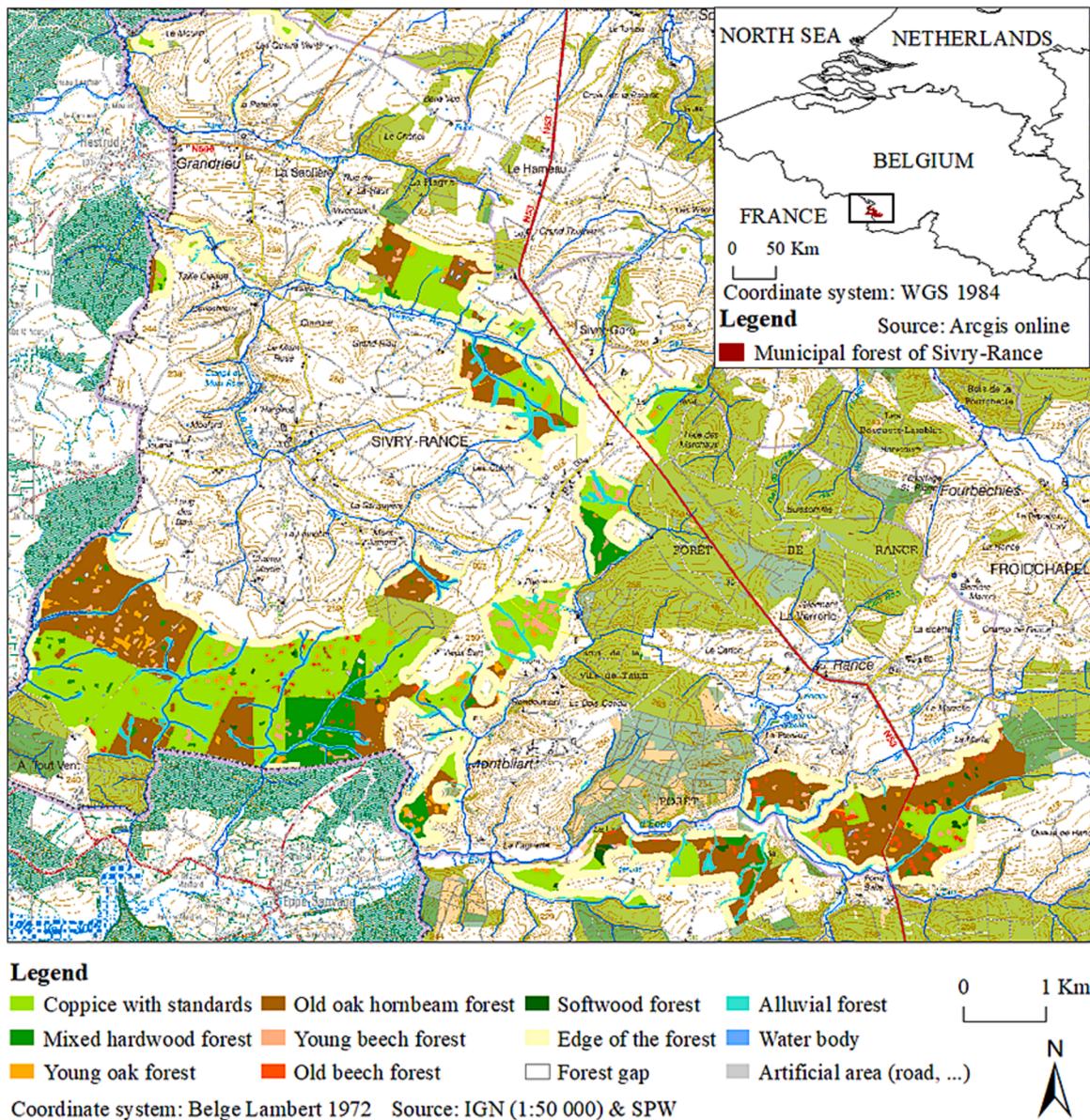
Fig. 1. Map of the municipal forest of Sivry-Rance depicting its location, the water network and the different forest stands.

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).

Finally, resilience is schematized in its three forms: (1) persistence, (2) adaptation, and (3) transformation, in different pathways. They 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, and (3) we did not change the depiction of the SES while in reality when the SES adapts or transforms, it changes.

3.2. 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
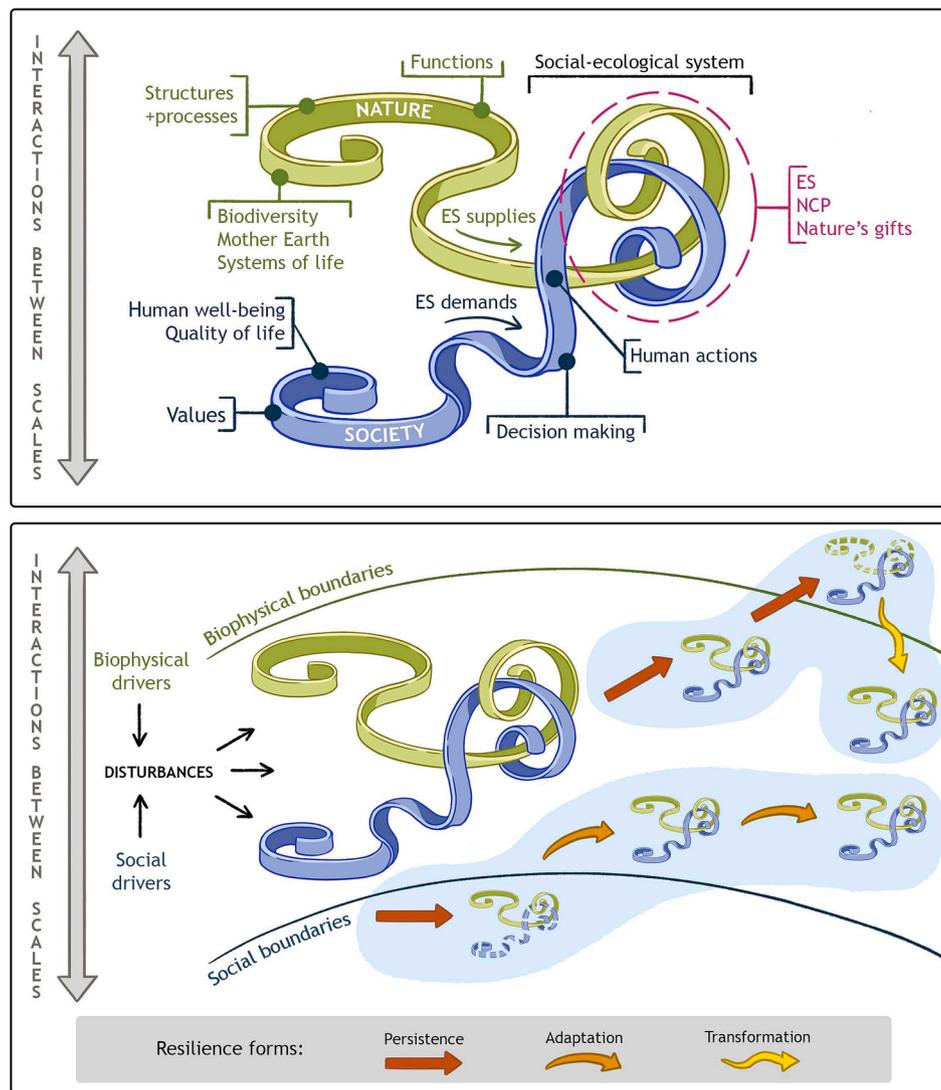
Fig. 2. The conceptual part of the Navigate framework. A. Representation of the social-ecological system (SES) and its multiple interactions by two intertwined curves. The first curve represents nature with its biodiversity that generates structures and processes performing functions. The functions used 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 part of the framework is inspired by Turner et al. (2003), Chapin et al. (2009a), 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).

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).

3.3. Operational part of the Navigate framework

The operational part of the Navigate framework is divided into six steps.

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; 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.

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

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

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 Palomo et al., 2011; Ruiz-Mallén et al., 2015; Tompkins et al., 2008 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.

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), and (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 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.

Step 5: Assess the 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 (i.e. the ability of groups or communities to cope with disturbances to sustain their well-being

(Adger, 2000; Hall and Lamont, 2013)) 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).

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).

3.4. The municipal forest of Sivry-Rance: A case study

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 (Fig. 3).

Step 1: Define the system

In the first step, the SES, its dynamics, interactions and multiple scales were defined based on an analysis of existing information about administration, soil, economics, recreation, etc. context supplemented by information collected from field measurements and experts. All this information is summarized in the section 2. Methods where the case study is described.

Special emphasis was given to understanding the stakeholders and their relationships. The interests and influence of the stakeholders as well as the synergies and potential conflicts between them were analyzed using the 'ecosystem services stakeholders matrix' method, developed by Lovens et al. (2014). This matrix 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 supply and use of ES. We conducted open interviews with key informants, persons with a specific knowledge on the focus area with a helicopter view (i.e., people who have many different perspectives and thus can provide an overview of what is going on in certain groups), and with different expertise (e.g. forest manager, owner, local organization), using a structured card game to depict the different ES. The resulting matrix can be found in Appendix C. 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 or nature associations), 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). 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).

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

All the stakeholders, pinpointed in the 'ecosystem services stakeholders matrix', were invited to a first participatory workshop. The first part of this workshop was dedicated to the identification of the problem and the stakes by asking the participants their main wish and fear concerning the future of the municipal forest of Sivry-Rance. The following problem: "how to ensure that this forest provides the ES needed by the different stakeholders in the face of the current and future disturbances" emerged from the discussion. The main stakes were the relationships between the different users, forest degradation including
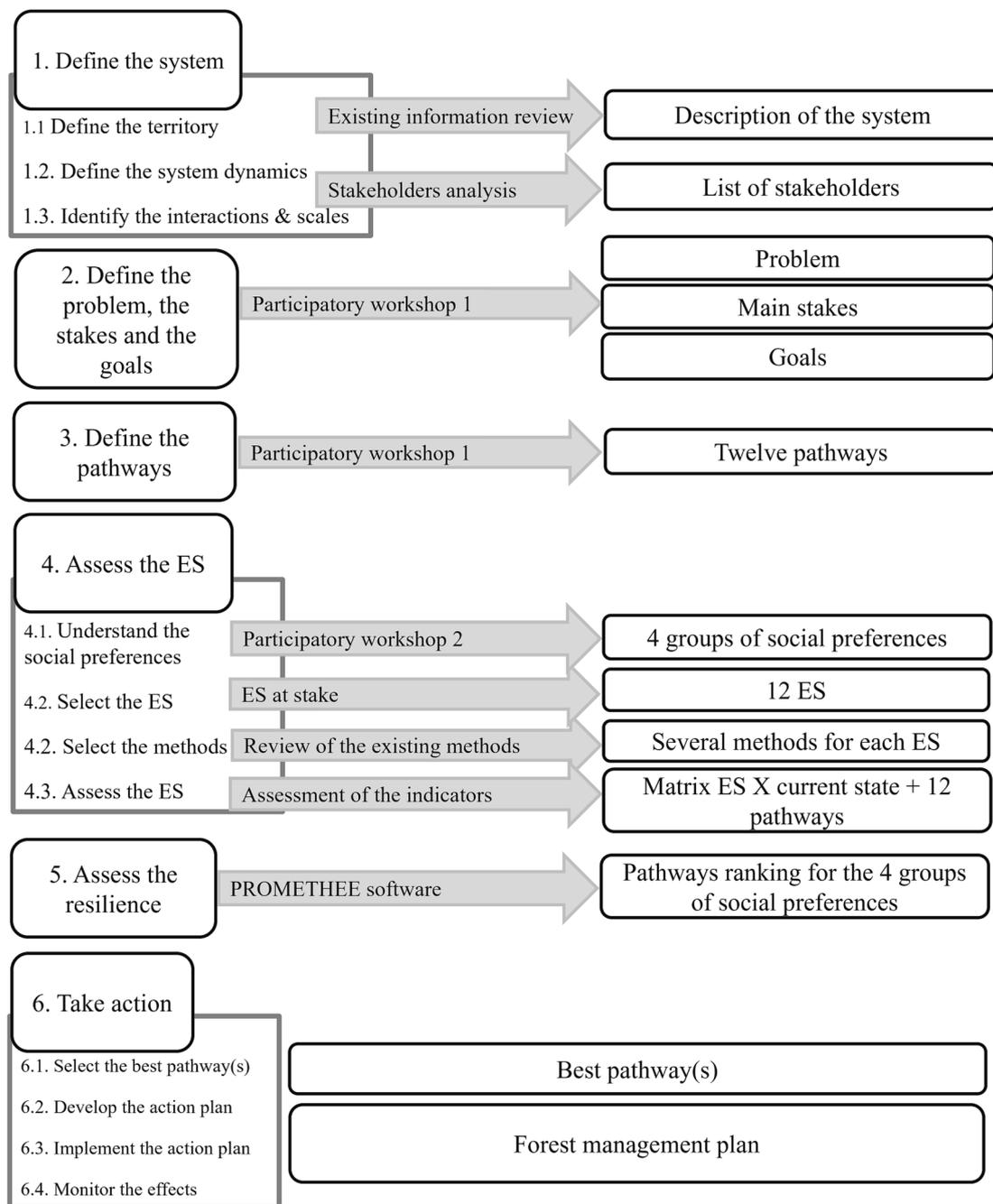
Fig. 3. Operational part of the Navigate framework applied to the municipal forest of Sivry-Rance with the six steps, the methods, and results of these steps. This part of the Navigate framework is inspired by Baral et al. (2016), Sarkki et al. (2017), Baskent et al. (2020), Ikematsu and Quintanilha (2020), Li et al. (2020) and Enfors-Kautsky et al. (2021).

climate change, the resilience of the forest, its biodiversity, and the balance between the different functions and uses. From these stakes and the understanding of the system gained in Step 1, the main goal of this case study was defined as having a resilient forest that provides multiple ES answering the various needs of the stakeholders in a balanced way.

Step 3: Define the pathways

Twelve pathways were selected by defining six management scenarios and two climate change scenarios. From the identification of the concerns of the different groups of stakeholders (based on the first part of the participatory workshop described in Step 2), the first four management scenarios were defined, representing the maximization of a certain ES of the forest: (1) Wood Production with an intensive

silviculture based on the plantation of productive and short-rotation softwood species, (2) Profitability by cutting trees as they become mature and by promoting hunting, (3) Recreation by developing the tourism infrastructures and improving the appeal of the forest, and (4) Biodiversity with restoration actions and designation of wilderness areas. In the second part of the first participatory workshop, the participants were separated into six heterogenous groups (i.e. each group including four to five different types of stakeholders such as a hunter, a recreation user, a forest manager, a representative of a local organization and the owner) and were asked to reflect upon their dream forest. In an attempt to strike a balance between their different expectations, they defined a multifunctional forest providing many different ES. From these

six dream forests, we defined the last two management scenarios: (1) the Multifunctional Forest that reconciles the different functions of the forest, and (2) the Users' Forest that represents a consensus between the different preferences of the stakeholders. For each of these six management scenarios, we explicitly considered climate uncertainty by means of two climate change scenarios (SSP1-2.6 (i.e. Shared Socio-economic Pathway with a shift toward sustainability and a rising of the global temperature of 1.8 °C by 2100) and SSP5-8.5 (i.e. Shared Socio-economic Pathway with global economy growth fueled by exploiting fossil fuels and energy-intensive lifestyles and a rising of global temperature of 4.4 °C by 2100) from the IPCC (2022)). 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). These twelve pathways were detailed in a storyline and in the form of maps representing the spatial distribution of the different forest stands, the restoration and wilderness areas, and the tourism infrastructures in 2085 (i.e. reference year of the pathways).

Step 4: Assess the ES

The social preferences were obtained during a second participatory workshop. Prior to the workshop, the participants were asked to weight the ES and give their opinion (i.e. if they want to maximize, minimize or keep the ES at the same level). From this information, we grouped the participants who had similar preferences (i.e. similar weighting and opinions) to create four groups. During the workshop, we asked each group to indicate their preferences: (1) weight the ES, (2) give their opinion, (3) state their acceptable level of the ES (i.e. the minimal level that the ES should have), and (4) state their satisfactory level of the ES (i.e. the level at which they would feel satisfied). The preferences of these four groups broadly are: (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. Although the preferences did differ among the four groups, all found the ES "Fauna and Flora" to be important.

The relevant ES were selected by choosing the ES at stake in the municipal forest of Sivry-Rance based on the information obtained in the three previous steps and the social preferences (Appendix D). Then, we compiled the various existing methods to assess the ES. We selected the most relevant methods based on the resources and data we had and their relevance (e.g. is the method suited to assess the ES provided by the forest and in different pathways?) (see Appendix E for the methods used and Appendix F for their corresponding indicators).

Finally, the ES were assessed in their current state and in the twelve pathways (Appendix F). 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 a the same management scenario, the two climate change scenarios have similar trends. For a given ES, different indicators can show contrasting trends on the pathways. For example, the Wood Production management scenario is the best one if we look at the indicators of the minimal and maximal percentage of precipitation interception of the ES "Control of soil erosion and flooding" thanks to softwood species planted in this scenario while the other indicators of this ES gave an opposite trend because of the softwood species.

Step 5: Assess the resilience

To study the resilience of ES and the social resilience, the values of the ES in the current state and in the twelve pathways as well as the weighting and evaluation parameters defined by each group (Step 4) were introduced in the PROMETHEE software (version 1.9) to rank the different pathways. We chose this software, developed by Brans et al. (1986), because it is a quite simple ranking method (Jactel et al., 2012; Martin and Mazzotta, 2018), that provides relevant and reliable results (Kiker et al., 2005; Zhang et al., 2009), well adapted to problems where a finite number of pathways have to be ranked considering several, sometimes conflicting, criteria (Albadvi et al., 2007).

To analyze the resilience of ES, the ranking of the pathways is discussed. The Wood Production and Profitability management scenarios

are generally bad scenarios (i.e. they have a negative Φ) meaning that they do not deliver the ES needed by the stakeholders while the others are generally good (i.e. they have a positive Φ) (Fig. 4). Little difference between the two climate change scenarios is evident as their ES values are quite similar.

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) (Fig. 4). For instance, the best pathways for the group that prefers all the ES are unsurprisingly the Users' Forest and Multifunctional Forest as they provide a diversity of ES. More surprisingly, the Biodiversity management scenario is the best one for the group that prefers the provisioning ES. 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. Anyway, two management scenarios (i.e. Users' Forest and Multifunctional Forest) 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.

Step 6: Take action

From the results of Step 5, the best management scenarios are the Users' Forest and the Multifunctional Forest. 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. 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 horsemen while others to the bikers). The DNF and the municipality of Sivry-Rance are continuously adapting this plan to the field depending on the health of the forest, the users' demands, and the lessons learnt from the implementation of this plan. For example, new hiking paths were created to meet the demand of the hikers.

4. Discussion

The implementation of the Navigate framework with the municipal forest of Sivry-Rance demonstrated the unique added values of both resilience and ES as well as the importance of considering the social perspective, and gave useful insights into the areas for improvement.

4.1. Unique added values of ES and resilience

The ES gave a comprehensive view of the SES and its interactions. Indeed, in the ES assessment, we have seen that different indicators of a given ES can have contrasting trends because each indicator reflects only one aspect of the ES. This indicates 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 is able to capture the full spectrum of values and that we need to select complementary valuation methods to cover all value dimensions.

The ES assessment also shows that in any pathway, some ES are not well provided. 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).

Resilience brings in the dynamic perspective of the SES. The integration of two drivers (i.e. climate change and varying social demand) in the analysis shows how they can impact the ES and subsequently the decisions made (Runting et al., 2017). 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
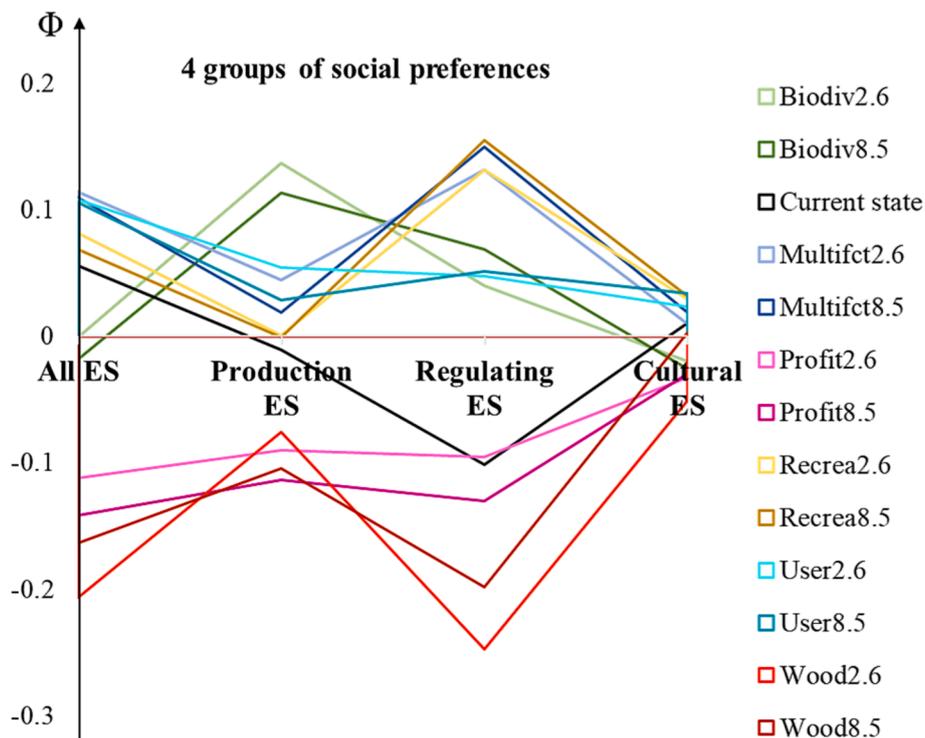
Fig. 4. Ranking of the current state and the twelve pathways forecast for 2085 based on the ES they provide and the social preferences of the four groups from the PROMETHEE software. Φ is the difference between the outgoing flow (i.e. how far a pathway outranks the others) and the incoming flow (i.e. how far a pathway is outranked by the others). The 'good' scenarios are the ones having a Φ > 0 while 'bad' scenarios have a Φ < 0. The higher is the Φ of a scenario, the better it is. With the following pathways: Biodiv2.6 = Biodiversity SSP1-2.6; Biodiv8.5 = Biodiversity SSP5-8.5; Multifct2.6 = Multifunctional Forest SSP1-2.6; Multifct8.5 = Multifunctional Forest SSP5-8.5; Profit2.6 = Profitability SSP1-2.6; Profit8.5 = Profitability SSP5-8.5; Recrea2.6 = Recreation SSP1-2.6; Recrea8.5 = Recreation SSP5-8.5; User2.6 = Users' Forest SSP1-2.6; User8.5 = Users' Forest SSP5-8.5; Wood2.6 = Wood Production SSP1-2.6; Wood8.5 = Wood Production SSP5-8.5.

et al., 2009; Runting et al., 2017). Indeed, climate change actually has a low impact on some ES; for instance, when the recreation infrastructure is still available and the visual characteristics of the forest do not drastically change. 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 a survey 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 asses ES incorporates climate change).

We have also 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. Therefore, to ensure that the

SES still meets the future needs of society, we need to take into account both environmental and social uncertainties (Seidl and Lexer, 2013).

4.2. Importance of the social perspective

The implementation of the framework also demonstrates the necessity of taking into account the social aspects that are still insufficiently considered in social-ecological research (Bretagnolle et al., 2019). We used various methods, ranging from surveys to participatory workshops, in every step of the Navigate framework. As every method has its blind spots (Jacobs et al., 2018), it is necessary to combine different participatory methods to reach the various stakeholders (e.g. in the users' surveys, we went directly into 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) and capture different points of view (e.g. in the users' surveys, we obtained the individual points of view of the stakeholders while in the participatory workshops, we obtained a collective point of view from a consensus between several stakeholders). As a result, a more complete understanding of the social aspect of the SES emerges (i.e. from each participatory method, we got one piece of the puzzle, and it is only by combining the pieces that we obtained a fuller picture).

Furthermore, the Navigate framework substantially gains from the involvement of the stakeholders. First, we broadened the understanding of ES and resilience by analyzing the cultural ES that are still largely disregarded in ES assessment (Cheng et al., 2019), the socio-cultural values of ES that are essential for interpreting the outcomes of the ES assessment (Breyne et al., 2021), and the social uncertainty that is still rarely accounted for despite its important role in the SES dynamics (Seidl and Lexer, 2013). The vulnerability of the stakeholders to climate

change was analyzed by looking at the ES and their respective stakeholders that are negatively impacted by climate change (e.g. the hunters will be negatively impacted by climate change as the hunting ES has on average lower values in SSP5-8.5 than in SSP1-2.6). Actions can then be designed to reduce the impacts of climate change on the ES and their respective stakeholders (e.g. tree diversity is planned to be increased to limit the degradation of the habitat quality for game).

Secondly, by informing and consulting the various stakeholders, the management plan of the municipal forest of Sivry-Rance became legitimate, transparent and a better fit with the needs of the stakeholders. Thirdly, the relationships between the stakeholders were improved as the potential conflicts between them were identified (i.e. from the stakeholders analysis, we know that conflicts can arise between the stakeholders negatively impacted by an ES and its owner, manager or beneficiaries) and measures were taken to reduce them. 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. Furthermore, the management plan became a collective solution where the stakeholders better understand 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).

4.3. Areas for improvement

Despite the attempt to be as holistic as possible, our analysis, 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; 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 (i.e. social-ecological definition and three forms 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.

Furthermore, every choice in the implementation of the Navigate framework has also implications. For example, in the participatory process, the representativeness of the stakeholders must be discussed. Both in the surveys and the participatory workshops, we recruited only the stakeholders who wanted to participate. Because we used the ecosystem services stakeholders matrix to select the stakeholders, we only identified the hat (i.e. the way they are related to the ES) of the stakeholders and not one individual. 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. Another example is the selection of the drivers: we only considered two drivers (i.e. climate change and the societal demand). By including other socio-economic drivers such as technical innovations or political changes (e.g. by considering the political aspects of the SSP scenarios that were not

integrated in our analysis), 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.

Furthermore, we did not have the time to go deeper into the resilience analysis because we spent a lot of time in the integrated assessment of ES and in the participatory process which are time-consuming but essential. We believe it is an important area of improvement of the Navigate framework. One way to do that is studying the temporal variation of ES over time. Indeed, we only assessed the ES in two specific time periods (i.e. currently and in 2085) without looking at how the ES could vary between these two time periods. 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. By analyzing ES over time, we could have understood how the ES and their interactions vary through time and how disturbances affect them. For example, Cantarello et al. (2017) 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. 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, for instance, 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., 2019; Egli et al., 2019; Van Strien et al., 2019).

To conclude, the Navigate framework accounts for the stakeholders' needs and perspectives and various forms of knowledge (Folke et al., 2010; Weichselgartner and Kelman, 2014) and addresses the trade-offs (Bennett et al., 2009) as well as the scales and their cross-scale interactions (Ruhl and Chapin, 2014). The interactions between the components are particularly important to study because they strongly characterize and influence the system (Brown, 2021), and they are an integral part of the solution (e.g. an ecological resilient system (in a desirable state) can produce a more resilient society (Hogan et al., 2021)). We also include the important drivers needed to understand the external factors that influence the SES so to avoid eroding resilience while managing the ES (Folke et al., 2004; Ruhl and Chapin, 2014; Seidl, 2014).

Other frameworks have been developed in the last years such as (1) Wayfinder by Enfors-Kautsky et al. (2021), (2) the analytical framework for resilience in regional management of Li et al. (2020), and (3) the conceptual framework illustrating the linkages between scenarios, models and relationships among ES for informing decision-making by Ikematsu and Quintanilha (2020). The first two frameworks put a strong focus on resilience while the last one uses ES modelling to analyze different scenarios. 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 reach sustainability. 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 analysing 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. Our Navigate framework is particularly suitable when the social aspects are predominant as a strong focus is put on society and its interactions with nature as well as stakeholder engagement. It is only applicable for researches or projects that have significant resources. Indeed, its implementation is time consuming and resources demanding to truly perform an integrated assessment of ES and resilience together with stakeholder engagement. Furthermore, a transdisciplinary team, including researchers of different disciplines and the stakeholders, is recommended to have the different and complementary methods needed for the integrated assessment and the skills for stakeholder engagement.

5. Conclusions

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).

We also demonstrated the importance of having a social perspective. 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.

With the Navigate framework, we propose a decision-support tool to explore different management strategies to find the best solution regarding the local context and the increasing uncertainty. Nevertheless, there is still room for improvement, particularly in the resilience analysis. There is already a number of researches analyzing the dynamics of the SES and its ES but they usually use only one method while the integrated assessment of ES advocates a combination of several complementary methods. Further research should be done on the integration of the dynamics of ES (i.e. how they vary over time and how they are impacted by disturbances) in the existing ES assessment methods. To further improve the Navigate framework, we invite researchers, practitioners and decision-makers to test this framework across different contexts and provide feedback.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

Appendixes

Annex A. 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; Horcea-Milcu et al., 2020; Ruhl and Chapin, 2014; Wu, 2013
Pairing of the ES and resilience concepts	Resilience is an ES	Díaz et al., 2018; Nahlik et al., 2012
	Resilience of ES	Biggs et al., 2015, 2012; Bradford and D`Amato, 2012; Cantarello et al., 2017; Kilonzi and Ota, 2019; Robards et al., 2011; Schoon et al., 2015; Sutherland et al., 2016; Temperli et al., 2012
	Resilience to sustain ES	Chapin et al., 2011, 2010, 2009b; Dawson et al., 2010; Fischer et al., 2006; Guerry et al., 2015; Lebel et al., 2006; Rist and Moen, 2013; Walker and Salt, 2012, 2006
	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	Field and Parrott, 2017; Lin et al., 2019; Nikinmaa et al., 2020; Polasky et al., 2011
	ES to manage for resilience	Hogan et al., 2021; Reyers et al., 2015
Critical analysis of ES and resilience	ES	Abson et al., 2014; Evans, 2019; Kull et al., 2015; Munns et al., 2015; Norgaard, 2010; Schröter et al., 2017, 2014
	Resilience	Baggio et al., 2015; Brand and Jax, 2007; Folke, 2016; Moberg and Hauge Simonsen, 2014; Newton, 2016; Olsson et al., 2015; Shahadu, 2016; Standish et al., 2014

Annex B. Synthesis of the 26 papers on the ES and/or resilience frameworks with their added values and limits as well as 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

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References	Framework's name	Concepts	Added values	Limits	Source of inspiration
Cavender-Bares et al., 2015	Framework to analyze 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	Focus on ES	Different terms to describe a concept to reveal the plurality of conceptualizations
			Multiple scales and their interactions are depicted	Conceptual framework that does not provide a method to assess the system	
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	Focus on ES	Multiple scales
			Multiple scales and their interactions are depicted	Conceptual framework that does not provide a method to assess the system	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 the concepts of 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 the concepts of 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 the concepts of 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 the concepts of ES and resilience Different forms of resilience Examples of implementation of this framework	Based on the resilience concept as we defined it in the paper 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 concepts consider together in a same framework

(*continued*)

References	Framework's name	Concepts	Added values	Limits	Source of inspiration
Enfors-Kautsky et al., 2021	Wayfinder framework	ES, resilience	The framework provides different steps to follow Different forms of resilience	The ES are not assessed	Planetary and social boundaries Pathways
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	Different steps to follow 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 the concepts of 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	The ES are not assessed	Different steps to follow

Annex C. 'Ecosystem services stakeholders matrix' of the municipal forest of Sivry-Rance.

Ecosystem services	Owner	Manager	Beneficiary	Negatively impacted	Influencer
Wood	Municipality of Sivry-Rance	Public Department of Nature and forest (DNF)	Merchants	Hunters	Walloon government (forestry code, land use code)
		Rural development associations	Wood sector	Recreation users	DNF (forest management plan)
		Municipality of Sivry-Rance	Inhabitants	Inhabitants	European Union (Natura 2000 legislation)
			Municipality of Sivry-Rance		
			CPAS (Public social action centre)		
Hunting		DNF	Hunters	DNF	
		Municipality of Sivry-Rance	Municipality of Sivry-Rance	Municipality of Sivry-Rance	
		Hunters		Recreation users	
				Forest operators	
				Pickers	
				River Contract[1]	
Picking		DNF	Pickers	DNF	Walloon government (forestry code)
				Municipality of Sivry-Rance	Municipality of Sivry-Rance (permit application to pick mushrooms)
				Forest operators	
				Hunters	
Fishing		Public Fishery Service	Fishing associations	Poachers	Walloon government (forestry code)
		Fishing associations	Fishers		European Union (Natura 2000 legislation)
		DNF			
Water quality and quantity		DNF	SWDE (Walloon public water company)		Walloon government (forestry code)
		Farmers	Local citizens		European Union (Natura 2000 legislation)
		River Contract	Fishers		
		Public Fishery Service			
Control of soil erosion and flooding		Farmers	Inhabitants		
		River Contract			
		Public Fishery Service			
Fauna and flora		DNF	DNF		
		River Contract	Bee-keeper		
			Naturalists		
Climate regulation and air purification		DNF	Local citizens		Walloon government (forestry code)
			Users		
Natural surroundings		DNF	Local citizens		
Recreation		DNF	Recreation users	Hunters	Walloon subsidies
		Cultural Centers[2]	Recreation associations	Recreation users (e.g. a biker on a pedestrian trail)	European subsidies
		Tourism associations	Tourism operators	DNF	

(*continued*)

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

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

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

Appendix D. List of the relevant ES studied in the municipal forest of Sivry-Rance with the connection with the CICES-Be V6 list (Turkelboom et al., 2013).

	List of relevant ES	CICES-Be V6
Provisioning ES	Wood	Plant fibres and materials
		Energy trees and woody residues
		Area for land-consuming productive activities
	Hunting	Edible wild animals, plants and fungi
		Area for land-consuming productive activities
	Picking	Edible wild animals, plants and fungi
		Edible water plants
		Ornamental plants & animals
		Landscape for outdoor recreation
	Fishing	Freshwater fish & shellfish
		Area for land-consuming productive activities
Regulating ES	Water quality and quantity	Surface water for drinking
		Ground water for drinking
		Surface water for non-drinking purposes
		Ground water for non-drinking purposes
		Water purification and oxygenation
		Nutrient regulation
	Control of soil erosion and flooding	Gravity flow protection (e.g. landslides, creep)
		Protection against water and wind erosion
		Natural flood protection & sediment regulation
	Fauna and flora	Pollination
		Maintaining nursery populations and habitats
		Control of (alien and/or local) invasive species
		Pest control
		Disease control
	Climate regulation and air purification	Capturing (fine) dust, chemicals and smells
		Global climate regulation by reduction of greenhouse gas concentrations
		Regional climate regulation (e.g. maintenance of regional precipitation patterns & temperature)
Cultural ES	Natural surroundings	Natural surroundings around buildings for living, working and studying
	Recreation	Green environment suitable for daily outdoor activities
		Landscape for outdoor recreation
	Nature observation, learning and inspiration	Natural landscapes and species for nature experience & education
		Landscape and biodiversity suitable for research
		Landscapes and species with cultural and symbolic values
	Natural heritage	Landscapes and species with cultural and symbolic values

Appendix E. A short description of the methods used to assess the ecosystem services (ES) in the current state and in the twelve pathways.

Method	ES	Description of the method
Data of forest management + IPRFW + expertise	Wood	From the data of the Walloon permanent inventory of forest resources (i.e. IPRFW - tool organizing the continuous characterization of the Walloon forest (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 the growing stock, the annual volume of harvested timber and the annual profit from timber harvesting of the different stands depending on the forest species and the site type (i.e. soil and

(*continued on next page*)

(*continued*)

Method	ES	Description of the method
		topographic conditions). Then, we summed up the value of each stand to have the total value of these three indicators for each pathway and in the current state.
Surveys of the forest users	Wood Hunting Picking Fishing Natural surroundings Recreation Nature watching, learning and inspiration	From 2019 to 2021, four surveys of the different forest users (i.e. hunter, fisher, recreation user and inhabitant harvesting firewood) were performed to understand their use of the forest (e.g. visit frequency, the reasons they come in the forest, the activities they do, what they like and dislike). From these surveys, we used the answers from the two following open 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? and the choice experiment. The choice experiment aimed to understand the users' preferences for the recreation infrastructures (e.g. path type, touristic information, infrastructures availability) and the forest characteristics (e.g. softwood vs hardwood, deadwood, tree height). Based on this information, we defined the ideal forest for each type of users. Then, we assessed, how close is the forest of the current state and of each pathway 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).
Literature review	Hunting Picking Fauna and flora Climate regulation and air purification Recreation Nature watching, learning and inspiration Natural heritage	A literature review was performed for each indicator to understand the forest and climate factors that influence the indicator. Then, we assessed to what extent each factor contributed positively or negatively to the indicator in the current state and each pathway, on a five-point scale ranging from very high (i.e. the forest contributes positively to the indicator for almost all the factors) to very low (i.e. the forest contributes negatively to the indicator for a majority of the factors).Here is the information used to assess each indicator:Habitat quality for game: Vospernik and Reimoser 2008, Reimoser et al. 2009, Morelle and Lejeune 2015, Colson and Baix 2020. Deer damage mitigation: Gerhardt et al. 2013, Spake et al. 2020 .Mean annual profit from hunting leases: Colson and Baix 2020, habitat quality for game, choice experiment of the hunters' survey, hunting method.Fungal potential distribution (abundance, occurrence, diversity including the edible ones): Olah et al., 2020, Pilz et al., 2001, Tomao et al., 2020, 2017.Habitat biological quality: Lejeune et al. 2007, Dorioz et al. 2018, Colson and Baix 2020, 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 .Forest temperature buffering capacity: Frey et al. 2016, Zellweger et al. 2019, De Frenne et al. 2019, 2021, Haesen et al. 2021 .Recreation supply, supply of nature watching, learning and inspiration areas, and supply of natural heritage areas: Colson et al. 2012, Pairon et al. 2022 .
Data from a paper	Water quality and quantity Control of soil erosion and flooding Fauna and flora Climate regulation and air purification	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. 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 of the indicators characterizing the ES, for each pathway and the current state.Bansept (2013) synthetized the minimal and maximal percentage of evapotranspiration, precipitation interception and infiltration of different land cover. For each pathway and the current state, we calculated the weighted mean by area of each land cover of the minimal and maximal percentage of these three indicators.Latte et al. (2013) developed a methodology to assess carbon stock in four forest pools in Wallonia: (1) aboveground living biomass, (2) belowground living biomass, (3) dead trees, and (4) soil biomass. We calculated the carbon stock in the four pools based on their methodology in each pathway and in the current state.
Existing model	Water quality and quantity	EcoServ-GIS (version V3.3) is a Geographical Information Systems (GIS) toolkit for mapping ES at the county or region scale (Winn et al., 2015). We calculated the water purification capacity score based on the Manning coefficient of each land cover (i.e. hydraulic roughness of the vegetation) and the slope, for each pathway and the current state.
	Fauna and flora	InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) (version 3.11.0) is a suite of open-source software models used to map and value the goods and services from nature that sustain and fulfill human life (Natural Capital Project, 2022). We derived, for each land cover, the insect pollinator nesting sites, floral resources and flight ranges from a literature review and data on floral resources and wild pollinators from Jacquemin et al. (submitted), the "Banque de Données Fauniques de Gembloux & Mons" ("BDFGM", established under the EU FP7 STEP project, (Rasmont and Iserbyt, 2014)) and the European Bee Traits database (Roberts, 2020). We entered these data in the InVEST Crop pollination model (Natural Capital Project, n.d.) to obtain the index of pollinator abundance on each cell of the landscape. We calculated a weighted mean of this index by area of each land cover to obtain the mean pollinator abundance of each pathway and the current state.
	Climate regulation and air purification	NVE (version 2.2 for Wallonia) (Nature Value explorer) focuses on pragmatic methods that value ecosystem services and helps planners, land managers and policy makers to map nature's socio-economic importance (VITO and Agency for Nature and Forests, Government of Flanders, n.d.). We used their formula that calculates the quantity of fine particles captured by the vegetation from the deposition rate defined for each land cover type, the concentration of fine particles and a resuspension constant (Pairon et al., 2022). 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 each pathway.

Appendix F. 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). The range taken by the indicator was divided in order to have all the five classes represented by a equivalent number of values. SSP1-2.6: Shared Socio-economic Pathway with a shift toward sustainability and a rising of the global temperature of 1.8 °C by 2100 and SSP5-8.5: Shared Socio-economic Pathway with 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	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
	Mean 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
	Mean 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

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