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MODELLING FOREST DYNAMICS TO ASSESS AND IMPROVE FOREST MANAGEMENT SUSTAINABILITY AT A REGIONAL SCALE: AN ANALYSIS OF FOREST CHANGES IN WALLONIA (SOUTHERN BELGIUM)

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Dissertation originale présentée en vue de l’obtention du grade de docteur en sciences agronomiques et ingénierie biologique

Promoteur : Pr. Philippe LEJEUNE
Copromoteur : Pr. Jacques HÉBERT
Année civile : 2020

Auteur : Jérôme Perin

Citation : Perin J. 2020. Modelling forest dynamics to assess and improve forest management at a regional scale: an analysis of forest changes in Wallonia (southern Belgium). Thèse de doctorat, Gembloux Agro-Bio Tech – Université de Liège, Gembloux, 182 p.

Covering one-third of the world's land, forests provide many essential resources and services on which more than 25% of the world's population directly depend for their livelihoods. Moreover, because of their importance in the carbon and water cycle and in the production of renewable materials, forests are one of the main means of mitigating the consequences of current and future global climate change. The need to balance ecological, economic and social roles to achieve sustainable management of forest resources is therefore evident from the local to the global scale.

Accurate and up-to-date information on forests dynamics is essential to design and implement sustainable forest management plans. In particular, the development of customized management scenarios based on forest stand characteristics require accurate growth and yield estimates that can only be derived from permanent forest inventory data.

This thesis focuses on the relevance of forest modelling from permanent forest inventory data to improve knowledge on current forest resource stocks and dynamics and help design sustainable forest management policies. The study concerns the forests of Wallonia, the southern Region of Belgium. Wallonia forests represent an interesting case study as they are intensively managed, highly fragmented, heterogeneous in structure and composition and undergoing fast change to adapt to new environmental and economic conditions.

The first part of this thesis concerns the research for an appropriate modelling methodology to assess the level of productivity and species-station suitability of forest plantations. We developed an easily replicable methodology relying on stem analysis data to fit robust site index (SI) models which make it possible to estimate the level of productivity of plantations according to their top-height and age. New SI models were calibrated for the three main plantation species in Wallonia: Norway spruce, douglas-fir and Larches. These new models make it possible to account for the significant changes observed in the SI distribution over time which caused biases in previous ones. Our work suggests that these changes are mainly due to later harvesting and lower replanting rate of softwood plantations located on less productive sites, practices that are not exclusive to Wallonia.

The second part of this work concerns the development of forest models able to accurately estimate the effect of original management scenarios on the development of forest resources. Using our new SI models and thousands of field experiment data allowed us to develop new harmonized growth models for even-aged pure stands of Norway spruce, douglas-fir and larches that have a wider validity than is possible with regional data. They highlight the very significant effect of stand density and social status on individual tree growth and demonstrate a lasting effect of early selective thinning on growth which does not decline as rapidly with age as previously thought. We also found that under similar growing conditions, douglas-fir yields are one-third higher than Norway spruce and larches. An economic analysis of the evolution of harvest revenues in Norway spruce and douglas-fir plantations also shows that although the actualized value of final harvests peaks at around 60 years, selective thinning can provide significant regular income until much later.

The final part of this thesis concerns the design of a forest modelling methodology that A) provides detailed estimates about stock, growth, yield and harvested volumes, B) allows a direct use of permanent forest inventory data for calibration and initiation of the simulation, and C) can be applied at the regional level. It resulted in the development of the individual-tree distance-independent forest model SIMREG which is based on permanent data from the Permanent Forest Inventory of Wallonia (IPRFW). The tree-level approach made it possible to identify several inconsistencies in previous estimates from the IPRFW. In particular, we conclude that the net growing stock increase between the first and the second IPRFW cycle was previously overestimated by several million m^3 while the total yield was underestimated by about 25%. These differences result from SIMREG's consideration of previously unmeasured forest resources and significant methodological changes between the two IPRFW cycles.

Our simulations also confirm the rapid decline of spruce in favour of douglas-fir and various hardwood species but suggest that the higher yield of douglas-fir and the renewal of aging/low productive Norway spruce plantations could mostly compensate for the net decline in softwood forest area.

We conclude that the standing stock of Walloon forests is managed sustainably overall but not at the species level. The decline of the Norway spruce plantations is arguably justified by numerous relevant reasons such as its presence in unsuitable stations, its sensitivity to drought, bark beetles and windfall damage, the higher yield of douglas-fir, etc. Nevertheless, Norway spruce is still the main production species in Wallonia and our work has resulted in several new recommendations to improve its management and that of its main substitute species: douglas-fir.

Forest modelling and simulation is a timely issue and similar work is currently being done worldwide. Although our study has focused on Wallonia, our modelling methods were designed to only use data collected by most permanent NFI. For example, SIMREG was successfully adapted to the Flemish and Brussels forests in order to develop the national forest accounting plan of Belgium. We are thus confident that our modelling framework is generalizable to other countries.

Couvrant un tiers des terres de la planète, les forêts fournissent de nombreuses ressources et services essentiels dont plus de 25% de la population mondiale dépend directement pour sa subsistance. En raison de leur importance dans le cycle du carbone et de l'eau et dans la production de matériaux renouvelables, les forêts sont également l'un des principaux moyens d'atténuer les conséquences du changement climatique mondial actuel et futur. La nécessité d'équilibrer les rôles écologiques, économiques et sociaux pour parvenir à une gestion durable des ressources forestières à toutes les échelles est donc évidente.

Des informations précises et actualisées sur la dynamique des forêts sont essentielles pour concevoir et mettre en œuvre des plans de gestion durable. En particulier, l'élaboration de scénarios de gestion personnalisés tenant compte des caractéristiques des peuplements forestiers nécessite des estimations précises de la croissance et de la production qui ne peuvent être obtenues qu'à partir de données d'inventaire forestier permanentes.

Cette thèse se concentre sur la pertinence de la modélisation à partir des données d'inventaire forestier permanent pour améliorer l'évaluation des ressources existantes et de leur évolution et aider à concevoir une politique de gestion durable des forêts. La zone d'étude est la Wallonie, la région qui occupe la moitié sud de la Belgique. Les forêts de Wallonie représentent un cas d'étude intéressant car elles sont très fragmentées, hétérogènes dans leur structure et leur composition, soumises à une gestion intensive et subissent des changements rapides pour s'adapter aux nouvelles conditions environnementales et économiques.

La première partie de cette thèse qui concerne ainsi la recherche d'une méthodologie de modélisation appropriée pour évaluer le niveau de productivité et l'adéquation essence-station des plantations résineuses. Une méthodologie facilement reproductible s'appuyant sur des données d'analyse de tiges a ainsi été développée pour ajuster des modèles robustes permettant d'estimer le niveau de productivité des plantations en fonction de leur hauteur de sommet et de leur âge. De nouveaux modèles de productivité ont ainsi été calibrés pour les trois principales essences résineuses de plantations de Wallonie : épicéa, douglas et mélèzes. Ils permettent de tenir compte de l'évolution récente de la productivité qui entrainait des biais dans les modèles précédents. Nos travaux suggèrent que cette évolution est due à une récolte plus tardive et à un taux de replantation plus faible des plantations résineuses situées sur des sites moins productifs, des pratiques qui ne sont certainement pas exclusives à la Wallonie.

La seconde partie de ce travail concerne le développement de modèles permettant d'estimer avec précision l'effet de scénarios de gestion originaux sur l'évolution des ressources forestières. Des modèles de croissance harmonisés pour les peuplements purs équiennes d'épicéas, de douglas et de mélèzes ont ainsi été développés sur base

de nos nouveaux modèles de productivité et de milliers de données issues de dispositifs expérimentaux. Ces nouveaux modèles ont une validité plus large que ce qui est possible avec des données régionales. Ils mettent en évidence l'effet très significatif de la densité et du statut social sur la croissance des arbres individuels et démontrent un effet durable des éclaircies sélectives précoces sur la croissance qui ne décline pas aussi rapidement avec l'âge qu'on le pensait auparavant. Nous avons également constaté que dans des conditions de croissance similaires, la production du douglas est supérieure d'un tiers à celle de l'épicéa et du mélèze. Une analyse économique de l'évolution des revenus issus des prélèvements dans les plantations d'épicéas de Norvège et de douglas montre également que, bien que la valeur actualisée des récoltes finales culmine à environ 60 ans, les éclaircies sélectives peuvent longtemps continuer à fournir un revenu régulier.

La partie finale de cette thèse concerne la conception d'une méthodologie de modélisation forestière pour A) fournir des estimations détaillées sur le stock, la croissance, la production et les volumes récoltés, B) permettre une utilisation directe des données d'inventaire forestier permanent pour le calibrage et le lancement de la simulation, et C) être compatible avec une application à l’échelle régionale. Elle a abouti à l'élaboration de SIMREG, un simulateur « arbre » indépendant des distances basé sur les données permanentes de l'Inventaire forestier permanent de Wallonie (IPRFW). Cette approche a permis d'identifier plusieurs incohérences dans les estimations précédentes de l'IPRFW. En particulier, nous concluons que la capitalisation du stock sur pied entre le premier et le deuxième cycle de l'IPRFW était auparavant surestimée de plusieurs millions de m³ alors que la production totale était sous-estimée d'environ 25%. Ces différences résultent de la prise en compte par SIMREG de ressources forestières jusqu'alors non mesurées et de changements méthodologiques importants entre les deux cycles de l'IPRFW.

Nos simulations confirment également le déclin rapide de l'épicéa au profit du douglas et de diverses essences feuillues. Elles suggèrent néanmoins que la production plus élevée du douglas et le renouvellement des pessières vieillissantes et peu productives pourraient en grande partie compenser le déclin net des surfaces enrésinées.

Nous concluons que, dans l'ensemble, le stock sur pied des forêts wallonnes est géré durablement, mais pas pour chaque espèce. Le déclin des plantations d'épicéas est certainement justifié par de nombreuses raisons pertinentes telles que sa présence dans des stations inadaptées, sa sensibilité à la sécheresse, aux dommages causés par les scolytes et les chablis, la production plus élevée du douglas, etc. L’épicéa reste néanmoins toujours la principale essence de production en Wallonie et nos travaux ont abouti à plusieurs nouvelles recommandations pour améliorer sa gestion et celle du douglas qui est sa principale essence de substitution.

La modélisation et la simulation forestière est une question d'actualité et des travaux similaires sont actuellement menés dans le monde entier. Bien que notre étude se soit concentrée sur la Wallonie, nos méthodes de modélisation ont été conçues pour ne nécessiter que des données collectées par la plupart des inventaires forestiers nationaux permanents. Par exemple, SIMREG a été adapté avec succès aux inventaires flamands et bruxellois afin d'élaborer le National Forest Accounting Plan de la Belgique. Nous sommes donc convaincus que nos méthodes et nos modèles sont généralisables à d'autres pays.

Cette thèse est l'aboutissement de 10 années de travail auquel de nombreuses personnes ont participé directement ou indirectement. Je remercie chaleureusement toutes celles et ceux qui m'ont aidé dans la réalisation de mon projet et plus particulièrement les personnes suivantes :

Jacques Hébert et Philippe Lejeune sans qui cette thèse n'aurait évidemment pas pu voir le jour. Merci de m'avoir accordé votre confiance, de m'avoir accompagné et épaulé tout au long de ce travail. Merci Jacques d'avoir toujours répondu présent lorsque j'avais besoin de ton aide, pour les innombrables heures passées à tester mes modèles, à relire et à corriger mes épreuves, ainsi que pour ta patience concernant mes nombreux angles morts. Merci Philippe pour ton approche pragmatique et constructive et de m'avoir inspiré à changer d'itinéraire plutôt que de continuer sur des voies qui se terminaient en cul-de-sac.

Yves Brostaux et Benoit Jourez qui m'ont apporté une assistance régulière au sein de mon comité de thèse. Merci Yves de m'avoir aidé à affiner mes analyses et mes modèles statistiques. Merci Benoit de m'avoir encouragé à développer les applications pratiques de mes modèles ; j'espère que nous aurons l'occasion d'intégrer la qualité du bois dans Gymnos.

Christine Deleuze, Holger Wernsdörfer et Patrick Dujardin qui ont accepté au pied levé la responsabilité de compléter mon jury de thèse. Merci de m'avoir aidé à sensiblement améliorer la qualité de mon travail ainsi que sa présentation grâce à vos questions, remarques et suggestions.

Hugues Claessens qui m'a toujours encouragé à diversifier mes connaissances et mes compétences. Merci Hugues pour tes précieux conseils et précisions concernant les domaines de la sylviculture et de l'autécologie qui m'ont aidé à mieux comprendre le pourquoi derrière les variables qui interviennent dans mes analyses et mes modèles.

Marie Fombona pour son support constant dans les activités moins visibles des dessous de la recherche. Je peux difficilement estimer les heures gagnées et les maux de tête évités grâce à ton aide pour naviguer les méandres de l'administration, compléter des documents et corriger mes épreuves.

Mikhail Pitchugin, Gauthier Ligot, Samuel Quevauvillers et Olivier de Thier qui ont programmé les outils informatiques présentés dans cette thèse. Merci Mikhail d'avoir rendu possible la matérialisation de mon modèle forestier régional, je suis impatient de continuer à l'améliorer avec toi.

Tous mes collègues Gembloutois passés et présents avec lesquels j'ai eu le privilège de travailler. Un remerciement particulier à Sébastien Bauwens, Nicolas Latte, Adeline Fayolle, Romain Candaele, Marie-Ange Golard, Cédric Geerts, Alain Monseur, Edwyn Defays, Adrien Schot, Frédéric Henrotay et Mathieu Alderweireld pour leurs importantes contributions à divers niveaux de cette thèse.

Mr. Jacques Rondeux qui m’a offert l’opportunité de commencer cette aventure au sein de l’unité de Gestion des Ressources forestières et des Milieux naturels de la Faculté universitaire des Sciences agronomiques de Gembloux.

Les services publics de Wallonie qui ont fourni le financement et les ressources nécessaires à la réalisation de ce travail au travers de l’Accord-Cadre de Recherche et de Vulgarisation Forestière et de l’Inventaire Permanent des Ressources Forestières de Wallonie.

Bonpapa, Bobonne, Papi, Mami, Papa, Didier et Maman qui m’ont toujours encouragé à poursuivre mes passions et m’ont transmis celles des sciences naturelles et agronomiques.

Tous mes amis et ma famille qui m’ont soutenu et m’ont aidé à recharger mes batteries quand je me sentais à plat et plus particulièrement Sam, Hélène, Sébastien, Florian, Pierrot, Bernadette, Jérémy, Mikhail et Alexandre.

Merci enfin à toi, Kristina qui m’a aidé à tenir bon dans les moments de stress intense et de doute qui ont ponctué cette thèse. Je n’aurai pas assez d’une vie pour te remercier mais je vais essayer quand même.

Wallonie
environnement
SPW

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Abbreviations

Alt	Elevation from sea level
AIC	Akaike Information Criterion
BMha	Total Biomass per ha (t/ha)
BS	Brier Score
Cbh or C_i	Circumference at breast height (cm)
Cdom	Mean circumference of the 100 largest tree per ha (cm)
Cg	Quadratic mean Cbh (cm)
Crel	Relative circumference (Ci/Cdom)
CV	Coefficient of Variation (SD/Mean)
Dbh	Diameter at breast height (cm)
dC_i or Ic_i	Cbh annual increment (cm/yr)
dG_i or Ig_i	Gbh annual increment (cm^2/yr)
dHdom	Hdom annual increment (m/yr)
Fext	Extension factor (reverted scale)
Gbh or G_i	Basal area at breast height (cm^2)
Gha	Total Basal Area per ha (m^2/ha)
Hdom	Mean height of the 100 largest tree per ha (m)
HW	Hardwood
IPRFW	Permanent Forest Inventory of Wallonia
ME	Mean Error
NFI	National Forest Inventory
Nha	Number of trees per ha (ha^{-1})
$Pcgha_{sp}$	Species share of the total basal area
StDev or SD	Standard Deviation
Sp	Species
SW	Softwood
PB	Public owner
PR	Private owner
PSP	Permanent Sample Plot
RMSE	Root Mean Square Error
SA	Stem Analysis
SI	Site Index (m)
TSP	Temporary Sample Plot
Vha	Total solid wood volume per ha (m^3/ha)

Chapter 1

Research Context

1. Introduction

Covering about 30% of the global land area (FAO, 2020), forests fulfil many roles, the critical importance of which has been heightened by recent developments and consequences of global warming (IPCC, 2014). Forests ecosystems represent 31% of the earth biosphere carbon stock (Pan et al., 2011) and continuously exchange CO2 with the atmosphere. They are a major source of renewable materials for the industry, energy and construction sectors and the highly energy-efficient processing of wood products strengthens their potential as “green” substitutes for steel, aluminium, concrete and synthetic polymers (Sathre, 2010).

Although significant progress has recently been made in many countries thanks to programs such as REDD+, the goal of global sustainable forest management is still far from being achieved (Keenan et al. 2015; Sloan & Sayer, 2015). The rate of net forest loss declined significantly these last decades but global forest area still decreased by 4.7 million ha per year between 2010 and 2020 (FAO 2020). There is also concern that these improvements could be threatened by recent developments (e.g. Margono et al., 2014; Enrici et al., 2016; Schielein & Börner, 2018). Moreover, deforestation may only be the tip of the iceberg as an additional 185 million ha of forests lost over 20% of their tree cover between 2000 and 2012 (FAO, 2016). While natural disturbances such as forest fire are on the rise (e.g. Aragão et al., 2018; Schielein & Börner, 2018), most global forest loss are still directly induced by human activities (Curtis et al., 2018).

In contrast, the European Union forest area (182 million hectares, 5% of the world’s forests) has expanded by about 11 million hectares between 1990 and 2010 and around 20% of it is currently protected under the Natura 2000 network. However, the temperate forests of Western, Central and Eastern Europe are already some of the most altered and reduced in original extent forest biome and almost no primary temperate forest remains (Gouvenain & Silander, 2016).

While remote sensing data allows for increasingly accurate estimates of forest resource stocks and their net changes between two time frames (Achard & Hansen, 2012), permanent forest inventory data are still required to properly assess forest growth and yield in managed forests (Romijn et al., 2015). Currently, the scarcity of permanent information about growth and harvest led to the usage of stock change approach to assess the sustainability of forest products management. Unfortunately, such approaches are very sensible to methodological changes related to the forest definition or the allometric relations used to estimate the stock from inventory data. Moreover, they generally do not provide much solution to potential management issue identified. In particular, accurate estimates about forest growth and yield are required to customization of management scenarios to optimize harvests without threatening forest sustainability.

National Forest Inventories (NFI) are the main source of information regarding forest resource state and change over time (Tomppo et al., 2010; Achard & Hansen, 2012; Vidal et al., 2016). NFIs use a wide variety of data acquisition methods (Tomppo et al., 2010), increasingly combining forest sample plot measurements with satellite or aerial remote sensing data (McRoberts et al., 2010; Achard & Hansen, 2012; Romijn et al., 2015). However, the lack of an internationally harmonized forest inventory methodology and changing needs has resulted in a multitude of methodological differences that can lead to inconsistencies and lack of comparability of NFI data across countries and time periods (McRoberts et al., 2010; Gabler et al., 2012). Yet, such comparability is essential to meet the growing needs for consistent global forest resources reporting (MacDicken et al., 2015). An international harmonization of information on forests has thus been initiated through the Global Forest Resources Assessment (FRA) and complemented by the National Forest and Monitoring Assessments (NFMA) to assist countries in developing national forest monitoring systems. In Europe, these harmonization efforts have recently been pursued through the European National Forest Inventory Network (ENFIN), the action COST E43 (Harmonisation of National Inventories in Europe: Techniques for Common Reporting) and the Horizon 2020 collaborative project DIABOLO (Distributed, Integrated and Harmonised Forest Information for Bioeconomy Outlooks).

Thus, there is a genuine interest in the development of simple generic analytical methods, models and tools that can easily be adapted to different forest inventory data in order to improve time series consistency and harmonize reporting.

2. Context

2.1. Study area

Our study focuses on Wallonia, the southern region of Belgium which is bordered by France to the west and south, Germany and the Grand Duchy of Luxembourg to the east, the Netherlands and Flanders to the north. It stretches over 200 km from east to west and 140 km from north to south covering a total area of 16 901 km^3 (around 55% of Belgium). The altitude varies from 20 m in the west (lower Belgium) to 690 m in the east (upper Ardenne).

The climate is temperate-oceanic: winters are generally mild and rainy and summers are warm and humid. Rainfall is generally well distributed throughout the year and dry periods are relatively rare and short. Rainfall and temperatures vary mostly according to the altitudinal gradient with annual estimates ranging from 800 mm and 10.5 °C in the west to 1400 mm and 7.5°C in the east (standards defined for the period 1981-2010 by the Royal Meteorology Institute).

Wallonia is the most densely forested region of Belgium: forests land use accounts for one third of the region's surface area and makes up about 80% of the country's total. Most of Wallonia's forests are located in the southern and eastern parts and in particular in the hilly natural region of the Ardenne, which contains almost half of Belgium's forests.

The forests of Wallonia are diverse (Table 1.1) and highly fragmented. Plantations of Norway spruce (*Picea abies (L.) H. Karst.*) are the main forest type and cover about 25% of the total productive forest area in Wallonia, followed by forests of native oak (*Quercus robur L.* and *Quercus petraea (Matt.) Liebl.*), common beech (*Fagus sylvatica L.*) and douglas-fir plantations (*Pseudotsuga menziesii (Mirb.) Franco*). Other notable tree species are birch (*Betula pendula Roth*), ash (*Fraxinus excelsior L.*), hybrid poplar (*Populus spp.*), larches (*Larix decidua Mill.*, *Larix kaempferi (Lamb.) Carr.* and *Larix x eurolepis*), scots pine (*Pinus sylvestris L.*), hornbeam (*Carpinus betulus L.*) and maple (*Acer pseudoplatanus L.* and *Acer platanoides L.*).

Table 1.1 Distribution of the forest area in Wallonia per main forest type estimated from the cycle 1 and first half of the cycle 2 of the IPRFW.

	Forest area (ha)		**Annual change**	
Forest type	**1994-2008**	**2008-2015**	**ha/yr**	**%/yr**
Pure native oak	84 650	82 200	-223	-0.3
Pure beech	43 600	44 400	73	0.2
Mixed oak/beech	24 150	29 600	495	1.8
Pure Birch	10 550	12 000	132	1.2
Pure poplar	9 100	7 700	-127	-1.5
Pure Ash	7 900	8 000	9	0.1
Misc. hardwood	66 300	77 500	1 018	1.4
Total hardwood	**246 250**	**261 400**	**1 377**	**0.5**
Pure N. spruce	153 650	123 200	-2 768	-2.0
Pure douglas-fir	13 850	20 300	586	3.4
Mixed spruce/douglas	8 900	12 000	282	2.7
Pure pine	12 150	8 300	-350	-3.4
Pure larch	7 550	7 000	-50	-0.7
Misc. softwood	10 350	11 200	77	0.7
Total softwood	**206 450**	**182 000**	**-2 223**	**-1.1**
Mixed hard/softwood	14 600	19 600	455	2.7
Recent clearcut	12 200	12 200	0	0.0
Total productive forest	**479 500**	**475 200**	**-391**	**-0.1**
Non-productive forest	74 500	81 000	591	0.8
Total forest land use	**554 000**	**556 200**	**200**	**0.0**

The forest area in Wallonia is divided almost equally between the public and private domains. Public forests are managed by the Department of Nature and Forests (DNF) of the Public Service of Wallonia (SPW), while the management of private forests is the responsibility of their owners which are about 100 000.

Significant management differences are observed depending on forest composition, structure and the type of owner (Alderweireld et al., 2015; Latte et al., 2016) but most Walloon forest stands are regularly thinned (every 5 to 12 years). Some 4350 ha of forest stands are clearcut every year, mostly softwood and poplar plantations (Latte et al., 2016). Harvested wood products are destined for various uses including sawn lumber, paper pulp, particle board, firewood, etc.

Currently, it is estimated (Latte et al., 2016) that about 2.5% of Norway spruce plantations are clearcut every year. This rate is generally considered unsustainable considering the recommended final felling age of 60 years for these plantations on suitable sites (Hébert et al., 2002). In addition, about 60% of those clearcuts are currently being replaced with other forest compositions (Latte et al., 2016) and some mature spruce plantations are gradually being transformed into mixed forest stands. This results in a rapid decrease of spruce forest area and growing stocks which raise a lot of questions about the future of the spruce sector in Wallonia and about the potential of douglas-fir as a replacement species.

2.2. *Permanent Forest Inventory of Wallonia*

Southern Belgium’s forest are monitored by the Permanent Forest Inventory of Wallonia (IPRFW) since 1994 and its first complete inventory cycle was completed in 2008. A second inventory cycle directly followed and is still ongoing. The IPRFW monitors an observation network consisting of 18 m radius permanent sample plots (PSP) installed at each intersection of systematic sampling grid of 500 m (north-south) x 1000 m (east-west) resulting in a sampling rate of 0.2% and approximately 11 000 PSP located in forest land area.

The latest IPRFW report on the totality of Wallonia's forest growing stock was authored by Alderweireld et al. in 2015. It presents the summarised data from the whole of the first cycle (1994-2008, mean date is 16 September 2000) and from the 30% of the sampling unit that were already remeasured at the time (2008-2012, mean date is 6 July 2010). Annual solid wood volumes growth and harvest were also estimated (Table 1.2) from a subset of the remeasured sampling unit that were first monitored during the second half of the first cycle (2000-2008, mean date is 6 July 2004), representing about 15% of a complete cycle.

Several inconsistencies have since been highlighted in this report, in particular concerning the estimates of growth and harvested stock. For example, the total harvesting rate (harvest/growth) between the two inventory cycles was estimated to be about 110% (Table 1.2), which appears inconsistent with the measured net increase in growing stock net of 5.16 Mm³ (516 000 m³/year).

Table 1.2 Previous IPRFW estimates (Alderweireld et al., 2015) of Wallonia's high forest living stock, growth and harvest of solid wood volume from the cycle 1 and first 30% of the cycle 2 of the IPRFW.

Tree species	High forest stock (10^3 m³)		Growth (10^3 m³)	Harvest (10^3 m³)	Harvest rate (%)
	1994-2008	**2008-2012**			
Native oak	20 980	23 040	384	243	63
Beech	14 260	16 100	444	428	96
Other hardwood	11 920	14 750	428	207	48
Total hardwood	**47 160**	**53 890**	**1 257**	**878**	**70**
N. spruce	50 210	45 820	1 986	2 840	143
Other softwood	10 530	13 350	516	425	82
Total softwood	**60 740**	**59 170**	**2 502**	**3 265**	**130**
Total	**107 900**	**113 060**	**3 759**	**4 143**	**110**

A thorough analysis of the IPRFW data and methodology was therefore conducted to identify the origin of these discrepancies. It revealed that these were not caused by simple measurement errors but by a combination of factors related to the IPRFW methodology. Several particularly significant sources of potential uncertainty in the estimation of stock change, production and harvest were identified:

- Changing methodology between the first and the second cycle of the IPRFW. In particular, the second cycle includes 1.7 Mm³ of trees located in linear stands that were not measured in the first one;
- The IPRFW included no methods to estimate unmeasured resources in inaccessible and impenetrable forest stands that represent about 7% of the total productive forest area;
- The inventory data used to estimate production and harvests are only a subset of those used to estimate stock changes. Moreover, this subset is representative of a significantly different and shorter time period as it only includes PSP that were monitored during the second half of the first cycle;
- The volumes produced and harvested are not estimated in about 15% of the PSP because they were displaced between their first and second monitoring;

- The coppice growing stock is not always included in forest volume estimates and the corresponding growth and harvests are not estimated. Yet, coppice represented a growing stock of about 5.8 Mm^3 in the first cycle that increased by about 165 000 m^3/year.

As a result, a questioning of the stock change, growth and harvest IPRFW estimates was due. A method for estimating unmeasured stand characteristics has since been developed in collaboration with the IPRFW. Although no tree measurements are made in unmeasured stands, stand-level information about their composition and structure are always available and often supplemented with top-height, plantation age and density estimates. These data are usually sufficient to accurately estimate the average characteristics of unmeasured trees using simple allometric models based on the data measured by the IPRFW. This makes it possible to complete the assessment of growing stock and to compensate mismatches between inventory cycles that led to biased estimates of stock change. The adjusted growing stock estimates for cycle 1 and the first half of cycle 2 (2008-2015, mean date is 27 November 2011) of the IPRFW are presented in table 1.3. They indicate that the total increase in stock was significantly overestimated by previous estimates.

Table 1.3 Complete forest growing stock estimates for Wallonia including high forest, coppice and unmeasured stands from the cycle 1 and first half of the cycle 2 of the IPRFW.

	Forest stock (10^3 m^3)		**Annual change**	
Tree species	**1994-2008**	**2008-2015**	**10^3 m^3/yr**	**%/yr**
Native oak	22 456	24 656	200	0.8
Beech	14 142	15 876	158	1.1
Ash	3 133	3 857	66	1.9
Birch	3 493	3 991	45	1.2
Hornbeam	2 618	3 227	55	1.9
Mapple	2 060	2 883	75	3
Poplar	1 922	1 759	-15	-0.8
Misc. hardwood	5 093	6 285	108	1.9
Total hardwood	**54 918**	**62 534**	**692**	**1.2**
N. spruce	53 123	47 858	-479	-0.9
Douglas-fir	4 692	6 589	173	3.1
Larches	2 647	2 683	3	0.1
Pines	3 575	3 366	-19	-0.5
Misc. softwood	1 016	1 116	9	0.8
Total softwood	**65 052**	**61 612**	**-313**	**-0.5**
Total	**119 971**	**124 145**	**380**	**0.3**

However, it appeared that this method was not sufficient to adjust growth and removals estimates that vary significantly according to several stand and tree characteristics. Therefore, the need for a precise regional forest model to extrapolate growth and harvesting to the entire resource became evident. Moreover such a model is needed to forecast the effect of the current significant forest composition changes (Table 1.1) on the future availability of wood products for the industry.

2.3. Forest modelling

Several modelling approaches have been used to simulate the development of forest resources depending on the nature and the purpose of the model, the data available and considerations related to software and hardware limitations.

Models are often classified as mechanist or empirical depending on whether they focus on causal or correlational relationship:

- Mechanistic forest models are usually designed to answer fundamental research questions, provide new knowledge and predict the potential effect of conditions for which no data already exist. These models are often very demanding in terms of experimental data for their calibration and resource intensive for their operation.
- Empirical forest models are more often designed as practical solution to applied research questions. Classical applications of these models concern the quantification of forest resources or decision support for their management. As such, they commonly try to take advantage of already existing data but the respect of their area of validity is much more critical.

Porté & Bartelink (2002) proposed another interesting classification of forest models based on their spatial resolution and explicitness that is presented in the figure 1.1. The interest of this classification is that it provides an overview of the level of detail represented in the model and consequently required in the data for its construction.

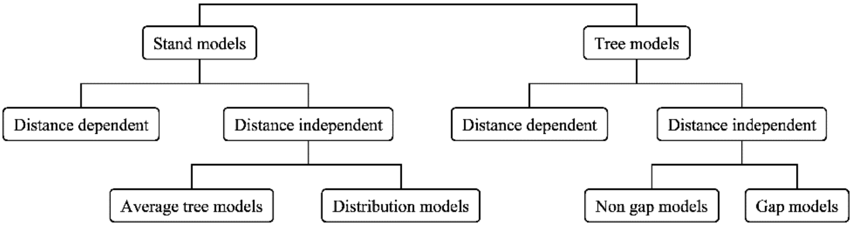


Figure 1.1 Forest growth models classification (Porté & Bartelink, 2002).

Whole stand models have been chosen for a wide variety of applications, from classic forest management tools such as site index models and yield tables to large scale forest simulation models (e.g. Sallnäs, 1990; Nabuurs et al., 2000; Vauhkonen et al., 2018) because they are generally simpler to calibrate and operate. However, these types of approaches are hardly suited to account for the potentially infinite combinations of composition, structure and management encountered in temperate forests (Pretzsch et al., 2008; Pretzsch et al., 2015). This results in an evident loss of information on forest composition and structure, leading to less precise and detailed estimates of yield and harvested volumes.

Conversely, distance-dependent tree-level approaches (e.g. Courbaud et al., 2001; Pretzsch et al., 2002; Chertov et al., 2006) make it possible to accurately represent the heterogeneity of tree species and size distribution inside a forest stand. However, the data needed to calibrate such models are difficult to acquire and spatial explicitness generally increase the computation needs by several orders of magnitude. Their operation thus requires a large amount of computing power, making them generally incompatible with large-scale applications (Taylor et al., 2009).

Tree-level distance independent models (e.g. Monserud & Sterba, 1996; Le Moguédec & Dhôte, 2012; Stadelmann et al., 2019) represent an interesting middle ground. First, it appears possible to optimize their operation for large-scale applications by limiting interactions between simulated trees, which always exponentially increase the calculation needs. Second, the data needed for their training are compatible with what is already collected by most permanent forest inventories. Finally, they are often only slightly less precise than distance-dependent ones (e.g. Wimberly & Bare, 1996; Contreras et al., 2011) and spatial variability can still be emulated using stochastic processes, gap models (Porté & Bartelink, 2002) and/or virtual neighbourhoods distribution (Perot et al., 2009).

Gap models are an interesting sub-type of tree-level distance-independent models that divide the simulated trees into different subareas or “gaps”. Using stochastic processes, the trees characteristics (composition, structure, etc.) can develop separately in each gap to represent the heterogeneity of the forest resource. This also allows these models to use variables aggregated at the gap level to simulate the effect of local competition. No interaction between gaps needs to be considered, which greatly simplifies the application of this type of model.

3. Research strategy

3.1. General objectives

This thesis is part of the research and development of models aimed at improving knowledge about the current state of forest resources, their management and ongoing changes. We attempt to provide some answers to the general questions: **What are the main factors influencing forest development?** And **How can forest modelling assist in the assessment and management of forest resources?**

An important challenge encountered in applied forest research stems from the vastly different scales at which the various parties involved in the forest sector work:

- Forest researchers often study how trees react to their environment;
- Foresters work at scales ranging from trees (selective thinning) to forest stands (clearcut, reforestation, etc.);
- Forest planners have to balance wood production, yield and harvest over time in a management area consisting of multiple forest stands;
- The wood industry is interested in the availability of wood products per species, size class and other relevant characteristics;
- Policy makers need to be able to make informed decisions that will impact large regions or even entire countries.

Consequently, developing multifunctional forest models capable of balancing the needs of those actors is difficult and rarely pursued. This has resulted in a multitude of very specialized modelling methodologies depending on the objectives and target users.

Our research stands out because we focus on finding robust multifunctional modelling methodologies that require only classic inventory data that are currently already collected in most countries. In this way, our modelling methodologies are conceived to be easily generalizable to other conditions and provide useful and convenient tools to assist in forest assessment and management. Finding a compromise between the diverse needs of forest stakeholders require models that operate at the level of the lowest common denominator, which is the tree. Considering their various advantages and in particular their high compatibility with forest inventory data, a tree-level distance-independent modelling approach appears interesting for this purpose. The final objective of this research is to evaluate the applicability of such an approach on a large scale and over a wide range of composition and structure.

3.2. Published work

Our thesis is structured around three scientific publications (in English) and two popular science papers (in French) introducing increasingly complete and multifunctional models to estimate forest development at larger scales:

- Perin J., Hébert J., Brostaux Y, Lejeune P., Claessens H. 2013. Modelling top-height Growth and Site Index of Norway Spruce. *Forest Ecology and Management* 298, 62-70.
- Perin J., De Thier O., Claessens H., Lejeune P., Hébert J. 2014. Nouvelles courbes de productivité harmonisées pour le douglas l'épicéa et les mélèzes en Wallonie. *Forêt Wallonne* 129, 26-41.
- Perin J., Claessens H., Lejeune P., Brostaux Y., Hébert J. 2016. Distance-independent tree basal area growth models for Norway spruce, Douglas-fir and Japanese larch in Southern Belgium. *European Journal of Forest Research* 136, 193-204.
- Perin J., Hébert J., Lejeune P., Claessens H. 2016. De nouvelles normes sylvicoles pour les futaies pures équiennes d'épicéa et de douglas en appui à la gestion de la forêt publique en Wallonie. *Forêt.Nature*, 139 : 57-67.
- Perin J., Pitchugin M., Hébert J., Brostaux Y., Lejeune P., Ligot G. 2020. SIMREG, a tree-level distance-independent model to simulate forest dynamics and management from national forest inventory (NFI) data. *Currently submitted to the journal Ecological Modelling*

Part of this work has also been integrated into the CAPSIS (Computer-Aided Projection of Strategies In Silviculture) project (Dufour-Kowalski, 2012). CAPSIS is a simulation platform for forestry growth / dynamics models developed in the AMAP laboratory of the CIRAD since 1999. Thanks to its flexible architecture, its openness to all interested scientists and the programming training session that it can provide, the CAPSIS community of forest modellers is growing rapidly and currently involves 80 active projects. This made it possible to implement our models into an accessible environment to run simulations and compare forest development scenarii.

3.3. Specific objectives and structure of the research

This thesis is divided in 7 chapters beginning by an introduction of the context and objectives and ending by a general discussion. Chapters 2 to 6 are based on the published work listed in the previous section.

Chapter 2 compares the performances of several well-known Site Index models on a dataset consisting of Norway spruce stem analysis data. It addresses questions such as "**are earlier site index estimations methods still reliable?**" and "**are stem analysis an appropriate substitute for long term permanent tree growth records?**" More generally, this chapter outlines the notable uncertainties and limitations associated with the reliance on non-permanent data to estimate forest development.

Chapter 3 applies the modelling methodology developed in chapter 2 to compare the Site Index distribution in pure even-aged stands of Norway spruce, douglas-fir and larches. It allows us to looks at **how do top-height growth and site index distribution differ between species?**

Chapter 4 covers new harmonized distance-independent individual tree growth models calibrated for Norway spruce, douglas-fir and Japanese larch plantations. These models were developed to investigate **what is the effect of site index and tree competition on individual tree growth?**

Chapter 5 introduces new updated yield table for Norway spruce and douglas-fir plantations produced using Gymnos, a forest simulation software integrating the models presented in the previous chapters. This chapter directly addresses **how productivity and management (planting density, selective thinning …) do interact and affect growth and yield?**

Chapter 6 describes the development and operation of SIMREG, a very complete forest model calibrated on data from the IPRFW to simulate growth, harvests and regeneration at the tree-level while being applicable at a regional scale. This chapter provides answers to some general research questions such as "**what are the main controlled factors affecting forest development?**" and "**are forest gap models suitable to complement and support national forest inventory estimates?**"**.** We also reply to some important local questions as to "**what are the main drivers of forest changes?**" and "**are the management of wood products sustainable?**" in the context of Wallonia's forests.

Chapter 7 summarises the main results achieved in the previous chapters and discusses their implications for forest research and management.

Chapter 2

Site index modelling

Adapted from

Perin J., Hébert J., Brostaux Y, Lejeune P., Claessens H. 2013. Modelling top-height Growth and Site Index of Norway Spruce. Forest Ecology and Management 298, 62-70.

1. Preamble

Site index models are important tools for forest research and management that helps assess the sites-species suitability and the resulting productivity. Until recently, most of the site index models used in Wallonia were still based on outdated data and statistical methods and their validity was being questioned. This chapter presents the development of a new, robust yet easy-to-implement site index modelling methodology to update those important tools.

2. Introduction

For a given tree species, the top-height (or dominant height) of a forest stand at a given age is well known for its strong correlation with the production potential of forest sites (Spurr, 1952; Hägglund, 1981; Clutter et al., 1983; Kramer, 1988; Sharma et al., 2002). This productivity indicator is also faster and easier to use than the mean annual growth in volume and is, to a certain extent, independent of planting spacing and thinning (Sjolte-Jørgensen, 1967; Lanner, 1985, Skovsgaard & Vanclay, 2008). Consequently, height growth models (or site index models) are commonly employed to estimate and classify the potential production of forest stands and represent an important component of forest growth prediction systems.

For coniferous species, top-height is generally defined as the height of the largest suitable tree in a 1 are (0.01 ha) plot (Rennolls, 1978; Forest Productivity Council, 1988) or the mean height of the x largest suitable trees in an x ares plot (Pardé & Bouchon, 1988; Rondeux, 1999). This last method is the one applied by the Permanent Regional Forest Inventory of Wallonia (IPRFW).

Three types of data are usually employed to adjust site index curves: temporary sample plot (TSP), permanent sample plot (PSP) and stem analysis (SA) data. PSPs are considered to be the best source of measurements for site models (Spurr, 1952; Hägglund, 1981; Clutter et al., 1983); however, they require repeated measurements over the course of several years in order to obtain usable datasets. SA deduces past height growth from growth-ring observations made on dissected sample trees. SA is the fastest way to obtain extensive growth information without the need for long term records (Curtis, 1964). However, it is always uncertain whether dominant sample trees have been dominant all their live or not, which could result in bias (Dahms, 1963; Magnussen & Penner, 1996; Raulier et al., 2003; Hu & Garcia, 2010).

Many growth model equations, adjustment methods and statistical procedures have been applied in order to construct site index models. Chapman-Richards, Johnson Schumacher, log-logistic models and variations of those models have probably been the most commonly used for site index modelling (e.g. Cieszewski, 2003; Weiskittel et al., 2009; Hu & Garcia, 2010). Methods employed to fit height growth models to a given dataset include the guide curve method, the parameter prediction method and the difference equation method (Clutter et al., 1983; Wang et al., 2008) through the application of alternative statistical procedures such as fixed parameter, dummy variable, or mixed parameter non linear regression (Weiskittel et al., 2009). Significant differences in performance can exist between models and fitting methods applied to a given dataset (e.g. Rathgeber et al., 2004; Krumland & Eng, 2005; Cieszewski & Strub, 2008). The best combination is very likely to be species dependent, but the issue is still being debated in the literature (Cieszewski & Strub, 2007; Wang et al., 2008).

According to Lecomte et al. (2006), Norway spruce (Picea abies (L.) Karst.) is the main wood production species of Southern Belgium. Spruce stands occupy about one third of the total forest area and account for more than 50% of the total wood volume production of this region. 98% of Southern Belgium spruce stands are even-aged, monospecific and of planted origin; 90% of these stands are found on acidic soils of the Ardens ecoregion, located at altitudes above 300 m (highest elevation point of Belgium is 694 m on the Ardens plateau).

The site index curves for Norway spruce currently in use in Southern Belgium were established by Dagnelie et al. (1988) using the modified Gaussian model formulation and the guide curves method on TSP data. However, these site index curves do not accurately describe the top-height increment rate that has been observed and measured in many sample plots from the IPRFW. Consequently, designing new site index curves had become essential in order to better assess the top-height growth in current spruce stands. These site index curves will constitute the first step in producing new yield tables.

3. Material

The study concern the southern Belgium at the south of the river Meuse, most of the stands are located in the Ardens ecoregion (Figure 2.1). All SA and PSP measurements were collected in even-aged stands where Norway spruce accounts for more than 80% of the total basal area. The past silvicultural treatments applied to sampled stands are generally unknown but spruce silviculture in Belgium is widely based on even-aged stands established by planting high density (2000 to 3000 /ha) of 3 years old planting stocks (Lecomte et al., 2006). Observations made in the sampled stands (logging residues, density, etc.) showed that most of them were regularly thinned. Unthinned stands are known to be fairly uncommon in Southern Belgium.

PSP data (Figure 2.2) were obtained from the Permanent Regional Forest Inventory of Wallonia (IPRFW) database. The sampling method applied by the IPRFW is a single-phase, non stratified inventory using a systematic sampling design with plots at the intersections of a 1000 m (east-west) x 500 m (north-south) grid. One-tenth of these PSP are remeasured each year according to a predefined scheme ensuring that the whole territory is uniformly covered (Rondeux et al., 2010). This ensure that this dataset represents all site conditions and the wide range of top-height, age and densities encountered in even-aged spruce mature stands of Southern Belgium. As of August 2012, a total of 282 sample plots in Norway spruce stands were already measured twice at intervals of 7 to 15 years. Following data quality control, the PSP dataset was composed of 265 top-height increments (530 top-height-age couples) and the corresponding basal area at first measurement. The main characteristics of the sampled stands are presented in table 2.1. Unfortunately, there were not enough data from stands under age 25 or over age 80 for the development of the new top-height growth model.

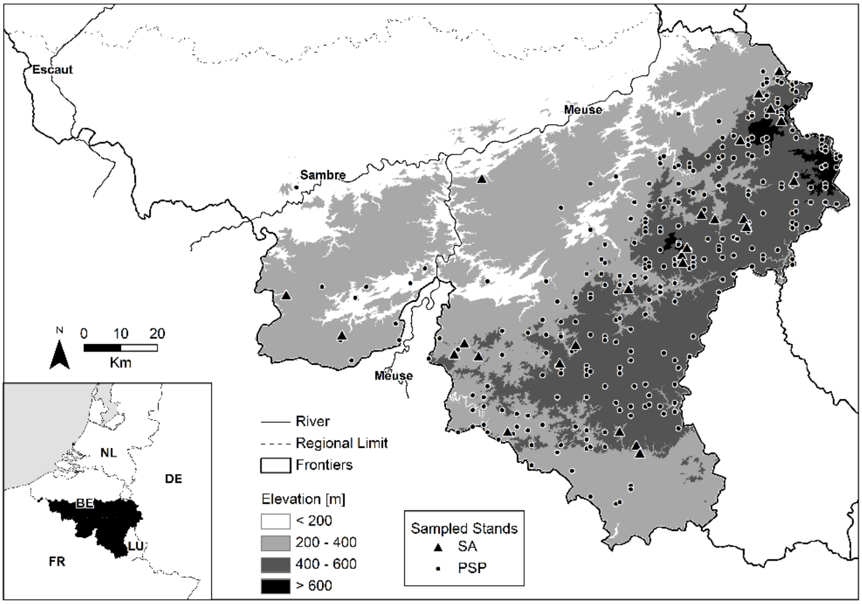


Figure 2.1 Repartition of the 291 sampled stands in the study area. The 265 permanent sample plots (PSP) are represented by round dots and the 26 sampled stands where stem analysis (SA) were conducted are represented by triangular dots.

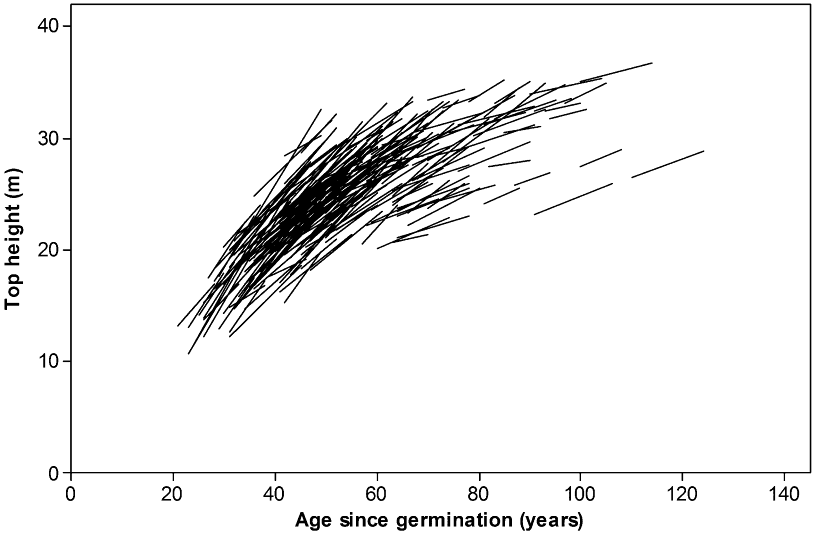


Figure 2.2 Permanent sample plot (PSP) dataset consisting of 265 top-height increments measured in PSPs established in stands aged 18 to 123 years at the time of measurement.

Table 2.1 Main attributes of the 265 PSP from the IPRFW database.

Attribute	MEAN	S.D.	MIN	MAX
Elevation (m)	444.2	104.6	160.0	677.0
Slope (%)	7.5	6.7	0.0	37.0
N (N/ha)	653.6	454.4	49.3	2546.4
G (m²/ha)	39.3	12.0	7.9	74.7
Age (years)	54.8	17.5	21.0	124.0
Hdom (m)	24.9	4.9	10.7	36.8

In addition, 86 SAs have been carried out in 26 pure Norway spruce stands aged 46 to 136 years (Figure 2.3). The sampled stands were selected to include the most diversified site conditions where Norway spruce is found in Southern Belgium in order to represent the largest range of site index as possible. Altitude range from 194 m to 621 m and the most frequent soils where spruce was planted are represented: acid soil with different moisture levels (from peaty soil to well drained soils) and nutrient availability (from podzolic soils to former agricultural land).

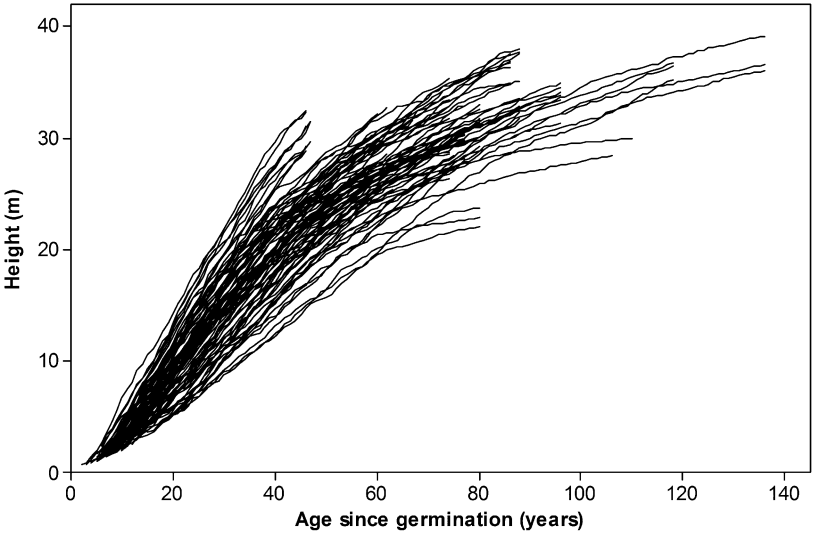


Figure 2.3 Stem analysis (SA) dataset consisting of 86 SAs in 26 pure Norway spruce stands aged 46 to 136 years at the time of measurement.

All these stands had reached harvesting dimensions (minimum 40 cm mean diameter at breast height: dbh), and measurements were performed during clearcutting, allowing to select dominant trees. In each stand, SAs were performed on trees whose dbh was the nearest to the mean dbh of the 10 largest trees within a circular temporary plot of 0.1 ha established in the middle of the sampled stand. It was originally planned to perform 4 SAs per stand but, due to technical constraint during the clearcutting, only 2 and 3 SAs per stands were performed in 4 and 10 of the 26 stands. Accurate height-age estimates were obtained by measuring the heights of all the branch whorls from the tree base all the way up to the top bud. Since branch whorls are formed every vegetation season (Riou-Nivert, 1996), the distance separating two consecutive whorls corresponds to the tree's height growth in a given year. Interestingly, this type of measurement can yield nearly as many height growth values as there are growth years. Cross sections were performed at several heights on each sampled trees to ensure the accuracy of the method. Since the age of the trees was known (due to the stand history and by counting the tree rings at the base), each whorl could be matched with its corresponding age (counting down from the top bud). The SA dataset was composed of 5975 height-age couples, which covered heights from 0.7 to 39.2 m and ages ranging from 2 to 136 years.

4. Methods

Breast-height age is known to reduce variability in the stand top height growth due to early growing conditions unrelated to site quality but which may nevertheless influence the stand site index. Consequently, the use of breast-height age may result in an improvement in the fitting indicators that is not necessarily linked to real improvement in the performance of the parameterized model. Moreover, total age is the most practical reference for future uses of the parameterized model and we thus chose to use it rather than breast-height age.

Several well-known growth model forms were selected (Table 2.2) to be evaluated on the SA dataset: Mitscherlich (1), Gompertz (2), modified Gaussian (3), log-logistic (4), arc-tangent (5), hyperbolic amplitude (6), Johnson Schumacher (7), Chapman-Richards anamorphic and polymorphic (8-9), Bailey & Clutter anamorphic and polymorphic (10-11) and Duplat & Tran-Ha I to V (12-16). Formulations for models 1-7 were taken from Debouche (1977); those for models 8-16 were taken from Rathgeber et al. (2004).

The equations were fitted using a nonlinear mixed effect regression with the nlme package (Pinheiro et al., 2012) in R (R Development Core Team, 2011). Residual autocorrelation and heteroscedasticity were addressed using the continuous first order autoregressive procedure (CAR1) and a variance power function of total age. Parameterizations were made on age since germination rather than age since planting, as most of the tested models predict a height of zero for age equal to zero. For each model, only one parameter was fitted individually in order for each stand to express its productivity level; a tree level random effect was also added on this parameter to account for differences between SAs made in each stand. A unique fixed value was fitted to the whole dataset for each of the other parameters: we will refer to these as shape parameters. This makes it possible to find an algebraic solution to site index calculation, which means that the site index (SI) can be estimated from any height-age couple without resorting to other regression or iterative processes.

Table 2.2 Formulation of the various models tested. The productivity level parameter is always represented by "bi" and shape parameters by "a", "c", "d", "p" and "r".

N°	Name	Formulation
1	Mitscherlich	bi*(1-exp((a-Age)/c))
2	Gompertz	bi*exp(-exp((a-Age)/c))
3	Modified Gaussian	$bi*(1-exp(-(((Age-a)/c)^2)))$
4	Log-logistic	$bi/(1 + (Age/a)^{-c})$
5	Arc-tangent	(bi/π)*(π/2 + atan((Age-a)/c))
6	Hyperbolic amplitude	(bi/π)*(π/2 + asin(tanh((Age-a)/c)))
7	Johnson Schumacher	bi*exp(-c/(Age-a))
8	Chapman-Richards anamorphic	$bi*(1 - exp(-a*Age))^c$
9	Chapman-Richards polymorphic	$a*(1 - exp(-bi*Age))^c$
10	Bailey and Clutter anamorphic	$exp(bi+a*(1/Age)^c)$
11	Bailey and Clutter polymorphic	$exp(a+bi*(1/Age)^c)$
12	Duplat and Tran-Ha I	$(a*Age+bi)*(1-exp(-(Age/c)^d))$
13	Duplat and Tran-Ha II	$(a*Age+bi)*(1-exp(-(Age/c)^d))+p*Age$
14	Duplat and Tran-Ha III	$(a*Age+bi)*(1-exp(-(Age/c)^d))^r+p*Age$
15	Duplat and Tran-Ha IV	$(a*ln(Age)+bi)*(1-exp(-(Age/c)^d))$
16	Duplat and Tran-Ha V	$(a*ln(Age)+bi)*(1-exp(-(Age/c)^d))+p*Age$

The resulting parameterizations of the equations had to follow several rules for further consideration. First, all shape parameters must be significantly different from zero with a probability of at least 95%. The parameterized model must also have a sigmoidal form and must produce no outliers over the entire range of possible ages or the site index.

Each parameterized model was then applied to the PSP dataset for validation. The first height-age couple (initial measurement) was employed to estimate productivity level parameter values for each stand. We were then able to predict the top-height of those stands at the age of the second measurements, which we compared with the measured ones.

Parameterized models were then compared according to their maximized log-likelihood, Akaike Information Criterion (AIC), root-mean-square error (RMSE) and distribution of residuals for SA and PSP datasets. The maximized log-likelihood can be used to compare model formulations but it is necessary to penalize more complex models by substracting between 0.5 and 2 log-likelihood units for each additional parameter (the AIC correspond to substracting 1 unit). The probability that a model with a higher AIC (AICmax) minimize the information loss compared to a model with a lower AIC (AICmin) can be estimated by calculating their relative likelihood: exp((AICmin−AICmax)/2). Thus, a difference of more than 6 units between the AIC of two models fitted on the same dataset may be considered significant (relative likelihood < 0.05).

Further analyses were made on residuals based on the average annual increases in height (Hf-Hi)/(Agef-Agei) predicted and measured over these periods rather than solely on total height prediction. Models in which a relationship was found to exist between residuals and ages or initial height or productivity level parameter values were considered as biased. All residuals presented were calculated by subtracting the measured value from the predicted value.

5. Results

Mitscherlich, Gompertz, modified Gaussian, arc-tangent and hyperbolic amplitude parameterized models (1, 2, 3, 5, 6) were characterized (Table 2.3) by the poorest statistics for AIC, RMSE and ME (with lower values for AIC and RMSE being better and value for ME closer to zero being better). Graphical analyses of the errors distributions showed us that all these models were giving significantly underestimated height growth predictions before age 50.

The best fitting statistics (Table 2.3) were provided by the Duplat and Tran-Ha parameterized models I, II, III and V (12, 13, 14 and 16). These models were characterized by AIC values at least 50 units lower than those of the other candidate models, which is very significant. Further analyses showed that the Duplat & Tran-Ha parameterized model V (16) was characterized by some highly correlated parameters and that the simplification needed to avoid this problem led to a model formulation similar to the Duplat & Tran-Ha model II (13).

Graphical analyses of error distribution, height and annual height increment prediction were used to find explanations for the poorer fitting performances of the other candidate models. The log-logistic (4) and Chapman-Richards anamorphic (8) were found to give a slight underestimation for annual height growth for trees before age 40. The Johnson Schumacher (7) model was inadequately expressing height growth before age 20. The Chapman-Richards polymorphic model (9) was characterized by a horizontal asymptote lower than the top-heights observed in several of the stands from the IPRFW. The Bailey & Clutter models (10 and 11) tended to significantly underestimate height growth before age 25. The Duplat & Tran-Ha IV (15) models predicted negative height before age 10 for lower productivity level parameter values.

Table 2.3 Maximized log-likelihoods (LogLik), Akaike Information Criterion (AIC), mean error (ME) and root mean square error (RMSE) based on the various growth models fitted to the SA dataset and validated on the PSP dataset. RMSE and ME 1 refer to residuals on the total height prediction for the SA dataset. RMSE and ME 2 and 3 refer to residuals on the annual top height increment predictions for the SA and the PSP datasets. Parameterized models are ordered according to their increasing AIC, lower AIC being associated with better fitting performances.

			SA dataset				PSP dataset	
Model	LogLik	AIC	RMSE 1 (m)	ME 1 (m)	RMSE 2 (m/an)	ME 2 (m/an)	RMSE 3 (m/an)	ME 3 (m/an)
14	3117.6	-6165.3	2.73	-0.13	0.15	-0.01	0.11	-0.01
16	3115.8	-6163.5	2.81	-0.21	0.15	-0.01	0.11	-0.01
13	3113.9	-6159.8	2.82	-0.25	0.15	-0.01	0.11	-0.01
12	3110.9	-6155.8	2.91	-0.35	0.15	-0.02	0.11	-0.01
15	3082.1	-6098.2	2.83	0.10	0.15	0.01	0.11	0.00
7	3073.8	-6083.6	3.14	-0.21	0.15	-0.01	0.11	0.00
4	3066.2	-6068.3	3.34	-0.51	0.15	-0.03	0.12	-0.01
9	3060.1	-6056.2	2.79	-0.23	0.15	-0.01	0.10	0.00
10	3025.5	-5987.0	3.21	0.22	0.20	0.03	0.12	0.01
8	3023.3	-5982.7	3.39	-0.62	0.16	-0.03	0.12	-0.01
11	2930.2	-5796.4	2.74	0.54	0.16	0.02	0.10	0.00
1	2909.5	-5755.1	8.28	-2.07	0.21	-0.12	0.14	-0.07
2	2826.0	-5588.0	8.64	-3.39	0.22	-0.12	0.13	-0.06
3	2711.5	-5358.9	9.38	-3.99	0.23	-0.13	0.13	-0.06
5	2673.4	-5282.7	24.84	-23.1	0.40	-0.34	0.32	-0.28
6	2647.1	-5230.1	18.17	-14.93	0.33	-0.25	0.22	-0.17

As already stated, Duplat & Tran-Ha I, II and III (12, 13 and 14) models (Duplat & Tran-Ha, 1986) fitted very well to the dataset and were characterized by a robust performance over the entire range of possible age and productivity level parameter values. Models I and II are in fact simplified versions of model III, whose formulation is presented below:

$$Hdom = (a * age + b_i) * \left[1 - \exp\left(-\left(\frac{age}{c} \right)^d \right) \right]^r + p * age \qquad \text{(Eq 1)}$$

where:

- Hdom is the top-height (in m);
- age is counted since germination;
- a, c, d, r, p are the shape parameters;
- bi is the productivity level parameter.

The Duplat & Tran-Ha III model was found to be characterized by some highly correlated and insignificant shape parameters (Table 2.4). Consequently, parameters d and p were removed from the model to avoid over parameterization while keeping the best level of performance. The resulting simplified model was an oblique asymptotic model characterized by 4 parameters: 3 shape parameters (a, c and r) and one parameter expressing the productivity level (bi):

$$Hdom = (a * age + b_i) * \left[1 - \exp\left(-\frac{age}{c}\right)\right]^r \qquad \text{(Eq 2)}$$

Table 2.4 Estimates, standard error and intercorrelation of shape parameters for the Duplat & Tran-Ha III parameterized model (Eq 1).

			Correlation			
Parameter	Value	Std.Error	a	c	d	p
a	0.252	0.045				
c	26.214	1.546	-0.302			
d	1.229	0.078	-0.133	0.917		
p	-0.107	0.047	-0.987	0.357	0.237	
r	1.311	0.146	-0.196	-0.848	-0.930	0.103

Results obtained for the parameterization of this model are presented in table 2.5. Analyses of residuals on height and annual height increment prediction indicated that these were always equally distributed around zero, with no appreciable bias over the full range of possible height, age or productivity level parameters. Figure 2.4 shows the distribution of the residuals on predicted annual height increment for the SA and the PSP datasets. Residuals were also plotted with the basal area of the stands measured in PSPs (Figure 2.5), showing that the stand densities encountered in Wallonia had no visible effect on top-height growth.

Table 2.5 Estimates and standard error of shape parameters and fitted statistics for the modified Duplat & Tran-Ha III parameterized model (Eq 2). RMSE 2 and 3 refer to residuals on the annual top-height increment predictions for the SA and the PSP datasets.

Parameter	Value	Std.Error
a	0.130	0.006
c	22.366	0.657
r	2.046	0.045
Fitted statistics		
Log Lik	3111.1	-
AIC	-6156.2	-
RMSE 1 SA (m)	2.794	-
RMSE 2 SA (m/an)	0.148	-
RMSE 3 PSP (m/an)	0.110	-

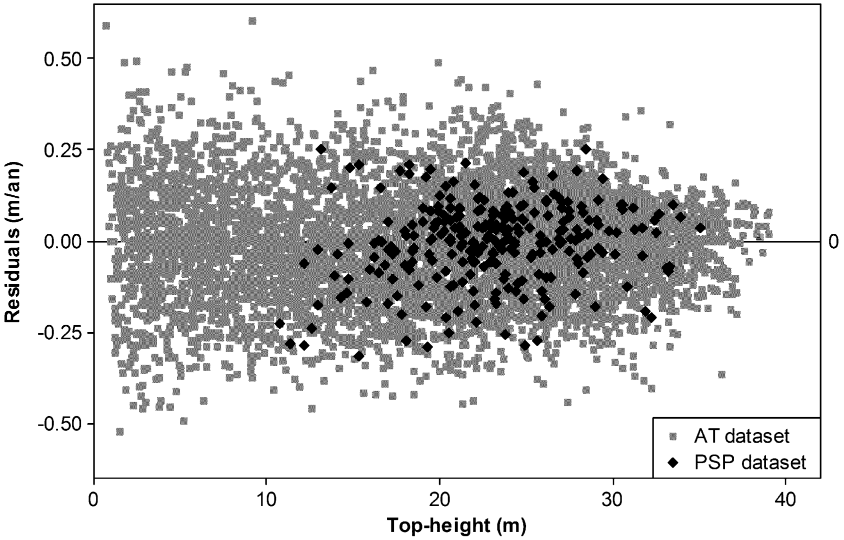


Figure 2.4 Distribution of the residuals (predicted - measured) on annual height increment prediction (Eq 5) related to initial height for SA (grey plots) and PSP datasets (Black plots).

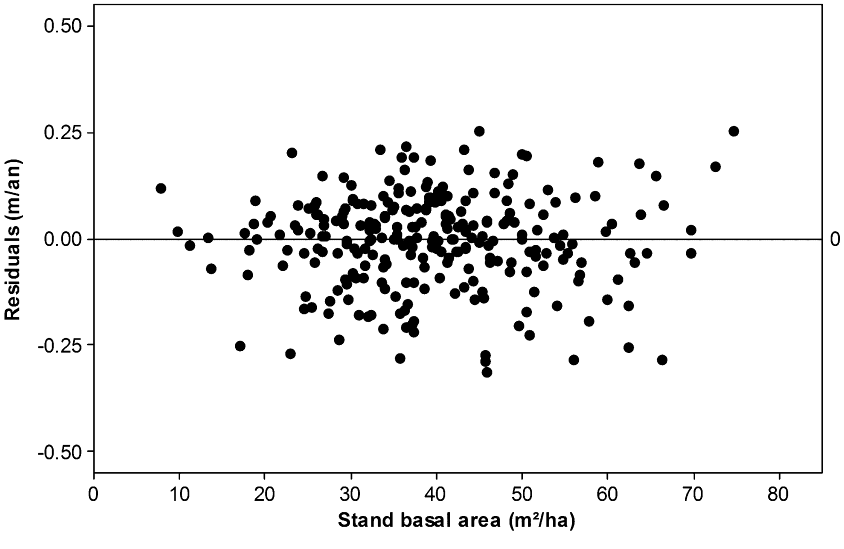


Figure 2.5 Distribution of the residuals (predicted - measured) on annual height increment prediction (Eq 5) related to basal area of the stands for PSP datasets.

A simple inversion of equation 2 makes it possible to estimate bi with any Hdom-age couple:

$$b_i = \frac{Hdom}{\left[1-\exp\left(-\frac{age}{c}\right)\right]^r} - a*age \qquad \text{(Eq 3)}$$

It is then possible to estimate the past and future top-height evolution of a stand when at least one height-age couple is known. The estimation is made by using this couple to calculate bi with equation 3 and using the obtained value in equation 2:

$$Hdom = \left[a*(age-age_M) + \left(\frac{Hdom_M}{\left[1-\exp\left(-\frac{age_M}{c}\right)\right]^r}\right)\right] * \left[1-\exp\left(-\frac{age}{c}\right)\right]^r \qquad \text{(Eq 4)}$$

where:

- Hdom – age is the predicted height-age couple;
- HdomM – ageM is the measured height-age couple.

The corresponding predicted annual height increment can be calculated as follows (Hdom being predicted with Eq 4):

$$dHdom = \frac{(Hdom - Hdom_M)}{(age - age_M)} \qquad \text{(Eq 5)}$$

Eq 4 can also be used to estimate the site index (SI, defined as the top height at a reference age) from any height-age couple or to model the top-height growth curve for a given SI. For coniferous species, the site index is generally related to the top-height at 50 years since planting (Rondeux, 1999). Since seedlings are usually three years old when planted, we thus assimilate the site index of the stand with the top-height at 53 years after germination. According to the dataset, the model validity domain would encompass the top-heights under 40 m when site index is comprised between 15 and 35 m.

The shapes of the former model (in dashed lines) and the new model (in solid lines) are compared in figure 2.6. The distribution of residuals against age on height increment prediction for those model are represented in figure 2.7. Both these figures show how the former model tended to overrate top-height at age 20 and to underrate top-height growth thereafter.

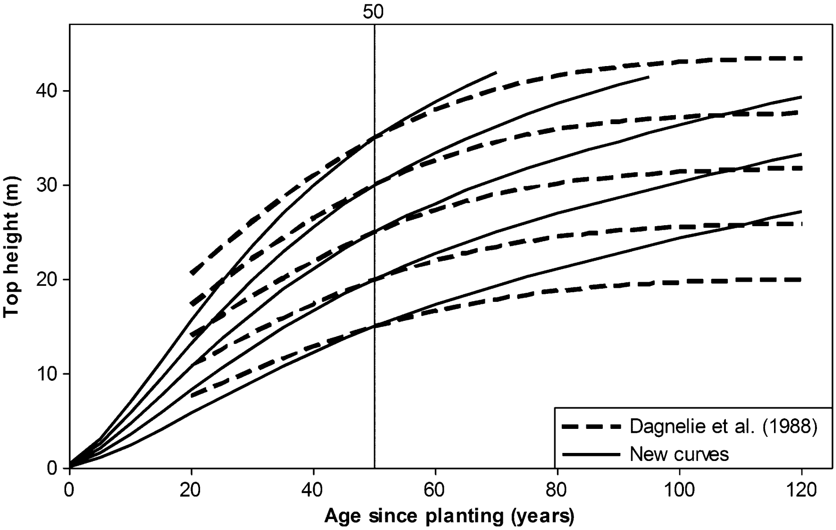


Figure 2.6 Comparison of the new height growth model (Eq 4) with the one of Dagnelie et al. (1988) for curves corresponding to site index of 15, 20, 25, 30 and 35 m (top-height at age 50 since planting).

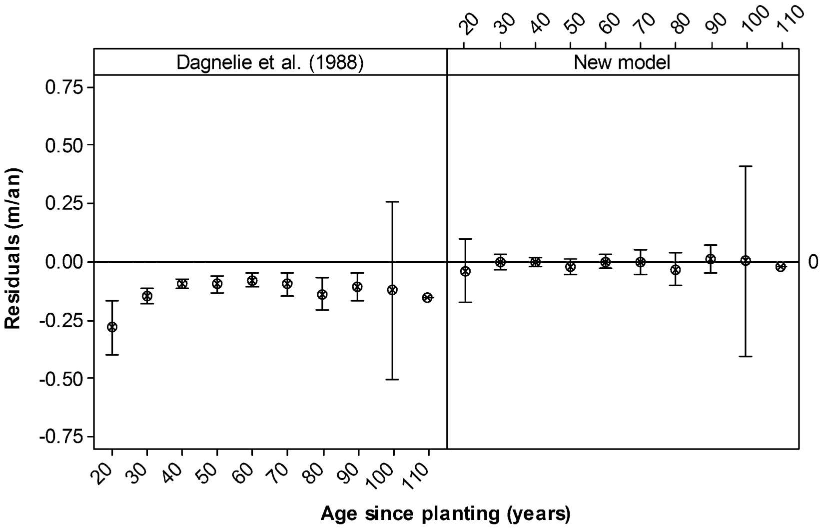


Figure 2.7 Mean residuals (predicted - measured) and the corresponding 95% intervals around the mean resulting from mean annual height increment prediction (Eq 5) in the 265 PSP using the Dagnelie et al. (1988) model (first panel) and the new model (second panel).

6. Discussion

The dataset representativity is probably the most critical component when fitting a growth model and it is essential to ensure that the dataset is representative of all possible fertility levels and ages observed in the study area. In our study, this was achieved by conducting stem analyzes in mature Norway spuce stands sampled to represent the most contrasted sites characteristics present in southern Belgium, even those where Norway spruce is very uncommon. This allowed our dataset to cover a wider range of fertility levels (from 15 to 35 meters height at age 50) than what is represented in the yield tables of Dagnelie et al. (1988) for Southern Belgium and in those of Decourt (1972) for north-eastern France (which do not represent fertility level higher than 30 m).

Another critical component is the choice of the model formulation as significant differences in performance can be observed between different models on a given dataset (e.g. Rathgeber et al., 2004; Cieszewski & Strub, 2008; Weiskittel et al. 2009). It is essential to select a model flexible enough to fit to the dataset while avoiding overparameterization. The comparison of several well-known growth model (Table 2.2) showed that the Duplat & Tran-Ha models I, II, III and V (12, 13, 14 and 16) were giving the best fitting performances on our dataset (Table 2.3). This is probably mostly due to their greater flexibility (more shape parameters) but also to their lack of horizontal asymptote. Indeed, most other tested models are characterized by a horizontal asymptote which may depend on the level of productivity. However, growth trajectories observed in forest stands aged of 200 years and more showed no upper limit to tree height (Duplat and Tran-Ha, 1997; Bontemps et al., 2009) and the biological relevance of maximum tree size is being questioned (Thomas, 2002; Bontemps & Duplat, 2012). Anyway, this maximum tree height was not observed in our dataset and a model formulation characterized by a slant asymptote seemed more appropriate.

Some studies have shown that using SA data for the development of height growth curves may cause bias due to unknown dominance changes during the growth of the stand (Dahms, 1963; Raulier et al., 2003; Hu & Garcia, 2010). However, validation of our model on PSP data has shown no evidence of such bias. In the Belgian context described by Lecomte et al. (2006), it seems relevant to expect that changes of dominance status would be uncommon in planted stands that are regularly thinned. Indeed, dominant trees are favoured by thinning from a very young age, preventing them from competition pressure. Most undesired dominant trees (usually because of their bad shape) are removed during the first thinning, which happens before the stands reach their maximum density. Stands are then thinned every 5 or 6 years to promote the growth of the 200 biggest suitable trees (Boudru, 1986). This ensures very little dominance change from the first thinning to the final cut. This also probably ensures that stand density has little to no influence on top-height growth in coniferous stands of Wallonia.

Nevertheless, SI predictions should be avoided in stands aged of less than 20 because the height of very young trees does not accurately reflect the productivity level of the stand. Very young trees can be greatly affected by events unrelated to site quality (weather, browsing, recovery after planting, etc.). Moreover, before the first thinning, the dominant height should also be estimated from dominant trees that are unlikely to be harvested due to their bad shape or to any other reason justifying their early removal.

Comparison of the new models with the former (Figure 2.6 and 2.7) highlights how the choice of the dataset and a good knowledge of current silvicultural techniques are essential for the development of such models. The former model was developed on a dataset of 2538 top-height-age couples measured in TSPs (Dagnelie et al., 1988) using the guide curves method and the modified Gaussian function. Despite the sheer amount of sampled plots involved, the model formulation, the fitting technique and the data type employed did not allow a correct height growth modelling. As we showed in the present study, the modified Gaussian function should be avoided for height growth modelling because it fits poorly and allows nonzero height prediction at age 0. Another issue was the dataset imbalance, which remained undetected because of the lack of height increment data. This imbalance can be explained by the interaction between site and management: the faster their growth, the more rapidly trees reach harvesting dimensions (usually between 40 and 60 mean dbh), so that the stands in the top class are usually harvested earlier than those in the bottom classes. This is particularly well illustrated in figure 2.3 because each SA was performed during the final cut of the stands. This figure shows that the most productive stands were harvested before age 50 while the least productive stands were harvested much later (sometimes after age 100). The application of a guide curve method to this kind of truncated dataset inevitably leads to an underestimation of height growth because the proportion of the least productive stands increases with age. It is therefore essential to use a fitting method that is insensitive to inevitable imbalances.

7. Conclusion and Perspectives

The new height growth model developed in the present study allows for unbiased top-height and top-height increment prediction over the entire range of age, height and the site index generally encountered in Norway spruce stands of Southern Belgium. It also makes it possible to directly estimate the SI corresponding to any measured height-age couple. Comparison of the new model performances with those of the Dagnelie et al. (1988) model showed that the new model represents a significant improvement over the former. We therefore recommend the replacement of the former model by ours.

Future uses of this new height growth model concern the development of models linking the site index to forest sites characteristics and to the annual growth in volume.

Chapter 3

New site index curves for softwood plantations

Adapted from

Perin J., De Thier O., Claessens H., Lejeune P., Hébert J. 2014. Nouvelles courbes de productivité harmonisées pour le douglas l'épicéa et les mélèzes en Wallonie. Forêt Wallonne 129, 26-41.

1. Preamble

This chapter presents the application of the site-index modelling method developed in the previous chapter to harmonize new site index curves for the 3 main softwood species in Wallonia: Norway spruce, douglas-fir and larch. These new tools are intended to allow in-depth comparative analysis of the distribution of productivity levels.

2. Introduction

Représentant 35% de la surface forestière productive et 55% de la production annuelle totale en volume, l'épicéa est sans nul doute la principale essence de production de Wallonie. Néanmoins, pour une série de raisons liées à l'historique des plantations, aux conditions socio-économiques et écologiques actuelles et futures, on constate depuis deux décennies une régression sensible des surfaces occupées par les pessières ainsi que le développement de la sylviculture d'autres essences résineuses telles que le douglas et les mélèzes. En effet, bien qu'elles n'occupent respectivement que 6% et 3% de la surface forestière productive de Wallonie, ces deux essences sont considérées comme d'intéressantes alternatives à l'épicéa en raison de leur production supérieure, des bonnes caractéristiques du bois qu'elles produisent et de leur souplesse face aux changements climatiques.

Dans un premier temps, les scénarios de gestion appliqués à ces nouvelles essences suivaient des standards proches de ceux appliqués à l'épicéa. Mais il est rapidement apparu que la mise au point de nouveaux scénarios sylvicoles spécialement adaptés à ces essences était indispensable. Ceux-ci doivent reposer sur une bonne connaissance des peuplements et de leur dynamique propre qui s’exprime au travers des lois de croissance en hauteur et en grosseur des arbres et de leur relation avec l'évolution des caractéristiques des peuplements comme la surface terrière, le volume ou le nombre de tiges.

Dans ce cadre, le présent article se focalise sur l’évolution de la hauteur dominante (définie comme étant la hauteur moyenne des 100 plus gros arbres par hectare). Il s'agit d'une relation essentielle dans tous les modèles de croissance des peuplements. L'évolution de la hauteur dominante au cours du temps est connue pour sa forte corrélation avec le potentiel de production des peuplements purs équiennes. Ainsi, pour les plantations résineuses, la hauteur dominante théoriquement atteinte à l'âge de 50 ans, connue sous le nom d'indice de productivité, peut être mise en relation avec les caractéristiques des stations forestières. En effet, s'agissant d'une variable dendrométrique relativement simple à mesurer et généralement non affectée par les opérations sylvicoles, elle permet d'estimer rapidement la productivité en évitant les fastidieuses et coûteuses mesures dendrométriques répétées dans le temps sur des placettes permanentes.

En Wallonie, les premières courbes de productivité adaptées aux peuplements d'épicéa, de douglas et de mélèzes ont respectivement été construites par Dagnelie et al. (1988), Thibaut et al. (1995) et Pauwels (2003). A l'usage, des écarts ont été observés entre les données du terrain et les valeurs estimées à l’aide de ces courbes dans certains peuplements. Dès lors, le développement de nouvelles courbes de productivité mieux adaptées à ces essences s'imposait. Les récentes avancées dans le domaine de la modélisation forestière permettent d’utiliser des modèles mathématiques, des méthodes statistiques et des jeux de données plus complexes et mieux adaptés.

Début 2009, un nouveau modèle de productivité avait ainsi été proposé pour le douglas (Perin et al., 2009). Depuis, ce nouveau modèle a été analysé par d'autres modélisateurs qui ont insisté sur le fait qu'autant la méthode statistique que le jeu de données employés ne pouvaient pas garantir complètement la validité des nouvelles courbes. Etant donné l'importance des modèles de productivité pour la gestion des peuplements résineux, il a été décidé de compléter le jeu de données et de continuer à améliorer la méthode d'ajustement en tenant compte des remarques émises. Une nouvelle méthode d'ajustement a été mise au point et validée pour l'épicéa (Perin et al., 2013). Dans un souci d'harmonisation, nous avons ensuite décidé d'utiliser le même modèle mathématique et la même méthode pour ajuster de nouvelles courbes pour le douglas et les mélèzes.

3. Matériel et méthode

Toute modélisation repose sur la sélection d'un jeu de données, d'un modèle mathématique et d'une méthode d'ajustement. La priorité doit être de constituer un jeu de données équilibré, représentatif des conditions de croissance les plus larges que possible, notamment en termes de niveau de productivité et de type de sylviculture. La littérature regorge de modèles et de méthodes d'ajustement, parmi lesquels le choix est également très important. Un modèle dont la forme s'éloigne de la dynamique de croissance du peuplement et qui n'est pas assez flexible sera inadapté. Il s'ajustera mal et sera à la base d’estimations biaisées. Quant à la méthode d'ajustement, elle doit être choisie en fonction du jeu de données, dont il est important de bien considérer les caractéristiques.

3.1. Données

L'idéal pour la mise au point de courbes de productivité est de disposer de longs suivis de l'évolution de la hauteur dominante obtenus dans des placettes permanentes installées dans des peuplements représentatifs de l'amplitude des âges et des différents niveaux de productivité. Ces données sont parfois disponibles grâce aux programmes d'inventaires régionaux qui sont souvent les seuls à même d'assurer pendant plusieurs décennies le suivi d'un vaste réseau d'observations. En Wallonie, ces données sont malheureusement limitées du fait de la relative jeunesse de l'Inventaire Permanent des Ressources Forestières de Wallonie (IPRFW). Il a donc été nécessaire de compléter le jeu de données fourni par l'inventaire.

Les données utilisées dans cette étude proviennent de plusieurs sources : l'IPRFW et le réseau de parcelles expérimentales de GxABT ainsi que des analyses de tige réalisées à l’occasion de plusieurs actions de recherches menées par GxABT et le DEMNA au cours de l'accord-cadre de recherche et de vulgarisation forestières. Des mesures de hauteur réalisées sur plus de 20 000 arbres issus de 3 380 placettes installées dans des peuplements résineux ont ainsi été réunies.

Après sélection et traitement, ces mesures se présentent sous la forme de 234 courbes expérimentales d'évolution de la hauteur issues d'analyses de tiges, 621 suivis d'accroissements périodiques en hauteur dominante et 2049 mesures ponctuelles de hauteur dominante. Ces données ont servi à ajuster, puis valider les nouveaux modèles de productivité, ainsi qu'à analyser la distribution des niveaux de productivité des peuplements résineux de Wallonie (Table 3.1).

Table 3.1 Jeux de données utilisés selon les essences et les objectifs.

Objectif	Type de données	Epicéa	Douglas	Mélèzes	Total
Calibration	Analyses de tige	86	32	116	234
	Placettes permanentes	-	23	-	23
Validation	Placettes permanentes	319	67	212	598
Analyse	Couples [Hdom, Age]	1776	147	126	2049

3.2. Choix et ajustement du modèle

Les choix du modèle et de la méthode d'ajustement sont expliqués en détails dans un article scientifique (Perin et al., 2013). Le modèle mathématique sélectionné pour l'ajustement des nouveaux modèles de productivité est une version simplifiée du modèle de Duplat et Tran-Ha III (Duplat et Tran-Ha, 1997). Le modèle a été ajusté dans R (R Development Core Team, 2011) à l’aide d’une méthode de régression non linéaire à effet mixte. Cette méthode tient compte de l'autocorrélation et de l'hétéroscédasticité des données de manière à assurer que les nouvelles courbes permettent des estimations non-biaisées sur tout le domaine d'application.

$$Hdom = \left[a * (age - age_M) + \left(\frac{Hdom_M}{\left[1 - \exp\left(- \frac{age_M}{c} \right) \right]^r} \right) \right] * \left[1 - \exp\left(- \frac{age}{c} \right) \right]^r$$

Où

- "Hdom" est la hauteur dominante que l'on veut estimer à l'âge "age"
- "HdomM" et "ageM" est un couple (hdom,âge) connu pour ce peuplement
- "age" et "ageM" expriment l'âge depuis la germination et non la plantation
- a, c et r sont des paramètres à ajuster pour chaque essence

Les valeurs des paramètres ajustés sont présentées dans la table 3.2.

Table 3.2 Valeurs ajustées des paramètres de forme a, c et r pour chaque essence.

Essence	a	c	r
Douglas	0,2418	31,1379	1,4668
Mélèzes	0,1449	14,9904	1,6818
Epicéa	0,1299	22,3659	2,0464

Cette seule équation permet la construction de courbes de productivité, l'estimation de l'indice de productivité et la prédiction de l'évolution de la hauteur dominante dans un peuplement à partir de n'importe quel couple (HdomM; ageM) connu sans nécessiter de transformation, d'analyse graphique ou de processus itératif. Ce modèle est donc, malgré son apparente complexité, relativement simple à utiliser en pratique.

Ce modèle exprime l'évolution de la hauteur dominante depuis la germination (hauteur nulle pour un âge nul). Dans le cas de peuplements dont l’âge est exprimé depuis la plantation, il est nécessaire d'ajouter l'âge des plants compté depuis la germination. Généralement, les plants de résineux sont âgés de 2 à 4 ans lors de la plantation. Par convention, nous considèrerons que l'âge des plants est toujours égal à 4 ans pour l'épicéa et 3 ans pour le douglas et les mélèzes lorsque nous ne disposons pas d'informations plus précises à ce sujet.

S’il est logique de construire les modèles en comptant l’âge depuis la germination, en pratique, l'immense majorité des peuplements résineux de Wallonie sont issus de plantation. Il semble donc pertinent que les applications qui seront faites de ces modèles et les outils qui en découlent utilisent l'âge compté depuis la plantation plutôt que depuis la germination. Ainsi, les indices de productivité seront estimés comme étant la hauteur dominante à 50 ans depuis la plantation et les courbes de productivité proposées pour ces essences seront également exprimées en fonction de l'âge depuis la plantation.

4. Les nouveaux modèles de croissance en hauteur dominante

Les figures 3.1 et 3.2 représentent respectivement les courbes de croissance en hauteur dominante modélisées pour les niveaux de productivité médians constatés en Wallonie selon les jeux de données de l'IPRFW (respectivement 27, 36 et 28 mètres de hauteur dominante à 50 ans pour l'épicéa, le douglas et les mélèzes) et les accroissements courants en hauteur dominante qui y correspondent.

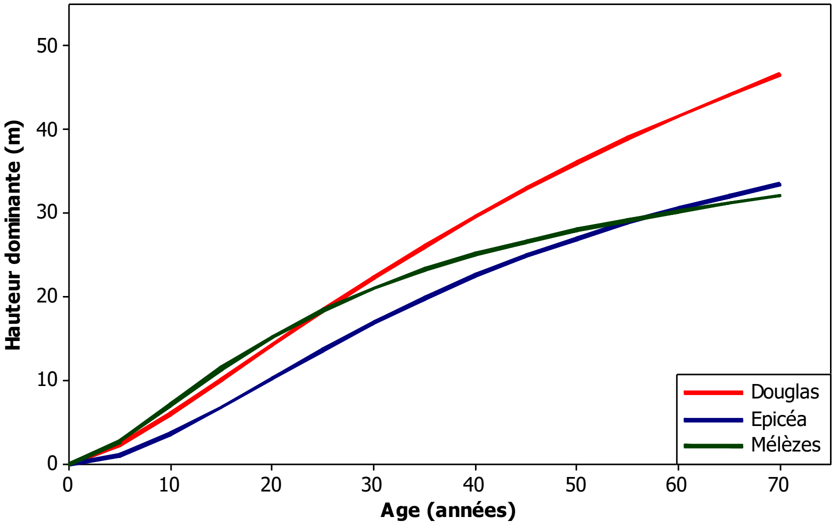


Figure 3.1 Courbes d'évolution de la hauteur dominante modélisées pour les niveaux de productivité médians de l'épicéa (en bleu, 27 m à 50 ans), du douglas (en rouge, 36 m à 50 ans) et des mélèzes (en vert, 28 m à 50 ans).

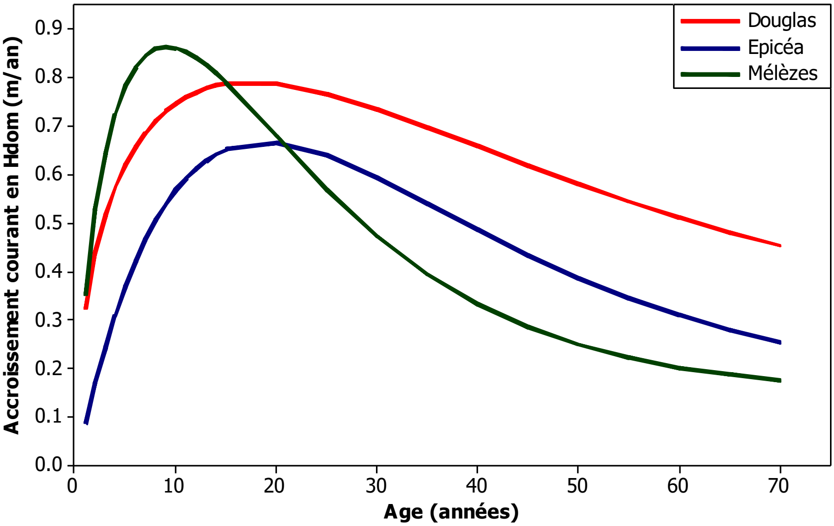


Figure 3.2 Courbes d'évolution de l'accroissement en hauteur dominante modélisées pour les niveaux de productivité médians de l'épicéa (en bleu, 27 m à 50 ans), du douglas (en rouge, 36 m à 50 ans) et des mélèzes (en vert, 28 m à 50 ans).

En comparant ces courbes de productivité moyenne, on constate que les mélèzières sont caractérisées par une croissance en hauteur dominante très précoce et très forte dans le jeune âge mais qui ne se maintient pas au-delà de 20 ans. La vitesse de croissance en hauteur dominante des douglasaies et des pessières est par contre beaucoup plus soutenue, leur permettant de finalement combler leur retard sur les mélèzes respectivement vers 25 ans et 55 ans. On constate aussi que les vieux peuplements de douglas sont capables de maintenir un accroissement en hauteur dominante près de 2 fois supérieur à celui des vieux peuplements d'épicéa et de mélèzes. Il explique les grandes hauteurs, largement supérieures à 50 m qu'atteignent les vieilles douglasaies centenaires de la première génération.

On peut s'étonner que les trois espèces de mélèze ne justifient pas l'utilisation de paramètres différents. Il a ainsi été observé que la forme de la croissance en hauteur dominante des trois espèces a la même allure mais que les niveaux de croissance sont en moyenne différents, à l'avantage du mélèze hydride qui se distingue de manière significative de ses parents européen et japonais.

Les données d'ajustement permettent de garantir la validité des nouveaux modèles pour des hauteurs dominantes allant jusqu'à 40, 50 et 36 m et des âges allant jusqu'à 120, 100 et 80 ans respectivement pour l'épicéa, le douglas et les mélèzes. Leur utilisation pour des peuplements âgés de moins de 20 ans est néanmoins déconseillée car la hauteur dominante y est fortement dépendante de très nombreux facteurs indépendants de l'essence et de la station (gelées tardives, mauvaise plantation, printemps sec, dégâts d'abroutissement, prélèvement des jeunes dominants mal conformés,...). Le domaine de validité des nouvelles courbes couvre les indices de productivité allant de 15 à 36 m, 24 à 46 m et 21 à 34 m respectivement pour l'épicéa, le douglas et les mélèzes.

5. Distribution des indices de productivité

La distribution des niveaux de productivité des peuplements d'épicéa, de douglas et de mélèzes de Wallonie a été analysée grâce aux hauteurs dominantes estimées dans le réseau de monitoring de l'IPRFW (Figure 3.3). Pour assurer une estimation aussi précise que possible de l'indice de productivité, les données issues de peuplements purs équiennes dont l'âge était inférieur à 25 ans au moment des mesures n'ont pas été sélectionnées pour cette analyse. De cette manière, on limite les erreurs d'extrapolation et les biais dus aux problèmes de reprise des plantations qui ont un fort impact sur les extrapolations de la hauteur dominante à 50 ans. Les peuplements âgés de 60 ans et plus ont également été écartés de cette analyse pour éviter de surreprésenter les classes de fertilité les plus faibles. En effet, d'une part les peuplements les moins productifs ont besoin de plus de temps pour atteindre les dimensions d'exploitabilité et sont donc généralement coupés plus tard. D'autre part, une part non négligeable des vieux peuplements les moins productifs ne seront jamais replantés avec des essences résineuses pour des raisons économiques (manque de rentabilité) et réglementaires (nouveau code forestier, Natura 2000, ...).

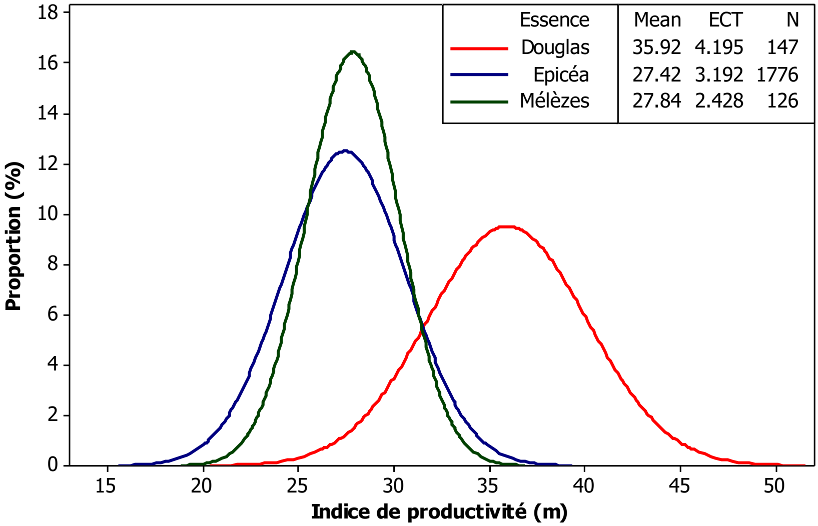


Figure 3.3 Distribution des niveaux de productivité observée dans les placettes permanentes de l'IPRFW installées dans des peuplements purs équiennes d'épicéa (en bleu), de douglas (en rouge) et de mélèzes (en vert) âgés de 25 à 60 ans au moment des mesures.

Conformément à ce qui avait déjà été observé dans les jeux de données d'ajustement, les indices de productivité rencontrés dans les douglasaies sont généralement largement supérieurs à ceux observés dans les pessières et les mélézières. On constate également que l'amplitude de variation des indices de productivité est plus élevée dans les douglasaies (36 m ± 20%) et les pessières (27,5 m ± 20%) que dans les mélézières (28 m ± 15%).

Ces différences d'amplitude découlent de facteurs stationnels, génétiques et sylvicoles. Ainsi, les épicéas ont été installés dans une très large gamme de station, depuis les tourbières jusqu'aux terres agricoles fertiles (Claessens et al., 2000) alors que les mélèzes et les douglas qui ont généralement été plantés sur des sols très favorables comme les bruns forestiers bien drainés et les terres agricoles (Claessens et al., 1996, 2002). En douglasaies, l'amplitude des niveaux de productivité, ne s'expliquant que très peu par des critères stationnels (Claessens et al., 1996), pourrait être essentiellement liée à la diversité des provenances utilisées, surtout pour les plantations réalisées avant 1980. Les problèmes de reprise suivant la plantation pourraient également avoir un effet durable et non négligeable sur le potentiel de production et causer un étalement vers le bas des niveaux de productivité des douglasaies.

La faible amplitude de variation de l'indice de productivité des mélèzes est quant à elle plus surprenante puisque le genre mélèze est représenté par deux espèces et leur hybride dont la productivité est supérieure (Claessens et al., 2002). Mais la rareté de plantations en stations contraignantes (20%) et la facilité de reprise à la plantation justifient probablement cette homogénéité. Par ailleurs, la croissance des mélèzes étant peu soutenue après 20 ans, les différences de hauteur dominante entre peuplements ne s'accentuent que faiblement avec le temps.

On peut supposer que l'évolution des connaissances sur les adéquations essence-station, le recours plus systématique à des graines de qualité génétique élevée et l'amélioration des techniques de plantation continueront à contribuer à l'augmentation du potentiel de production des peuplements résineux et plus particulièrement à la disparition progressive des niveaux de productivité les plus bas, comme cela a déjà été le cas pour l'épicéa.

6. Les nouvelles classes de productivité

En considérant la dispersion des indices de productivité, nous avons cherché à construire, pour chaque essence, trois classes de productivité centrées sur la valeur moyenne de l'indice de productivité en forêt wallonne, et qui, ensemble, représentent la grande majorité des peuplements. D'un point de vue opérationnel, cela permet au forestier de classer ses peuplements selon un niveau de productivité élevé, moyen ou faible et d'y faire correspondre la sylviculture adéquate.

En pessière et en mélézières, cette équation a été résolue avec des classes d'une amplitude de hauteur dominante de 3 m (Figure 3.4). Selon l'IPRFW, cette amplitude permet de classer plus de 85% des peuplements dans les classes de productivité 1 à 3. En dehors de cette amplitude, on rencontre les peuplements d'une productivité exceptionnellement haute (classe 0) ou exceptionnellement basse (classe 4). Au-delà de ces limites, les peuplements sont quasi inexistants. Il s'agit soit de conditions stationnelles tout à fait extrêmes, voire de données dendrométriques douteuses. En épicéa, cette définition des classes correspond exactement à celle de Dagnelie et al. (1988).

Pour les douglasaies, dont l'amplitude de variation de l'indice de productivité est plus grande, nous avons retenu une amplitude de 4 m par classe (Figure 3.4). D'une part, cette amplitude permet aussi de classer 83% des peuplements dans 3 classes centrées sur la moyenne wallonne, et d'autre part, cette amplitude tient aussi compte de la grande variabilité des hauteurs que l'on rencontre au sein de la population d'arbres dominants d'une douglasaie. En effet, parmi les 100 arbres à l'hectare qui définissent la hauteur dominante, l'écart type des hauteurs est relativement élevé dans le cas du douglas, rendant les estimations de la hauteur dominante d'un peuplement assez imprécises lorsqu'on les calcule sur base de quelques placettes de quelques ares, comme c'est souvent le cas dans la pratique.

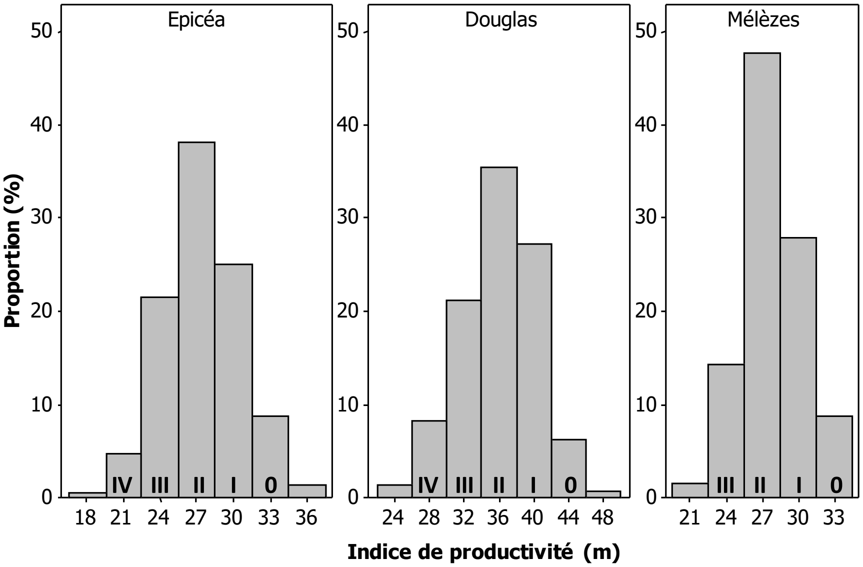


Figure 3.4 Distribution des classes de productivité rencontrées dans les placettes permanentes de l'IPRFW installées dans des peuplements purs équien d'épicéa (en bleu), de douglas (en rouge) et de mélèzes (en vert) âgé de 25 à 60 ans au moment des mesures.

Pour les trois essences, l'indice de productivité moyen est de cette manière toujours compris dans la classe II (centrée à 27 m pour l'épicéa et les mélèzes et 36 m pour le douglas) qui est également toujours la classe la mieux représentée (Figure 3.4). En mélèzes, on notera que les deux espèces et leur hybride ne se distribuent pas de la même manière au sein des classes de données de l'IPRFW, environ 80% des peuplements d'hybrides, dont on connait la haute productivité, se retrouvent en classes 0 et 1 (moyenne de 30 m, soit en classe 1), tandis qu'environ 80% des mélèzes d'Europe et du Japon relèvent des classes 1 et 2 (moyenne de 28 m, soit en classe 2).

Les faisceaux de courbes de productivité correspondant au centre des classes de productivité définies pour l'épicéa, le douglas et les mélèzes sont représentés respectivement dans les figures 3.5, 3.6 et 3.7. Ils sont aussi proposés sous la forme de tables de valeurs (Table 3.3 à 3.5).

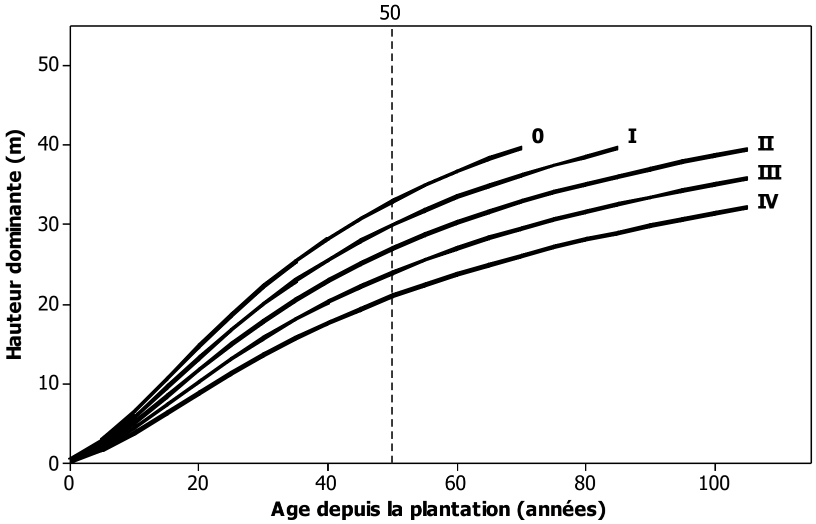


Figure 3.5 Evolution de la hauteur dominante selon les nouvelles courbes de productivité définies pour l'épicéa.

Table 3.3 Evolution de la hauteur dominante des pessières avec l'âge selon les 5 classes de productivité (valeurs centrales) qui représentent 97.5% des peuplements de Wallonie.

	Classe de productivité				
Age	**IV**	**III**	**II**	**I**	**0**
20	8.8	10.3	11.8	13.3	14.7
25	11.3	13.1	14.9	16.8	18.6
30	13.6	15.7	17.9	20.0	22.2
35	15.7	18.1	20.5	23.0	25.4
40	17.6	20.3	22.9	25.6	28.3
45	19.4	22.2	25.1	27.9	30.8
50	21.0	24.0	27.0	30.0	33.0
55	22.5	25.6	28.7	31.8	35.0
60	23.8	27.0	30.2	33.5	36.7
65	25.0	28.3	31.6	34.9	38.3
70	26.1	29.5	32.9	36.3	39.6
75	27.1	30.6	34.0	37.5	-
80	28.1	31.6	35.1	38.6	-
85	29.0	32.5	36.1	39.6	-
90	29.9	33.4	37.0	-	-
95	30.7	34.3	37.9	-	-
100	31.5	35.1	38.7	-	-

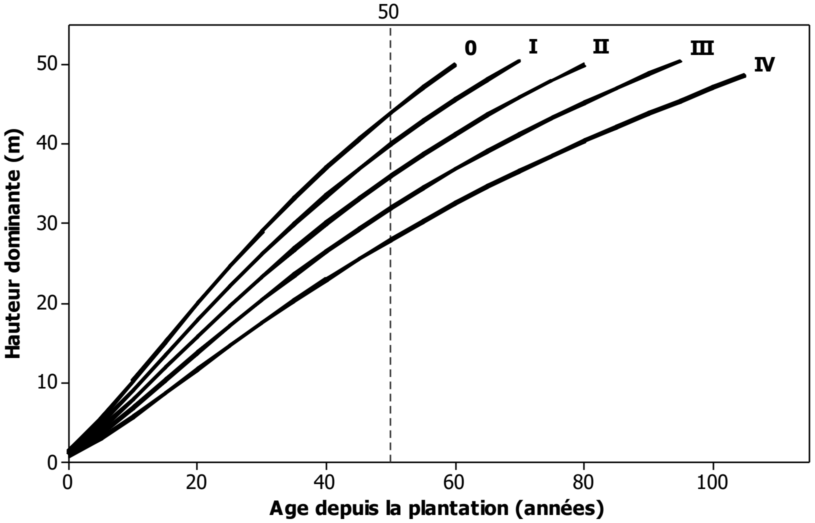


Figure 3.6 Evolution de la hauteur dominante selon les nouvelles courbes de productivité définies pour le douglas.

Table 3.4 Evolution de la hauteur dominante des douglasaies avec l'âge selon les 5 classes de productivité (valeurs centrales) qui représentent 98% des peuplements de Wallonie.

	Classe de productivité				
Age	IV	III	II	I	0
20	11.7	13.8	15.9	17.9	20.0
25	14.7	17.2	19.7	22.2	24.7
30	17.6	20.4	23.3	26.2	29.1
35	20.3	23.6	26.8	30.0	33.2
40	23.0	26.5	30.0	33.6	37.1
45	25.6	29.3	33.1	36.9	40.7
50	28.0	32.0	36.0	40.0	44.0
55	30.3	34.5	38.7	42.9	47.1
60	32.5	36.9	41.2	45.6	50.0
65	34.6	39.1	43.6	48.1	-
70	36.6	41.3	45.9	50.5	-
75	38.5	43.3	48.0	-	-
80	40.4	45.2	50.0	-	-
85	42.1	47.0	-	-	-
90	43.8	48.8	-	-	-
95	45.5	50.5	-	-	-
100	47.1	-	-	-	-

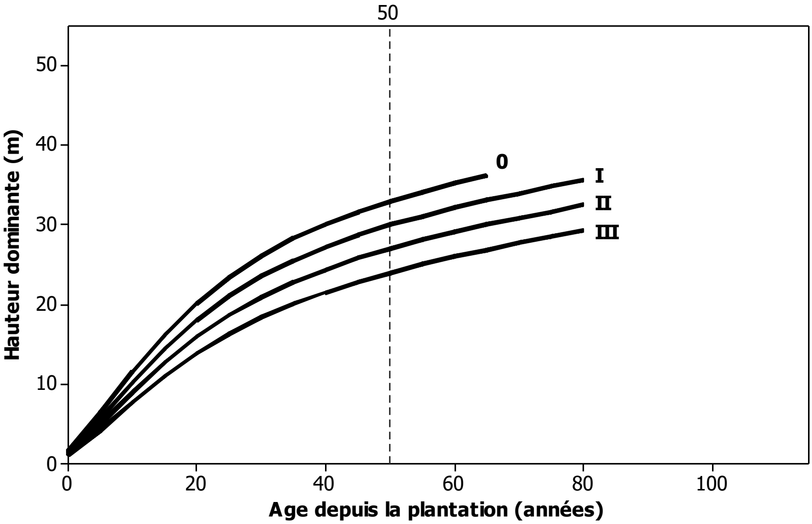


Figure 3.7 Evolution de la hauteur dominante selon les nouvelles courbes de productivité définies pour les mélèzes.

Table 3.5 Evolution de la hauteur dominante des mélézières avec l'âge selon les 4 classes de productivité (valeurs centrales) qui représentent 98.5% des peuplements de Wallonie.

	Classe de productivité			
Age	**III**	**II**	**I**	**0**
20	13.9	16.0	18.1	20.2
25	16.3	18.7	21.0	23.4
30	18.3	20.9	23.5	26.1
35	20.1	22.8	25.6	28.3
40	21.5	24.4	27.3	30.1
45	22.8	25.8	28.7	31.7
50	24.0	27.0	30.0	33.0
55	25.0	28.1	31.1	34.2
60	26.0	29.1	32.2	35.2
65	26.9	30.0	33.1	36.2
70	27.8	30.9	34.0	-
75	28.6	31.7	34.8	-
80	29.4	32.5	35.6	-

7. Outil d'estimation de l'indice de productivité

Un outil d'utilisation rapide et simple permettant d'estimer l'indice de productivité dans les peuplements purs équiennes a été développé et mis à disposition du public dans la section "outils" du site de l'unité de Gestion des Ressources Forestières et des Milieux Naturels de Gembloux Agro-Bio Tech - Université de Liège (http://www.gembloux.ulg.ac.be/gestion-des-ressources-forestieres-et-des-milieux-naturels/outils/h50/). Cet outil mis au point initialement pour les pessières, les douglasaies et les mélézières, a depuis été étendu aux principales essences feuillues de production rencontrées en Wallonie. Il est également prévu de compléter cet outil avec des modèles permettant de lier l'indice de productivité avec des estimations précises de l'accroissement potentiel en surface terrière et en volume.

Valeurs d'entrée

Entrez les valeurs des peuplements :

ID	Essence	Âge	HDom
Test01	Ep	65	34
Test02	Dg	29	27
Test03	Mz	35	22

Essences acceptées :

- Epicéa (**Ep**)
- Douglas (**Dg**)
- Mélèze (**Mz**)

Résultats

ID	Essence	Âge	HDom	H50	Classe	Production	Remarques
Test01	*EP*	*65*	*34*	*29.15*	*I*	*Haut*	
Test02	*DG*	*29*	*27*	*42.27*	*0*	*Haut*	
Test03	*MZ*	*35*	*22*	*26.12*	*II*	*Moyen*	

Figure 3.8 Interface de l'outil développé pour calculer l'indice de productivité et mis à disposition du public sur le site de l'unité de GRFMN, GxABT - ULg à l'adresse : http://www.gembloux.ulg.ac.be/gestion-des-ressources-forestieres-et-des-milieux-naturels/outils/h50/

L'outil, présenté dans la figure 3.8, se présente sous la forme de deux tableaux. Les valeurs nécessaires pour l'estimation de l'indice de productivité doivent être encodées dans le premier tableau (valeurs d'entrée) :

- **ID** : (optionnel) identifiant pour le peuplement (nom, numéro,...).
- **Essence** : essence forestière qui compose le peuplement (code de 2 lettres prédéfini)
- **Âge** : nombre d'années écoulées depuis la plantation du peuplement.
- **HDom** : hauteur dominante (en mètres) du peuplement.

Il suffit ensuite de cliquer sur "Calculer" pour obtenir dans le second tableau (résultats) un diagnostic des niveaux de productivité estimés à partir des données encodées :

- **H50** : indice de productivité (hauteur dominante théoriquement atteinte à 50 ans).
- **Classe** : classe de productivité correspondante.
- **Production** : appréciation du niveau de production (bas, moyen ou haut) du peuplement par rapport à ce qui est habituellement observé en Région wallonne pour cette essence.
- **Remarques** : remarques éventuelles concernant les mesures encodées (identification des données aberrantes ou situées en dehors du domaine d'application des modèles).

Chapter 4

Growth and yield modelling

Adapted from

Perin J., Claessens H., Lejeune P., Brostaux Y., Hébert J. 2016. Distance-independent tree basal area growth models for Norway spruce, Douglas-fir and Japanese larch in Southern Belgium. European Journal of Forest Research 136, 193-204.

1. Preamble

The previous two chapters dealt with the development of new site-index models for softwood plantations in southern Belgium. The interest of the index site lies in its strong correlation with the level of productivity of forest stands, allowing for an easy comparison of the relative productivity of different forest stands. However, it does not provide any concrete estimation of the production of a stand.

This chapter is focused on the development of growth models based on the new site index models to eventually link site index to actual production estimates.

2. Introduction

Forest growth and yield modeling is used to analyze and estimate the key relationship linking forest stand development to various factors such as species composition, site characteristics and silvicultural management. There are various modeling approaches which are often classified in two main groups: mechanistic or process-based models which are based on presumed or observed mechanisms and attempt to explain the eco-physiological processes of forest growth (Bossel, 1991; Twery, 2004) and empirical models which are based on measured data and describe the relation linking several stands or tree characteristics.

Empirical growth and yield models are commonly used in forestry to predict forest growth and production (Johnsen et al., 2001) and to compare the likely effects of various management scenarios on the evolution of forest resources (Peng, 2000; Courbaud et al., 2001; Burkhart and Tomé, 2012). Successful practical applications of such models range from simple growth and yield curves to more advanced forest management simulation software. Yield tables are probably the oldest and best known models used in forestry science and forest management (Pretzsch, 2009). Early yield tables were based on inventory data and were not able to reflect the effects of changing management practices and environmental conditions and are therefore no longer valid in many cases (Pretzsch, 2009; Pretzsch et al., 2014). Modern variable density yield tables and stand density management diagrams rely increasingly on growth and yield modeling to estimate the effect of variable management practices and environmental conditions on stand evolution (eg Longchang et al., 1991; Valbuena P., 2008; Vacchiano et al., 2013).

The ever increasing use of computer technology has made it easier to use more complex growth models to improve the resolution scale and to take more explanatory variables into account. Therefore, whole stand modeling approaches are now considered outdated and individual tree level modeling is the new standard (Weiskittel et al., 2011). These models are labeled distance-independent or distance-dependent depending on whether or not they include spatially explicit explanatory variables. Distance-dependent models are very useful for research purpose: they have a high potential for estimating the impact of silvicultural treatment on individual tree growth and are well suited for both homogenous and heterogeneous stands structure and composition (e.g. Courbaud et al., 2001; Porté & Bartelink, 2002; Pretzsch et al., 2002). However, distance-independent models are generally simpler and are considered as more practically oriented (e.g. Monserud & Sterba, 1996; Andreassen & Tomter, 2003; Deleuze et al., 2004) and their performances are known to generally only be slightly lower than distance-dependent ones in even-aged pure stands (e.g. Vanclay, 1994; Wimberly & Bare, 1996; Contreras et al., 2011).

Taking advantage of tree level modeling, traditional yield tables are progressively replaced by simulation software of silvicultural treatment (eg Pain, 1997; Pretzsch et al., 2002; Pauwels et al., 2007; Dufour-Kowalski et al., 2012) that allow simulation of customized silvicultural management scenarios at the tree level to accurately estimate growth and production based on the forester preferences. However, it is difficult, if not impossible to ensure that the validity limits of the models introduced in simulation software are always respected. Consequently, growth models should be designed with a greater focus on their structure to ensure that they exhibit a relevant behavior not only inside but also outside of their validity area (Deleuze et al., 2004).

Although not native to Western Europe, Norway spruce (Picea abies (L.) Karst) is the most important timber production species in Southern Belgium (Alderweireld et al., 2015), where it is estimated that pure spruce stands account for about 30% of the productive forest area (≈ 140 000 hectares) and approximately 40% of the standing timber volume (≈ 46 million m^3). However, for a variety of historical, socio-economic and ecological reasons (Claessens, 2001), the area devoted to this species declined steadily since the early 90s partly in favor of other softwood species such as douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) and Japanese larch (Larix kaempferi (Lam.) Carrière). These two species were brought in Belgium over one century ago (Crahay, 1900; Millard, 1949) but large-scale plantations only started after the middle of the 20th century (Claessens et al., 1996; Claessens et al., 2002). Their higher growth rate and the technological quality of their wood makes them interesting alternatives to Norway spruce.

In Southern Belgium, the first yield tables and site index curves fort these species were built by Dagnelie et al. (1988) for Norway spruce, by Rondeux et al. (1991) and Thibaut et al. (1995) for douglas-fir and by Pauwels et al. (2007) for larch. More recently, differences were observed in Norway spruce and douglas-fir stands between the field data and the values estimated using these tools, especially in stands aged 50 and over where the growth rate and the level of production was significantly underestimated (Perin et al., 2013). Therefore, the development of new growth and yield models was required to update the existing site index curves and yield tables.

In this context, we began the development of new harmonized growth and yield models that will be integrated in a simulation software to provide accurate tools for comparison and growth simulations in even-aged stands of Norway spruce, douglas-fir, and larch. New harmonized top height growth and site index models (Perin et al., 2013; Perin et al., 2014) constituted the first step, the next being harmonized girth increment models which are presented thereafter. Our forest simulation software will primarily be used to estimate the effect of various thinning regimes on individual tree growth and stand structure and to predict the evolution of existing stands using actual forest inventory data. As a result, we require growth models that offer good predictive performance while only using simple explanatory variables usually collected in forest inventory. We thus favor a tree level distance-independent empiric modeling approach.

3. Material

All the sampled plots (Figure 4.1) are located in even-aged and pure stands (Norway spruce, douglas-fir or larch account for more than 90% of the stand basal area). The past silvicultural treatments applied to sampled stands is not always known but coniferous silviculture in Belgium is widely based on even-aged stands established by planting high density (1500 to 3000 stems/ha) of 3 to 4 years old planting stocks (Alderweireld et al., 2015). Coniferous stands are normally thinned every 5 to 10 years after reaching 13 to 20 meters of dominant height, unthinned stands are known to be fairly uncommon in Southern Belgium. Clearcutting is then usually applied shortly after those stands reach a top height of respectively 30 m for Norway spruce and larch stands and 40 m for douglas-fir.

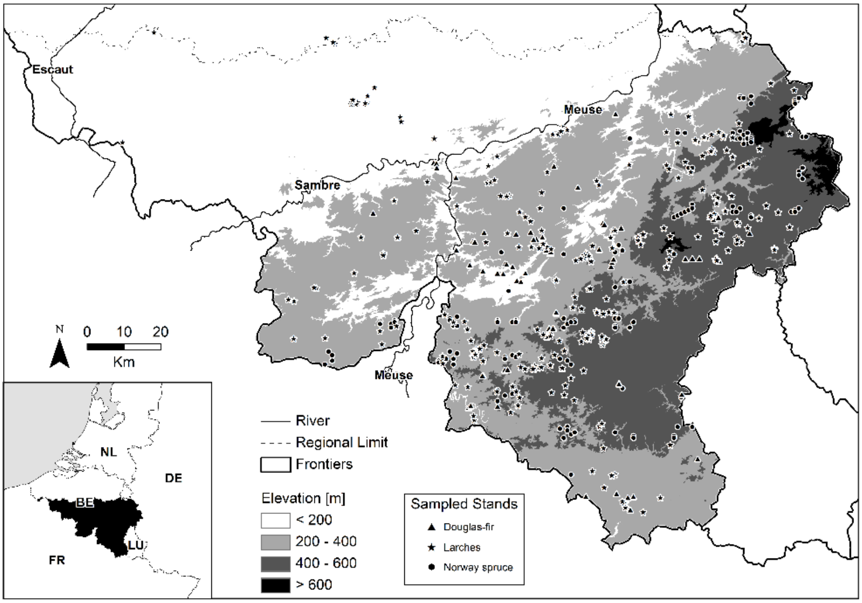


Figure 4.1 Repartition of the sampled stands in the study area. Norway spruce stands are represented by round dots, douglas-fir by triangular dots and larch by star dots.

Thousands of growth measurements were gathered from several monitoring plots, forest management inventories and silvicultural field experiments in pure even-aged stands of Norway spruce, douglas-fir or larch. This include several silvicultural field experiments installed during the 70s in Norway spruce stands and monitored for close to 3 decades (Hébert et al., 2002) and an extensive plot network installed and monitored during the 90s in larch stands (Pauwels et al., 2007). As a result, the sampled plots design are rather heterogeneous: round and rectangular plot shapes, sizes ranging from 50 to 2 400 square meters and monitoring durations varying from

3 to 27 years. We then selected all individual tree girth growth segments of 3 to 6 years measured over bark in stands of known age and where top-height (Hdom), density (Nha) and total basal area (Gha) were measured. Following data quality control, the recovered dataset is composed of 51 159 growth segments measured on 18 135 trees in 537 plots monitored between 1979 and 2013. Norway spruce account for 33 931 of these data (7 220 trees in 181 plots), larch for 14 382 (8 988 trees in 289 plots) and douglas-fir for 2 846 (1 927 trees in 67 plots).

These data represents all site conditions and the wide range of forest management scenarios applied to even-aged Norway spruce, douglas-fir and larch stands of Southern Belgium, as well as more unusual silvicultural management scenario tested in several silvicultural field experiments (Table 4.1). Site Index (SI, top-height at 50 years since planting) were evaluated for every sampled stands by using the online tool "H50" v1.1 (Perin & De Thier, 2014). The age, top-height and density range of the sampled stands are representative of what is mostly encountered in coniferous stands between the first thinning and the clearcutting.

Table 4.1 Main attributes of the selected permanent sample plots installed in even-aged pure stands of Norway spruce (181), douglas-fir (67) and larch (289). Area = sample plot area; Age = total age of the stands since planting; Hdom = top-height; SI = Site index; Nha = number of trees per hectare; Gha = total basal area per hectare; Cg = quadratic mean girth at breast height.

	Norway spruce (Picea abies)				Douglas-fir (Pseudotsuga menziesii)				Larch (Larix kaempferi)			
	Min	Mean	Max	StDev	Min	Mean	Max	StDev	Min	Mean	Max	StDev
Area (m^2)	50	448	707	128	200	585	1500	346	100	626	2400	409
Age (years)	19	43	92	13	14	39	93	17	9	35	91	13
Hdom (m)	11.1	21.2	34.7	4.3	9.9	26.8	48.9	8.4	8.0	22.2	34.4	5.7
SI (m)	13.1	25.4	32.7	2.3	19.3	36.0	44.7	4.3	20.8	28.4	37.5	2.6
Nha (N/ha)	141	1226	6020	807	60	614	2250	463	98	729	3700	558
Gha (m^2/ha)	6.6	35.3	61.5	10.3	18.2	36.2	59.6	9.1	9.3	26.4	55.5	7.3
Cg (cm)	26.3	67.3	150.3	20.9	39.1	106.4	265.8	47.6	28.4	80.1	170.8	26.1
Elevation (m)	158	425	654	105	154	318	550	103	36	361	606	117
Slope (°)	0	6	23	4.6	1	6	21	4.8	0	6	29	5.1

4. Methods

We decided to evaluate the tree level distance independent growth model of Deleuze et al. (2004) on our data because of its interesting formulation. This model has already been tested in similar site conditions (Northeastern France) for Norway spruce and douglas-fir stands subject to silvicultural management practices comparable to those encountered in Southern Belgium. It is a nonlinear hyperbolic model that describes annual tree basal area increment (Igi) as a function of initial circumference (Ci):

$$Ig_i = 0.5 \ast P \ast \left(C_i - m \ast A + \sqrt{(m \ast A + C_i)^2 - 4 \ast A \ast C_i}\right) \qquad \text{(Eq 1)}$$

The 3 parameters A, P and m can all be expressed as functions of the stands characteristics and each affects the model in very different ways (Figure 4.2). The parameter m has to be greater or equal to 1 and affect the general shape and the flexibility of the model. If m is equal to 1, the model is the segmented linear function of Dhôte (1991) where Igi is null from Ci = 0 to the threshold A and then increase with a slope equal to P. Greater values of m give more flexibility to the model around the threshold A, essentially leading to a more gradual increase of tree basal area increment in relation to increasing circumference.

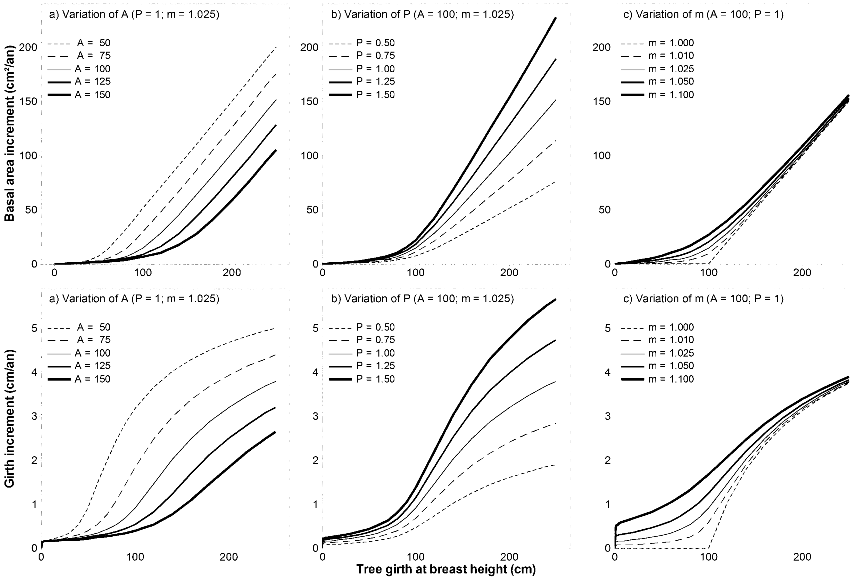


Figure 4.2 Influence of the variation of one of the parameter A, P or m value on the tree growth model shape, other being constant: a) variation of A (50 to 150); b) variation of P (0.5 to 1.5); c) variation of m (1 to 1.1). Upper panels represent tree basal area increment (cm²/yr), lower ones represent tree girth increment (cm/yr).

Deleuze et al. (2004) proposed the following formulation for parameter A and P:

$$A = (Aa + Ab * Hdom) * (1 + Ac * \exp(-\alpha * Gha/Hdom)) \qquad \text{(Eq 2)}$$

$$P = (Pa + Pb * dHdom) * (1 + Pc * \exp(-\alpha * Gha/Hdom)) \qquad \text{(Eq 3)}$$

Where Gha is the initial stand basal area per hectare in m²/ha, Hdom is the initial stand top-height in meters and dHdom is the annual top-height increment during the growth interval in meter per year.

As final top-height was not always measured in the recovered inventory data, the annual top-height increment is not consistently available. Thus, we will always use an estimated value for this variable, calculated with the corresponding top-height growth model fitted on stem analysis data by Perin et al. (2013, 2014), whose formulation and parameters values are presented in Eq 4 and table 4.2.

$$Hdom = \left[a * (age - age_M) + \left(\frac{Hdom_M}{\left[1 - \exp\left(-\frac{age_M}{c} \right) \right]^r} \right) \right] * \left[1 - \exp\left(-\frac{age}{c} \right) \right]^r \qquad \text{(Eq 4)}$$

Where Hdom – age is the predicted height-age couple and HdomM – ageM is the measured height-age couple.

Table 4.2 Corresponding parameters values of the top-height growth models fitted by Perin et al. (2014) for Southern Belgium Norway spruce, douglas-fir and larch pure even-aged stands.

	Norway spruce (Picea abies)	Douglas-fir (Pseudotsuga menziesii)	Larch (Larix kaempferi)
a	0.1299	0.2418	0.1449
c	22.3659	31.1379	14.9904
r	2.0464	1.4668	1.6818

First, we tested the parameterized formulations of Deleuze et al. (2004) for Norway spruce and douglas-fir directly on our data by comparing predicted and observed values to check its accuracy and applicability for Southern Belgium data. We then adapted the model to our data using the nls() nonlinear regression procedure in R (R Core Team, 2012). Several new formulation for parameters A, P and m were also tested in order to try to simplify the model while improving its performances on our dataset.

The recovered data were quite heterogeneous as they were obtained from different sources that used different sampling and measurement methodology. In particular, the number of trees monitored in each sampled stands ranged from 10 to 300. This needed to be addressed to avoid that some sampled stands outweighs too much the others during the parameterization of A, P and m formulations. We applied a simple weighting method to ensure that each sampled stands contribute to the fitting of the model in accordance with the length of the period it was monitored rather than the number of growth segments which were measured: each growth segment data was weighted by its length (in years) divided by the number of growth segments measured at the same time in the permanent sample plots (PSP). In this way, every sampled plot has a total weight equal to the total duration of its monitoring.

To take heteroscedasticity into account, Deleuze et al. (2004) weighted observations by $1/Ci^2$ but this does not solve the issue for our dataset. We instead choose to fit the model on girth increment value (Ici) rather than tree basal area increment data (Igi obtained from Eq 1):

$$Ic_i = (C_i{}^2 + 4\pi \, Ig_i)^{0.5} - C_i \qquad \text{(Eq 5)}$$

We then validated the model by using a K-fold cross-validation procedure (Kohavi, 1995). For each species, the sampled stands were sorted according to their size in the dataset (number of growth segments) and then spread in 4 independent and roughly equal-sized parts. The model was then fitted on 3 parts (training dataset) and then applied on the remaining part (validation dataset), this was done 4 times to ensure that every parts were used as validation dataset. This way, the validation mean error and validation root mean square error can be used as estimator of the predictive performance of the model when applied on an independent dataset.

All confidence intervals presented thereafter are calculated with a significance level of $\alpha = 0.05$ (95% confidence level) unless stated otherwise.

5. Results

At first glance (Table 4.3), the original model and the fitted parameters values proposed by Deleuze et al. (2004) seemed to perform quite well on our data with an RMSE on the annual tree girth increment estimation of 0.60 cm/yr for Norway spruce and 1.00 cm/yr for douglas-fir. Nevertheless, a bias was observed: on average, tree girth increment is overestimated by 0.18 cm/yr for Norway spruce and by 0.23 cm/yr for douglas-fir. Moreover, we observed significant correlation between the residuals values and the girth of the measured trees (Figure 4.3): increments are generally rightly estimated for girth under 90 cm (dbh under 30 cm) but are noticeably overestimated for bigger trees.

Table 4.3 Evaluation on our dataset of the prediction errors of the models parameterized by Deleuze et al. (2004) for Norway spruce and douglas-fir: root mean square error (RMSE) and mean error (ME) for the annual tree girth increment estimation (cm/yr) and the annual tree basal area increment estimation (cm^2/yr).

	Norway spruce (Picea abies)		Douglas-fir (Pseudotsuga menziesii)	
	Ic (cm/yr)	Ig (cm^2/yr)	Ic (cm/yr)	Ig (cm^2/yr)
Prediction RMSE	0.600	8.527	0.997	26.648
Prediction ME	0.183	2.696	0.231	8.389

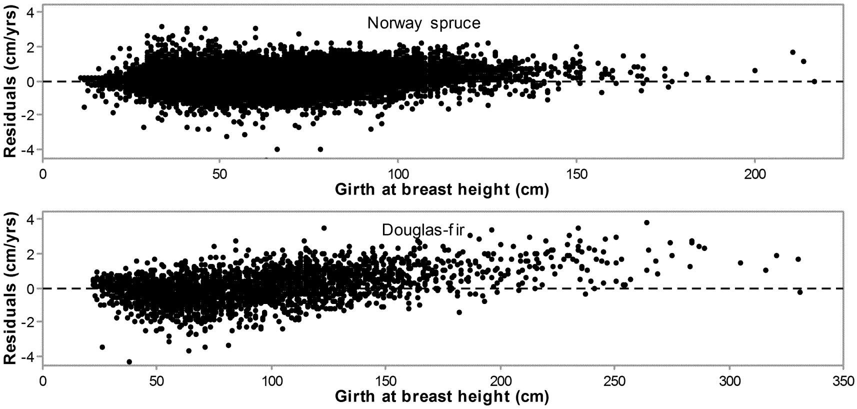


Figure 4.3 Distribution of the residuals (predicted - measured) on the annual girth increment estimation (in cm/yrs) obtained by applying the parameterized models of Deleuze et al. (2004) for Norway spruce and douglas-fir on our dataset.

We then parameterized the original model formulation on our dataset (Table 4.4) but were unable to meet the convergence criteria for douglas-fir and Japanese larch (step-size factor was reduced below minFactor). This type of non-convergence issue can often be explained by the use of an over-parameterized model and the correlation matrix of the parameters showed that the formulation for A and P were characterized by highly correlated parameters. Further test also highlighted that the suppression of either parameter Aa, Ac or Pc greatly facilitated convergence while having little impact on the fitting performance of the models for all 3 species. Thus, it seemed relevant to seek for a simpler formulation of A and P.

Table 4.4 Parameter values and fitting statistics of the original model formulation after parameterization on our data for Norway spruce, douglas-fir and larch; the confidence interval (1- α = 95%) is presented in italic next to each parameter value and non-significant parameters values are followed by a hash symbol (#); Akaike Information Criterion (AIC), training and cross-validation values of the root-mean-square error (RMSE), adjusted R² and mean error (ME) are also presented for the annual tree girth increment estimation (cm/yr) and between bracket for the annual tree basal area increment estimation (cm²/yr).

	Norway spruce (Picea abies)	Douglas-fir (Pseudotsuga menziesii)	Larch (Larix kaempferi)
Aa	-2.7140 ±*0.8053*	-25.6905 ±*36.2994* $^{\#}$	-41.3189 ±*15.9502*
Ab	2.2520 ±*0.0787*	5.5801 ±*7.4928* $^{\#}$	8.0782 ±*2.9599*
Ac	-0.8097 ±*0.09*	-0.6923 ±*0.3444*	-0.8739 ±*0.0464*
Pa	0.1685 ±*0.0094*	0.3124 ±*0.1718*	0.0306 ±*0.1203* $^{\#}$
Pb	0.5931 ±*0.0298*	0.8482 ±*0.4304*	0.0866 ±*0.3434* $^{\#}$
Pc	1.0827 ±*0.1938*	0.0521 ±*0.7005* $^{\#}$	11.0773 ±*47.6943* $^{\#}$
α	1.0228 ±*0.0892*	0.2306 ±*0.6124* $^{\#}$	0.2216 ±*0.1103*
m	1.0077 ±*0.002*	1.0287 ±*0.0121*	1.0361 ±*0.0067*
AIC	4 737 673 837	15 278 967	480 512 653
Training RMSE	0.530 (7.141)	0.757 (16.417)	0.608 (8.918)
Adjusted R²	0.620 (0.691)	0.505 (0.726)	0.630 (0.677)
Validation RMSE	0.539 (7.250)	0.775 (16.810)	0.614 (8.997)
Validation ME	-0.005 (-0.117)	0.017 (0.089)	0.000 (-0.134)

We determined that the model could be significantly simplified while keeping most of its fitting performances by transferring the expression of the stand density effect from the threshold and slope parameters (A and P) to the shape parameter (m). In this way, we found that the threshold parameter A could be expressed as a simple power function of dominant height and the slope parameter P as a simple linear function of annual top-height growth. Shape parameter m was best expressed as an exponential function of top-height and total basal area that ensure that its value is always greater than 1. The proposed formulations for parameters A, P and m are presented below:

$$A = Aa * Hdom^{Ab} \qquad \text{(Eq 6)}$$

$$P = Pa + Pb * dHdom \qquad \text{(Eq 7)}$$

$$m = 1 + exp(ma * Hdom - mb * Gha) \qquad \text{(Eq 8)}$$

These formulations reduce the total number of parameters that need to be fitted to 6 instead of 8 in the original formulation. Moreover, the formulations for the threshold and slope parameters (A and P) are simpler and no longer share the same explanatory variable.

The fitting of the new formulations easily met the convergence criteria for all three species and provided parameters estimates that were at least significant to the 0.05 level (Table 4.5). Compared to the original, the new formulation led to a small increase of the validation RMSE on annual tree girth increment estimation for Norway spruce (+1.1%) and larch (+2.1%) and to a minor decrease for douglas-fir (-0.5%). Further graphical analysis of the training and validation errors distributions according to each explanatory variables showed that the fitted models were unbiased and characterized by robust performance over the entire range of girth at breast height, age, top-height, site index and density represented in our dataset. As an example and for comparison with figure 4.3, the distribution of validation errors according to girth at breast-height is represented in figure 4.4.

Table 4.5 Parameters values and fitting statistics of the proposed 6 parameters model formulation after parameterization on our data for Norway spruce, douglas-fir and larch; the confidence interval (1- α = 95%) is presented in italic next to each parameter value; Akaike Information Criterion (AIC), training and cross-validation values of the root-mean-square error (RMSE), adjusted R² and mean error (ME) are also presented for the annual tree girth increment estimation (cm/yr) and for the annual tree basal area increment estimation (cm²/yr, between parenthesis).

	Norway spruce (Picea abies)	Douglas-fir (Pseudotsuga menziesii)	Larch (Larix kaempferi)
Aa	3.9825 ±*0.3010*	1.9987 ±*0.4563*	4.7358 ±*0.5610*
Ab	0.7802 ±*0.0239*	1.0544 ±*0.0619*	0.8241 ±*0.0361*
Pa	0.2160 ±*0.0089*	0.3725 ±*0.0595*	0.3435 ±*0.0182*
Pb	0.8014 ±*0.0258*	0.8500 ±*0.1103*	1.0514 ±*0.0428*
ma	0.1345 ±*0.0107*	0.0415 ±*0.0256*	0.0522 ±*0.0081*
mb	0.1853 ±*0.0081*	0.1225 ±*0.0230*	0.1328 ±*0.0067*
AIC	4 737 674 321	15 278 788	480 504 651
Training RMSE	0.537 (7.173)	0.758 (16.334)	0.622 (9.065)
Adjusted R²	0.607 (0.685)	0.499 (0.729)	0.612 (0.666)
Validation RMSE	0.545 (7.284)	0.771 (16.619)	0.627 (9.125)
Validation ME	-0.005 (-0.141)	0.009 (-0.067)	-0.001 (-0.145)

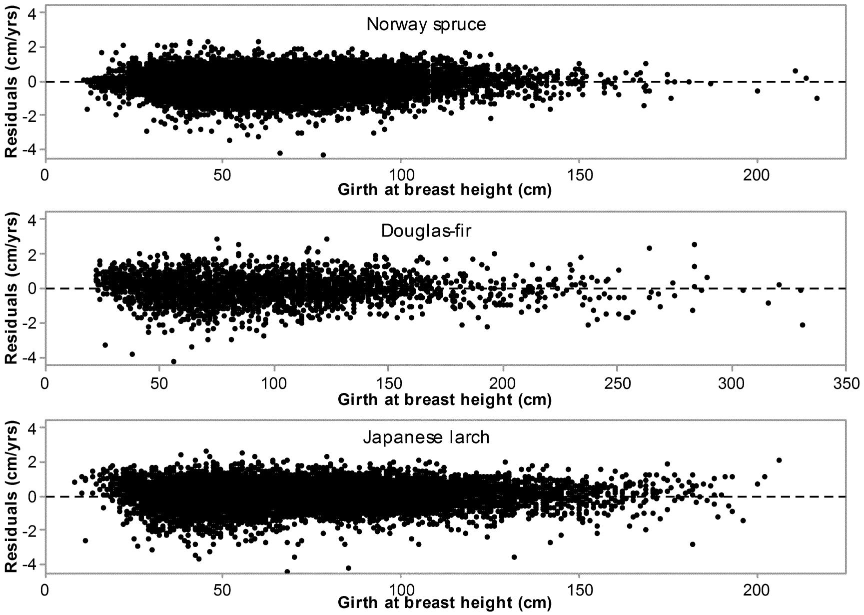


Figure 4.4 Distribution of the validation residuals (predicted - measured) on the annual girth increment estimation (in cm/yrs) obtained for Norway spruce, douglas-fir and larch with our new formulation.

6. Discussion

The dataset representativity is always the most critical component in empirical growth modeling as it is essential that it covers all the conditions for which the model will have to be valid. We worked in collaboration with other researchers and the Nature and Forest Department of Wallonia (DNF) to collect measured data from all known observation networks, field experiments and forest inventories relevant to our study and representative of the wide diversity of conditions (sites, age, density, etc.) encountered in coniferous stands of Southern Belgium. The Site index estimated in the sampled stands range from 13 to 32.5 for Norway spruce, 19.5 to 44.5 for douglas-fir and 21 to 37.5 for larch. These amplitude are generally wider than those previously estimated by Perin et al. (2014) thanks to data recovered from some unusually low-productivity stands located in site conditions where these species are no longer planted (e.g. peatland and humid clay soils). We also recovered data from several silvicultural field experiments where a wide variety of planting spacing and thinning intensity were tested (e.g. Hébert et al., 2002; Pauwels et al., 2007). Thus, density and total basal area variability are also greater in our dataset than what is found in most Southern Belgium young and mature coniferous stands managed for timber production. The number of sampled stands, trees and measured growth segments in our dataset are consistent with what is typically used in this type of research (e.g. Monserud & Sterba, 1996; Andreassen & Tomter, 2003; Monty et al., 2007).

To fit on our dataset, we selected a model which had recently been proven adequate for Norway spruce and douglas-fir in neighboring France (Deleuze et al., 2004) in sites and management conditions similar to those encountered in our study area, for example in the wooded plateau of the Ardennes which covers both part of Southern Belgium and Northern France. However, further test showed that the original parameterized models were not directly applicable in Southern Belgium as they lead to significantly overestimate Norway spruce and douglas-fir growth when applied on our dataset (Figure 4.3). It is possible that French coniferous stands are generally more productive than their Belgian counterpart but these divergences are more likely related to dataset and methodological differences. In particular, these models were fitted on data from experimental permanent plots of the AFOCEL's network which, according to a report of Gastine et al. (2003), were almost all installed in stands under the age of 45 years at the time of the study. The parameters estimates fitted by Deleuze et al. (2004) are thus probably less valid for coniferous stands over the age of 45 years which are quite common in Southern Belgium (Alderweireld et al., 2015) and represents 45% and 20% of the sampled Norway spruce and douglas-fir stands in our dataset.

The Deleuze et al. general model formulation (Eq 1) is interesting as it allows to distribute the effect of the stand-level explanatory variables in 3 different parameters (A, P and m) that influence the shape of the relation between individual girth and tree basal area increment in very contrasted way (Figure 4.2), making this model very flexible while always ensuring a biologically plausible constrained form. In addition, individual girth being the only tree-level variable makes it really easy to represent and understand the influence of the explanatory variables on growth estimates, to evaluate the model robustness, and finally to integrate it in a simulation software.

The parameter A determines the girth value below which tree growth is near zero and therefore represents a threshold below which trees could be considered as heavily suppressed. Our analysis showed that, consistently with the conclusion of Deleuze et al. (2004), this parameter was best expressed using variable related to the stand development stage (top-height, age, mean dbh,...) and the most suitable formulation appeared to be a power function of top-height. Combining height or top-height with tree girth value to identify suppressed trees can be linked to the tree height to diameter ratio (H/D) which is an already well known indicator of individual tree stability (e.g. Bruchert et al., 2000; Wonn & O’Hara, 2001; Slodicak & Novak, 2006) and of crown dimension (Dyer & Burkhardt, 1987; Hasenauer & Monserud, 1996) and has already been investigated as a potential competition index (Opio et al., 2000; Bachofen & Zingg, 2001). Therefore, dividing tree girth by the corresponding A parameter calculated value could provide an interesting indicator which would be inversely proportional to the past cumulative level of competition experienced by the tree and proportional to its present potential for utilizing growing space. In particular, estimates of this ratio close to (or less than) unity would probably indicate highly unstable trees with small crown ratio and low potential vigor that were heavily suppressed during a significant part of their lifetime.

The parameter P has a simple multiplicative effect on the increment estimation that is independent of the dominance status of the trees. In accordance with Deleuze et al. (2004), we obtained excellent results by expressing this parameter as a simple linear function of the estimated top-height annual growth (dHdom). In our data, dHdom was always calculated using the corresponding top-height growth models (Perin et al., 2013; Perin et al., 2014) which are nonlinear function of age, site index and species. Thus, the parameter P value is proportional to the estimated site index and increase to a maximum around the age of 10 years for larch and 20 years for Norway spruce and douglas-fir, slowly decreasing thereafter. In practice, top-height annual growth also depends on annual climate variability and thus, parameter P would probably be the most suitable to integrate weather variables in its formulation.

The parameter m determines the model flexibility around the threshold A, its value has an important positive influence on the growth estimation of trees with a girth at breast height inferior or close to A but almost none for bigger ones (Figure 4.2). We identified m as the ideal parameter to express the effect of density on growth. With the proposed formulation (Eq 8), m converge to 1 in denser stands, bringing the model closer to a segmented shape that ensure very low basal area growth estimation value for small suppressed trees which suffer from the intense competition for resources. This is consistent with the fact that dominant trees are less affected by competition than dominated ones (Schütz et al., 2015). The "competition effect" simulated by the parameter m is also inversely proportional to the dominant height which indicate that a given total basal area value account for a higher level of competition in younger forests stands than in older ones.

Thereby, the stand density variable (Gha) was transferred into the formulation of the parameter m, allowing us to greatly simplify the formulations of A and P so that they no longer share the same explanatory variables (Hdom and Gha). This allowed us to reduce the number of fitted parameters to 6 by species (instead of 8 in the original formulation) and to significantly facilitate the fitting process convergence. Unlike the original formulation of Deleuze et al. (2004), this new formulation converged easily without requiring an initial estimation of the starting values for the model parameters (or a self-starting function): using a starting value of 1 for each parameters proved to be perfectly appropriate on our dataset. We thus consider that the benefit of this new formulation more than offset the negligible loss of flexibility and fitting performance.

The calculated adjusted R^2 shows that our parameterized models explain 61, 50 and 61% of the annual girth increment variance and 68, 73 and 67% of the annual basal area increment variance for Norway spruce, douglas-fir and larch. Their level of performance (Table 4.5) seems relatively good (e.g. Monserud & Sterba, 1996; Andreassen & Tomter, 2003; Monty et al., 2007, Pauwels et al., 2007) and are probably close to the maximum that is possible to obtain with a distance independent growth model that does not take climate annual variability into account. Thus, this model represents an interesting compromise between performance and utility as it only uses simple explanatory variables (Age, Hdom, Gha, Ci) that are usually collected in forest management inventories. This greatly facilitates the collection of an appropriate training dataset and allows a direct application of the parameterized model on actual forest inventory data in order to predict the growth of existing trees.

A theoretical application of these new growth models is presented in figure 4.5: individual tree girth growth curves were built for each species in order to compare the development of dominant and suppressed trees in high and low density stands. We used values for the explanatory variables (Table 4.6) that are consistent with what can be encountered in Norway spruce, douglas-fir and Japanese larch stands of average site index from Southern Belgium (Dagnelie et al., 1988; Rondeux et al., 1991; Pauwels et al., 2007; Perin et al., 2014). The initial age was selected to match a dominant height of 14 m because it is consistent with the model validity range and usually corresponds to the first thinning stage in Southern Belgium coniferous stands (Alderweireld et al., 2015). The initial tree girth corresponds to a dominant tree juvenile growth of 2.5 cm/yrs for Norway spruce and 3.5 cm/yrs for douglas-fir and Japanese larch and to 60% of those values for suppressed trees. In those examples, the stand total basal area (density) is initially fixed for low and high density stands at respectively 25 m²/ha and 35 m²/ha and then increase by 0.25 m²/ha each year.

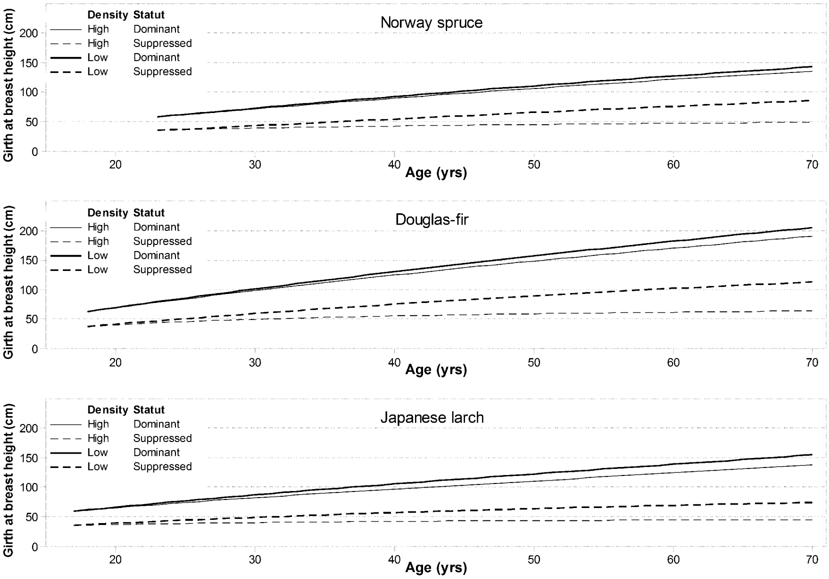


Figure 4.5 Simulation with the new growth models of the evolution of the individual girth at breast height of dominant and suppressed trees of Norway spruce, douglas-fir and Japanese larch in high and low density forest stands.

Table 4.6 Parameters of the growth simulation presented in figure 4.5.

	Norway spruce (Picea abies)	Douglas-fir (Pseudotsuga menziesii)	Larch (Larix kaempferi)
Site index (top-height at age 50)	27 m	36 m	27 m
Initial age (14 m top-height)	23 yr	18 yr	17 yr
Initial tree girth (dominant)	57.5 cm	63 cm	59.5 cm
Initial tree girth (Suppressed)	34.5 cm	37.8 cm	35.7 cm
Initial stand density (high)	35 m²/ha	35 m²/ha	35 m²/ha
Initial stand density (low)	25 m²/ha	25 m²/ha	25 m²/ha
Annual stand density change	+ 0.25 m²/ha/yr	+ 0.25 m²/ha/yr	+ 0.25 m²/ha/yr

These growth curves (Figure 4.5) show that douglas-fir is characterized by a substantially faster growth rate (≈ +50%) than that of Norway spruce and Japanese larch which is consistent with the general knowledge about these species in Southern Belgium. It also highlights that density has a much greater effect on the growth rate of suppressed trees than that of dominant ones which is an important feature of this model that was already discussed before. The differences between the mean annual girth increment estimated in low and high density stands are equal to 8%, 10% and 18% for dominant trees compared to 73%, 65% and 74% for suppressed trees, respectively for Norway spruce, douglas-fir and larch. It also indicates that Japanese larch growth rate appears to be particularly sensitive to stand density variation as already highlighted by Pauwels et al. (2007) who recommended lower stand density for larch than for Norway spruce and douglas-fir.

7. Conclusion and Perspectives

The new girth growth parameterized models presented in this study allow for unbiased increment prediction over the entire range of girth at breast height, age, top-height, site index and density encountered in most monospecific Norway spruce, douglas-fir and larch stands managed for timber production in Southern Belgium.

The model formulation is purposely ideal for forest simulation software as the explanatory variables needed are simple and usually collected in forest inventory: individual girth at breast height, total basal area, top-height and estimated annual top-height growth (calculated from the top-height and the age of the stand by using the corresponding site index model).

Future uses of these models concern the development of a forest simulation software to help optimize silvicultural management techniques and to predict medium and long term changes in softwood forest resources of Wallonia. We also intend to further test the generic capabilities of this model formulation with other species in regular stands, especially with hardwood.

Chapter 5

New yield tables for softwood plantations

Adapted from

Perin J., Hébert J., Lejeune P., Claessens H. 2016. De nouvelles normes sylvicoles pour les futaies pures équiennes d'épicéa et de douglas en appui à la gestion de la forêt publique en Wallonie. Forêt.Nature, 139: 57-67.

1. Preamble

In previous chapters, we have shown that the growth rate of Norway spruce and douglas-fir was previously significantly underestimated and that an update of the growth and yield models was required. This chapter concerns the development of new silvicultural guidelines and updated yield tables for Norway spruce and douglas-fir plantations based on the new site-index and growth models.

2. Introduction

L'épicéa est la première essence de production en Wallonie. On estime que les pessières pures représentent environ 25% des surfaces forestières productives (≈ 120 000 ha) et près de 40% du volume de bois sur pied (≈ 40 millions de m³). Néanmoins, la surface forestière consacrée à cette essence diminue régulièrement depuis le début des années 1990 pour une série de raisons liées à l'historique des plantations, aux conditions socio-économiques et écologiques actuelles et futures : 25 000 ha d'épicéa ont ainsi disparu entre 2000 et 2010 pour être convertis en d'autres peuplements résineux ou feuillus, en milieux ouverts ou tout simplement laissés en friches (Alderweireld et al., 2015).

Le douglas est l'essence résineuse qui a le mieux profité de la régression de l'épicéa. Il représente en effet une alternative intéressante en raison de sa productivité supérieure, d'une meilleure stabilité au vent, des bonnes caractéristiques de son bois et de sa souplesse présumée face aux changements climatiques. On estime que la surface des douglasaies pures a pratiquement doublé depuis 1995, se situant maintenant à environ 21 000 ha. De même, les surfaces occupées par des peuplements en mélange épicéa-douglas ont également fortement progressé ces deux dernières décennies, pour atteindre environ 12 000 ha. Ainsi, les peuplements où le douglas est l'objectif final de production représentent près de 7% de la surface forestière productive wallonne.

A la fin des années 1980, les premiers outils quantitatifs d'aide à la gestion ont été développés pour guider les sylviculteurs dans la conduite des pessières en Wallonie. Ces outils ont été synthétisés dans des tables de production décrivant l'évolution théorique des principaux paramètres dendrométriques d'un peuplement pur équienne soumis à des scénarios sylvicoles contrastés (Dagnelie et al., 1988). Des outils du même type ont ensuite été développés pour le douglas (Rondeux et al., 1991, Thibaut et al., 1995). Ils se présentent sous la forme (1) de tables de production décrivant l'évolution théorique des principaux paramètres dendrométriques d'un peuplement soumis à une sylviculture moyenne ou (2) de courbes exprimant le niveau de productivité via une relation entre l'âge et la hauteur dominante des peuplements. Ces tables de production n'ont toutefois pu être construites qu'à partir de données issues des peuplements existants qui relevaient d'une sylviculture globalement moins dynamique que celle qui est pratiquée actuellement.

Depuis lors, la politique forestière a mis l'accent sur la multifonctionnalité de la forêt et notamment sur les fonctions écologiques. Il y a donc lieu d'adapter la densité des peuplements afin de favoriser la biodiversité et le maintien de la fertilité des sols via la minéralisation des litières. Pour ce qui est des pessières, la sensibilité des peuplements aux chablis est devenue un paramètre déterminant de la sylviculture suite aux évènements extrêmes de 1990 et 1999. On considère désormais que le risque de chablis dans les pessières denses devient élevé dès qu'elles dépassent 30 mètres de hauteur dominante (Hébert et al., 2002).

La dernière norme de traitement de la pessière équienne que préconise le DNF via la circulaire 2707 publiée en 2009 tient déjà compte de ces évolutions. Elle vise à installer une sylviculture plus dynamique en imposant une première éclaircie hâtive (vers 13 mètres de hauteur dominante) et une surface terrière voisine de 30 à 35 m2/ha selon la position du peuplement au sein de la rotation. De cette manière, les pessières en forêt soumise devraient progressivement devenir moins denses.

En ce qui concerne le douglas, les itinéraires de gestion appliqués suivent encore souvent des standards proches de ceux appliqués à l'épicéa. Le douglas est pourtant caractérisé par une vitesse de croissance et un potentiel de production nettement supérieurs (de l'ordre de 30%), auxquels ces itinéraires ne sont pas adaptés.

En outre, l’analyse approfondie de données issues de divers réseaux d'observations et de plusieurs dispositifs expérimentaux a permis de mettre en évidence d’importants écarts entre les accroissements mesurés et les valeurs de référence présentées dans les tables de production. Ce constat est particulièrement marqué dans les pessières et les douglasaies âgées de plus de 50 ans où la vitesse de croissance et le niveau de production seraient significativement sous-estimés. Un tel écart justifiait pleinement le développement de nouveaux modèles de croissance permettant de mieux prédire la dynamique de croissance de ces deux essences et leur réaction aux traitements sylvicoles pratiqués.

L’objet de cet article est de présenter la synthèse des travaux récemment menés sur la construction de nouveaux modèles de croissance pour l’épicéa et le douglas en Wallonie et d’illustrer l’utilisation de ces derniers pour la définition de normes sylvicoles adaptées spécifiquement à chacune de ces deux essences.

3. Méthode

3.1. Développement des outils

De nouveaux modèles de croissance en hauteur dominante ont récemment été mis au point pour l'épicéa et le douglas (Perin et al., 2013; 2014). Tirant profit des derniers développements statistiques ainsi que de séries d’observations plus adéquates et récentes, ces nouveaux modèles sont plus performants et d'utilisation plus simple que leurs prédécesseurs. Les classes de productivité ont par ailleurs été redéfinies pour ces essences de manière à, d'une part, centrer le niveau de productivité moyen sur la seconde classe et, d'autre part, s'assurer que l'amplitude des classes (3 m pour l'épicéa et 4 m pour le douglas) permette de rassembler la quasi-totalité (≈ 97.5%) des douglasaies et des pessières dans 5 classes de productivité (Figure 5.1) et soit compatible avec la variabilité des hauteurs totales observées chez les arbres dominants dans ces peuplements.

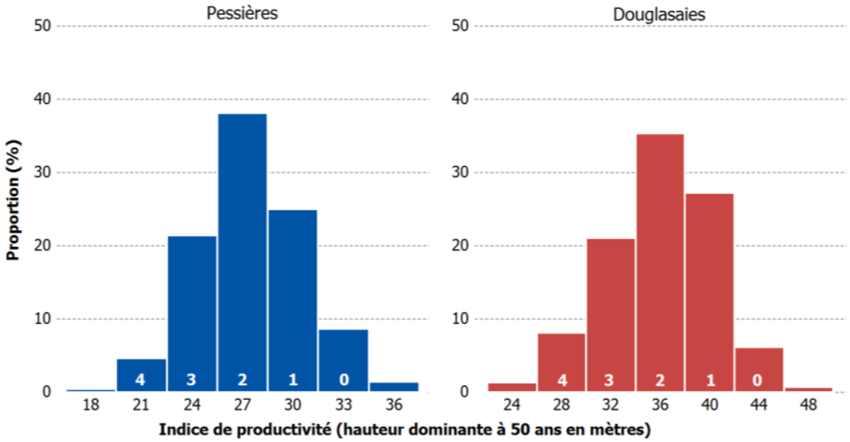


Figure 5.1 Distribution des classes de productivité rencontrées dans les placettes permanentes de l'IPRFW installées dans des peuplements purs équiennes d'épicéa (en bleu) et de douglas (en rouge) âgés de 25 à 60 ans au moment des mesures.

De nouveaux modèles de prévision de la croissance individuelle en circonférence des arbres ont également été développés pour les deux essences. Les estimations fournies sont basées sur le statut social de l'arbre au sein du peuplement, ainsi que sur le niveau de production, l'âge et la densité du peuplement.

Ces modèles (courbes de productivité et croissance en grosseur) ont ensuite été intégrés dans un logiciel de simulation nommé GYMNOS qui fait partie de la plateforme de simulation forestière CAPSIS (Dufour-Kowalski et al., 2012). GYMNOS permet d'anticiper l'évolution d'un peuplement théorique (caractérisé par une couverture forestière complète, sans effet de bordure) de densité initiale connue et soumis à un itinéraire sylvicole donné. Néanmoins, dans la pratique, le couvert n'est jamais parfaitement continu (bordures, chablis, trouées,...) et ce type de simulation mène ainsi généralement à surestimer la production. Cette surestimation est corrigée dans GYMNOS en considérant une production réelle diminuée de 10% par rapport à la production théorique.

Le résultat fourni par GYMNOS se présente sous la forme d'une table de production, complétée par d'autres informations qui sont :

- un facteur d'élancement à l'échelle du peuplement correspondant au rapport entre la hauteur dominante et le diamètre moyen quadratique pouvant être utilisé comme un indicateur d'instabilité aux vents des peuplements résineux;
- la distribution par classe de grosseur des volumes sur pied avant éclaircie et des volumes prélevés à chaque éclaircie;

- la valeur marchande des volumes sur pied délivrés lors des éclaircies et de la coupe rase finale, calculée sur base d’une liste de prix ajustée sur les données des ventes publiques de 2012 à 2014.

L’itinéraire sylvicole est décrit par l’écartement à la plantation (ou après le dépressage dans le cas de régénérations naturelles), l’âge de la première éclaircie, les caractéristiques des prélèvements (rotation, intensité et type) et la durée de la révolution.

3.2. Elaboration de scénarios sylvicoles

A l’initiative du DNF, un groupe de travail composé de sylviculteurs, de technologues du bois et de modélisateurs a été réuni pour mettre au point des normes de sylviculture adaptées à l’épicéa d’une part et au douglas d’autre part. Pour ce faire, divers scénarios de gestion ont été élaborés, puis simulés à l’aide du logiciel GYMNOS de manière à tester l'influence de paramètres sylvicoles sur les caractéristiques des peuplements attendus. Les critères considérés pour comparer les différents scénarios concernent la vitesse de croissance en grosseur, certaines caractéristiques du bois, les volumes produits et la stabilité des peuplements. Les résultats chiffrés des simulations combinés à l'expertise des membres du groupe de travail ont permis d'identifier et de construire, pour chacune des deux essences, les scénarios de gestion jugés les plus en adéquation avec une gestion forestière multifonctionnelle.

4. Résultats

Les normes sylvicoles proposées concernent les peuplements purs équiennes d'épicéa et de douglas issus de plantations ou de régénérations naturelles dépressées. Les principaux objectifs associés à ces nouvelles normes peuvent se résumer comme suit :

- maximiser la production en volume et raccourcir les révolutions;
- produire un bois de qualité apte à des usages à haute valeur ajoutée;
- assurer la stabilité des peuplements face aux tempêtes;
- favoriser la protection des sols et la biodiversité.

La démarche sylvicole retenue consiste à éliminer les arbres mal conformés dès les premières coupes d’éclaircie et de mettre en place des arbres d'avenir dominants et co-dominants bien conformés dont la production en volume sera favorisée par les éclaircies tout en maintenant des cernes avec une largeur inférieure à 6 mm, compatible avec la meilleure qualité structurelle des sciages définie par la spécification technique "STS 04" (SPF Economie, 2008).

4.1. Production des pessières et des douglasaies

Les nouveaux modèles de croissance montrent que l'accroissement courant en volume bois fort augmente rapidement jusqu'à atteindre un maximum vers la hauteur dominante de 20 et 28 m respectivement pour l'épicéa et le douglas, c'est à dire entre 30 et 40 ans en fonction de la classe de productivité (Figure 5.2). Ce maximum varie entre la classe de productivité la plus basse (4) et la plus haute (0) : de 15 à 26,5 m³/ha/an pour l'épicéa et de 19 à 31,5 m³/ha/an pour le douglas. Les douglasaies les plus productives situées dans les stations les plus favorables (classe 0) peuvent ainsi dépasser les 30 m³/ha/an d'accroissement courant en volume entre 20 et 40 ans. La production en volume diminue ensuite d'environ 0,7%/an dans les pessières et 0,4%/an dans les douglasaies. En conséquence, si on considère cette fois l'accroissement moyen en volume (Figure 5.3), on peut voir qu’il atteint son maximum dans des peuplements ayant déjà acquis les dimensions d'exploitabilité et reste ensuite relativement stable, en particulier dans les douglasaies.

A classe de productivité égale, les douglasaies matures sont caractérisées par une production totale en volume environ 30% supérieure à celle des pessières. La production totale en volume à 60 ans en classe 2 (moyenne) serait ainsi d'environ 900 m³/ha dans les pessières et de 1200 m³/ha dans les douglasaies. Pour une même essence, les différences de production en volume entre deux classes de productivité adjacentes sont de l'ordre de 15%, de sorte que la production des pessières matures situées en classe 0 (très haute) est comparable à celle des douglasaies situées en classe 2 (moyenne).

Comparés aux tables de production de Dagnelie et al. (1988) pour l'épicéa et de Rondeux et al. (1991) pour le douglas, ces nouveaux modèles mettent en évidence des accroissements en volume beaucoup plus soutenus dans le temps. Les anciennes tables menaient ainsi à une sous-estimation significative de la production en volume dans les peuplements plus âgés. Dans les pessières, cette différence apparaît dès l'âge de 40 ans et la production totale en volume serait ainsi sous-estimée d'environ 6% à 60 ans dans les anciennes tables. D'autre part, les classes de productivité du douglas ont récemment été redéfinies (Perin et al., 2014) pour mieux tenir compte de sa croissance exceptionnelle : la nouvelle première classe de productivité est désormais caractérisée par une production en volume environ 15% supérieure à celle de l'ancienne classe 1 qui est désormais assimilée à la nouvelle classe 2 (productivité moyenne).

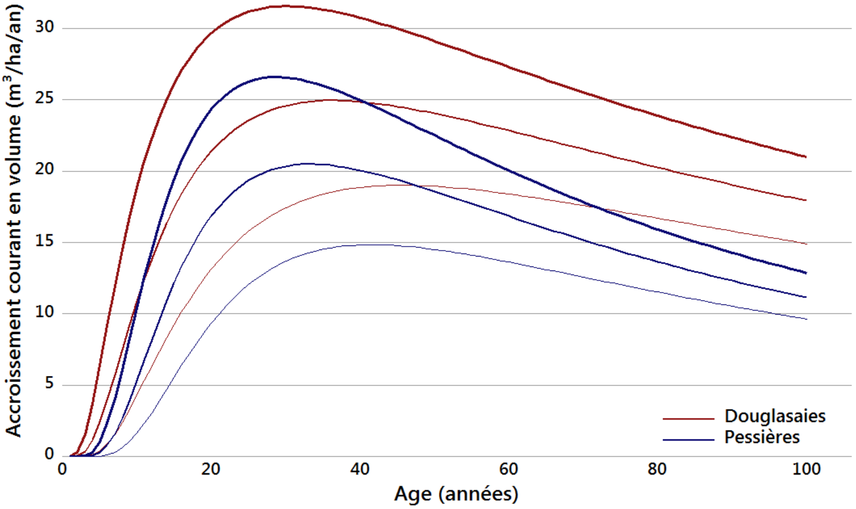


Figure 5.2 Evolution de l'accroissement courant en volume bois fort tige (m3/ha/an) dans les pessières (en bleu) et les douglasaies (en rouge) équiennes en fonction de leur âge. Pour chaque essence : la courbe centrale représente la classe 2 (productivité moyenne), la courbe supérieure en gras représente la classe 0 (très haute productivité) et la courbe inférieure en trait fin représente la classe 4 (très basse productivité).

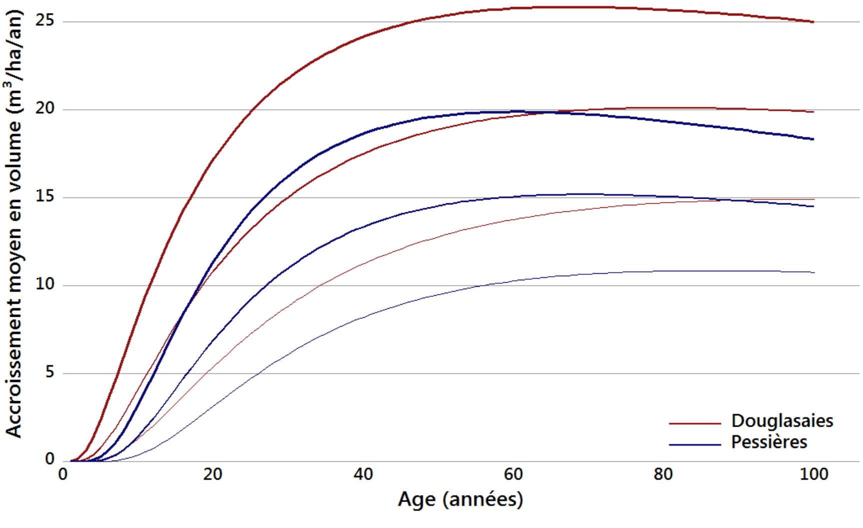


Figure 5.3 Evolution de l'accroissement moyen en volume bois fort tige (volume produit total divisé par l'âge) dans les pessières (en bleu) et les douglasaies (en rouge) équiennes en fonction de leur âge. Pour chaque essence : la courbe centrale représente la classe 2 (productivité moyenne), la courbe supérieure en gras représente la classe 0 (très haute productivité) et la courbe inférieure en trait fin représente la classe 4 (très basse productivité).

4.2. Itinéraires sylvicoles

4.2.1. Les écartements à la plantation

La densité de plantation influence directement l'âge auquel se produit la fermeture du couvert et débute la phase de compression. Ainsi, la qualité du bois est favorablement influencée par des densités initiales élevées, synonymes d’une phase de compression plus précoce, limitant ainsi la production de bois juvénile, la grosseur des nœuds et le défilement. A l’inverse, la vitesse de croissance, la stabilité et la biodiversité sont favorisées par les plantations à plus larges espacements où les arbres peuvent mieux développer leur cime et leur ancrage au sol et où la végétation d'accompagnement profite de plus d'éclairement lors des premières années.

Les simulations réalisées avec GYMNOS, combinées à l'analyse d'expérimentations sylvicoles telles que les C.C.T. plots (Delvaux, 1983), montrent que des écartements à la plantation de 2 mètres entre les arbres et 2 à 2,5 mètres entre les lignes (2000 et 2500 tiges/ha) constituent un bon compromis entre ces différents objectifs, en accord avec les conclusions de Hébert et al. (2002). L'écartement de 2 mètres entre les lignes est surtout prévu pour les situations plus difficiles (climat rigoureux de la haute Ardenne, faibles niveaux de productivité) pour lesquelles les risques de perte sont plus grands, alors que l'espacement de 2,5 mètres convient aux conditions plus optimales.

Pour toutes les simulations, aucun regarnissage n'a été envisagé et des taux de reprise de 90% pour l'épicéa et de 85% pour le douglas ont été retenus. Dans le cas des régénérations naturelles, une mise à distance moyenne de 2 m entre semis dès que la hauteur de la plage de semis atteint 1 à 2 mètres, a été retenue comme hypothèse de travail.

4.2.2. La première éclaircie

Le déclenchement de la première éclaircie doit avoir lieu après le début de la phase de compression qui est favorable à la rectitude des tiges et à la qualité du bois, mais avant l'apparition du processus d’auto-éclaircie qui entrainerait une perte de production par mortalité. Dans une plantation de 2000-2500 tiges/ha d'épicéa ou de douglas, les modèles montrent que la phase de compression, caractérisée par une diminution sensible des accroissements individuels (particulièrement forte chez les arbres dominés), démarre lorsque les peuplements atteignent environ 9 à 10 mètres de hauteur dominante, soit vers 15 ans pour l'épicéa et 10 ans pour le douglas en classe de productivité moyenne (classe 2). La mortalité naturelle due à la compétition et la perte de production qui en résulte deviennent quant à elles significatives à partir de 17 mètres de hauteur dominante, soit vers 27 ans pour l'épicéa et 22 ans pour le douglas en classe de productivité moyenne.

La phase de compression est liée à une diminution de la quantité de lumière qui pénètre le peuplement, qui en retour, cause la mortalité des branches basses (remontée des cimes vivantes). Il est important d'éviter une remontée de cime trop importante qui aurait pour conséquence de diminuer la capacité de réaction des arbres aux éclaircies. On conseillera ainsi d'intervenir lorsque que la hauteur sans branche vivante pour les arbres dominants est supérieure à 4 mètres mais inférieure à la moitié de la hauteur dominante. Il est également important d'éclaircir suffisamment tôt pour placer individuellement les arbres dans une dynamique de développement qui permette, par la suite, un régime d'éclaircies dynamiques soutenant leur croissance. Par la même occasion, ce régime d'éclaircies favorisera l'apport de lumière en sous-bois dont les essences d'accompagnement et la végétation herbacée ont généralement besoin. Intervenir lorsque la hauteur dominante du peuplement atteint entre 13 et 14 mètres (selon la densité de départ) est un compromis qui répond bien à toutes ces exigences.

Lors de la première éclaircie, il est conseillé de réaliser une coupe systématique d'une ligne tous les 20 mètres (1 sur 11 si l'interligne est égal à 2 mètres, 1 sur 9 s'il est égal à 2,5 mètres) qui servira de cloisonnement d'exploitation sur lequel circuleront les machines d’exploitation durant toute la vie du peuplement afin d'éviter le tassement de l'ensemble des sols de la coupe. Cette coupe systématique est complétée par un nettoiement visant à prélever environ un arbre sur 4 (ou 1 sur 3 dans le cas de régénérations naturelles et de plantations à 2 x 2 m) entre les cloisonnements. Cette proportion ne concerne que les arbres encore vivants après la crise de l'installation et les mortalités du début de la phase d'auto-éclaircie. La priorité doit être donnée à la coupe des arbres mal conformés (les "loups"), en particulier ceux qui occupent l'étage dominant et qui se développent au détriment des tiges d'avenir. Il est également suggéré d'éliminer les arbres les plus chétifs, sans avenir et potentiellement nuisibles à la stabilité du peuplement pour aérer le peuplement en faveur de la biodiversité. Cette première éclaircie structure le peuplement par ses cloisonnements et comporte une part de nettoiement et de dépressage, tout en maintenant encore une certaine compression pour la formation des tiges d’avenir. Cette phase de compression est particulièrement importante pour le douglas dont certains individus ont parfois tendance à produire de trop grosses branches.

4.2.3. Les éclaircies suivantes

Avant la seconde éclaircie, il est suggéré de désigner environ 150 arbres d'avenir bien répartis dans le peuplement parmi les plus gros (potentiel de croissance) qui présentent une cime équilibrée et bien développée (stabilité et potentiel de réaction aux éclaircies) et un fût bien conformé et finement branchu (qualité du bois). Un élagage artificiel des arbres d'avenir peut s'envisager sur une hauteur de 6 à 8 mètres (surtout pour le douglas) avant que la circonférence du fût ne dépasse le tiers de la circonférence espérée de la grume, mais la rentabilité de cette opération n'est malheureusement pas garantie. Ensuite, sans pour autant détourer totalement les arbres désignés, on tâchera de mener les éclaircies en leur faveur, de manière à concentrer la production du peuplement dans les plus beaux arbres. Dans ce but, les deuxième et troisième éclaircies sont assez fortes (25 à 30 % des tiges en épicéa; 30 à 35% en douglas) et déterminantes car elles mettent en place la dynamique de croissance des arbres d'avenir.

Lors de chaque coupe d’éclaircie, on tâchera toujours en priorité d'améliorer la qualité du peuplement en supprimant les arbres mal conformés et ceux qui ont une cime déséquilibrée ou mal développée. On s'attachera ensuite à pratiquer des éclaircies par le haut en prélevant les arbres dont les cimes concurrencent celles des tiges d'avenir.

Les éclaircies doivent aussi assurer le maintien d'une compétition constante, bénéfique pour la formation de cernes annuels d'épaisseur régulière et de nœuds sains (mortalité des branches basses). Cette compétition doit toutefois rester modérée de manière à contribuer à la formation d'arbres stables avec des cimes équilibrées et à favoriser l'apport de lumière en sous-bois pour favoriser la minéralisation de l'humus et développer la biodiversité. Il faudra ainsi veiller à maintenir chez les arbres d'avenir une proportion de cime vivante comprise entre le tiers et la moitié de la hauteur totale.

Les normes de sylviculture proposées doivent traduire l’effet des coupes d’éclaircie au cours des rotations successives, depuis les premières éclaircies assez fortes, jusqu'aux dernières, qui capitalisent sur les arbres d'avenir. Dans les pessières, Hébert et al. (2002) définissent un critère simple, « maintenir la surface terrière entre 30 et 35 m²/ha par le jeu des éclaircies », pour concilier vitesse de croissance, stabilité et qualité technologique du bois. Néanmoins, l'analyse de plusieurs expérimentations sylvicoles et les simulations montrent qu'une norme basée sur une valeur constante de la surface terrière conduit à une pression de compétition décroissante au cours du développement du peuplement. Ainsi, la norme de 30-35 m²/ha apparait idéale entre 20 et 25 mètres de hauteur dominante mais cette densité semble trop élevée avant 20 mètres et trop légère au-delà de 25 mètres. Il semble donc plus pertinent d'appliquer une norme de densité qui évolue avec la hauteur dominante. En effet, maintenir un niveau de compétition harmonisé permettra d'équilibrer l'ambiance forestière en sous-bois tout en contenant la largeur de cerne et en assurant une capitalisation régulière de volume pour la coupe finale.

Pour éviter ce problème, le module qui simule les éclaircies dans GYMNOS intègre une estimation du niveau de compétition dans les pessières et les douglasaies avec un paramètre qui combine l'essence, la surface terrière et le stade de développement. Le développement des nouvelles normes vise à maintenir dans les pessières et les douglasaies une pression de compétition équivalente à celle observée dans une pessière caractérisée par une surface terrière à mi rotation de 35 m²/ha et une hauteur dominante de 25 mètres (Table 5.1). L'intensité des prélèvements est donc toujours calibrée sur l'accroissement périodique en surface terrière et en volume, permettant ainsi une capitalisation progressive du volume sur pied en vue de la coupe finale. Cela mène, après trois éclaircies initiales assez fortes, destinées à placer les arbres dans de bonnes conditions de croissance, à une diminution régulière de l'intensité des prélèvements en termes de proportion des tiges éclaircies.

Table 5.1 Normes de densité après éclaircie conseillées pour les pessières et les douglasaies équiennes. Hdom = hauteur dominante; Gha = surface terrière à l'ha; Vha = volume sur pied à l'ha.

	Pessières		**Douglasaies**	
Hdom (m)	**Gha** (m^2/ha)	**Vha** (m^3/ha)	**Gha** (m^2/ha)	**Vha** (m^3/ha)
13	20,2	115	19,1	100
14	21,5	136	20,1	117
16	24	179	22,1	150
18	26,3	221	24,1	184
20	28,4	263	25,9	218
25	33,1	366	30,1	303
30	36,7	467	33,7	389
35	39,3	566	36,8	474
40	40,8	663	39,3	561
45			41,2	648
50			42,5	735

Ces nouvelles normes ont été établies pour une durée de rotation de 6 ans entre les passages en éclaircie car elle représente un bon compromis pour :

- maintenir une pression de compétition constante mais modérée;
- délivrer des volumes suffisants pour rentabiliser chaque coupe d'éclaircie, même dans des peuplements de faible superficie (≈ 1 ha);
- mettre au point une norme compatible avec les rotations en vigueur dans la plupart des plans d'aménagement des forêts publiques en Wallonie.

La productivité des douglasaies étant sensiblement supérieure à celle des pessières, il pourrait sembler pertinent d'y envisager des rotations plus courtes (3 ou 4 ans par exemple), surtout dans le jeune âge. Néanmoins, la mise en pratique de prélèvements aussi fréquents peut s'avérer fastidieuse. Par ailleurs, l'intérêt de prélèvements aussi rapprochés semble finalement limité pour le douglas qui n'a pas les problèmes de stabilité au vent que connait l'épicéa. Nous avons donc préféré harmoniser les durées des rotations pour ces deux essences tout en privilégiant des prélèvements plus forts dans les douglasaies de manière à équilibrer la densité moyenne entre deux passages en éclaircie et à maintenir le potentiel de croissance élevé de l'essence. Un passage en éclaircie à mi-rotation peut néanmoins toujours être envisagé dans les jeunes peuplements résineux les plus productifs.

4.2.4. Coupe rase et terme d'exploitabilité

Pour l'épicéa, la coupe rase est proposée lorsque la majorité des arbres se situe dans la classe de circonférence de 120-150 cm à hauteur de poitrine. Selon les simulations réalisées, cette dimension correspond à un peuplement d'environ 30 mètres de hauteur dominante et est atteinte entre 55 et 70 ans selon le niveau de productivité. Au vu des risques croissants de chablis à partir d’une telle hauteur, il n'est pas souhaitable de prolonger la vie de ces peuplements. Toutefois, pour autant que les conditions stationnelles (bon enracinement, protection contre le vent) et les caractéristiques du peuplement tempèrent les risques de chablis, des objectifs particuliers peuvent justifier l'allongement de la révolution, comme par exemple, l'étalement des récoltes au niveau d'une propriété ou la mise en œuvre d'une régénération naturelle.

Pour le douglas, l'exploitation du peuplement peut se faire lorsque la majorité des arbres ont atteint le seuil de 180 cm de circonférence. En deçà, la grume comporterait trop peu de bois valorisable en raison de la forte proportion de bois juvénile, d'écorce et d'aubier qui caractérisent le douglas. A ce stade, la hauteur dominante du peuplement avoisine 42 à 44 m pour un âge se situant entre 60 et 75 ans selon le niveau de productivité. Contrairement aux pessières, les douglasaies sont peu sensibles aux volis. Il est donc possible de retarder l'exploitation pour produire de très gros bois, étaler les récoltes ou encore, profiter au mieux de la régénération naturelle. En effet, il est fort probable qu'à ce stade, un tel peuplement soit en cours de régénération (Petit et al., 2013).

4.3. Présentation des nouvelles tables de production

L'évolution des peuplements soumis à ces normes de sylviculture est synthétisée dans de nouvelles tables de production. Ces tables sont au nombre de 10 pour chaque essence en fonction de la classe de productivité (0 à 4) et des écartements à la plantation (2 x 2 m ou 2 x 2,5 m). Elles sont téléchargeables en format PDF sur la plateforme ORBI de l’ULg (dépôt bibliographique institutionnel) : http://hdl.handle.net/2268/198122

Pour illustrer ces tables de production, les figures 5.4 et 5.5 proposent des représentations graphiques de l’évolution du nombre de pieds et de la circonférence moyenne du peuplement en fonction de l’âge, respectivement pour l'épicéa et le douglas (classe de productivité 2).

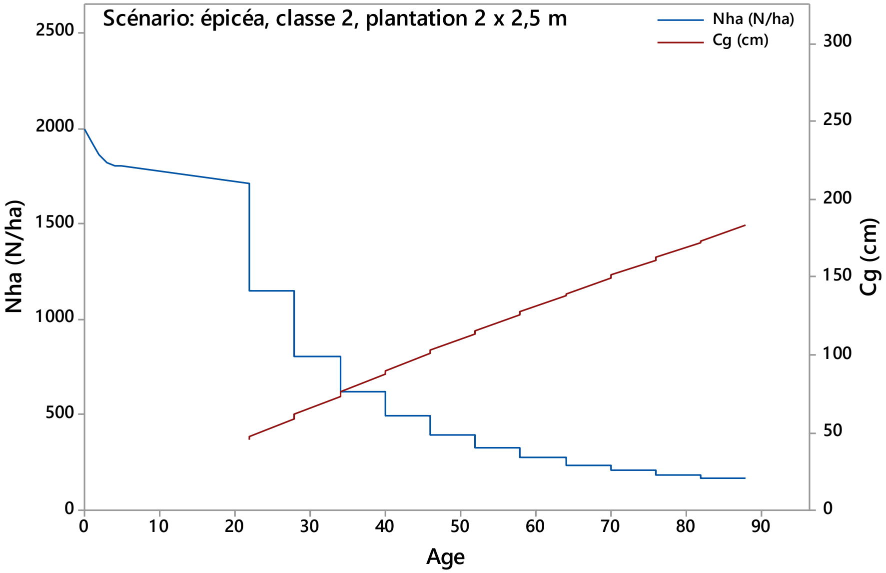


Figure 5.4. Représentation graphique de la norme sylvicole proposée pour l'épicéa (peuplement pur équienne de la classe de productivité 2, plantation à 2000 tiges/ha).

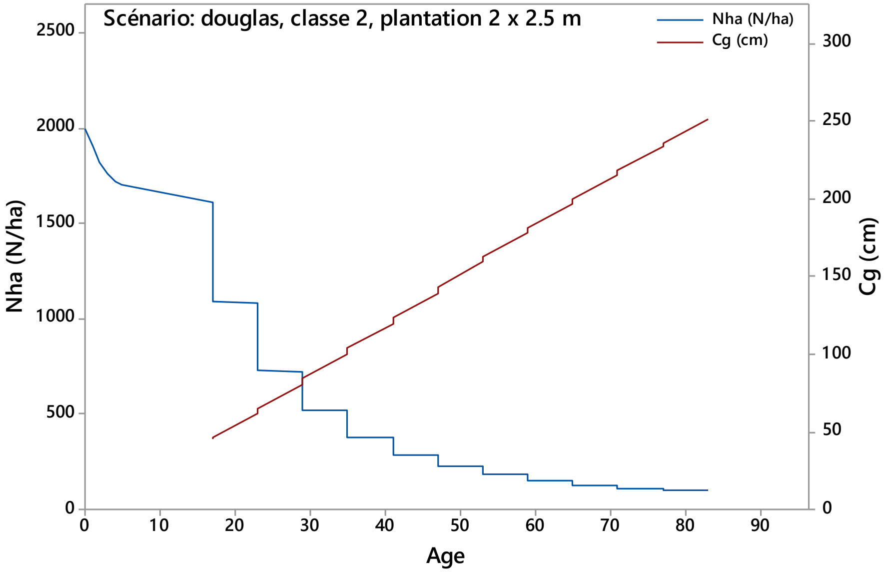


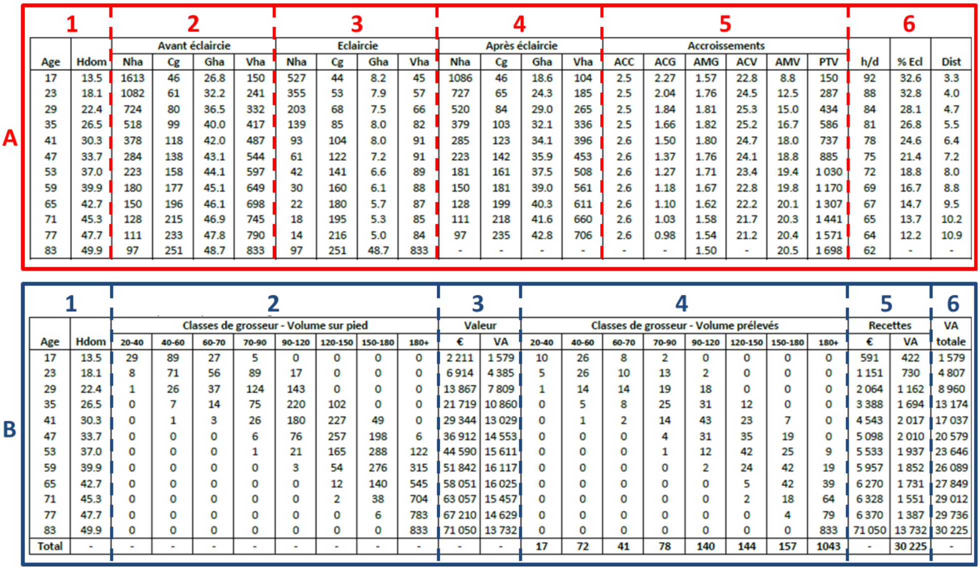
Figure 5.5. Représentation graphique de la norme sylvicole proposée pour le douglas (peuplement pur équienne de la classe de productivité 2, plantation à 2000 tiges/ha).

Ces nouvelles tables de production sont divisées en deux tableaux (Figure 5.6). Le premier tableau (A) présente l'évolution des caractéristiques dendrométriques du peuplement et des éclaircies (ramenées à l'ha) :

1) Âge et hauteur dominante du peuplement;
2) Caractéristiques dendrométriques du peuplement avant éclaircie : nombre de tiges (Nha), circonférence moyenne quadratique (Cg en cm), surface terrière (Gha en m^2/ha) et volume sur pied (Vha en m^3/ha);
3) Caractéristiques dendrométriques des éclaircies (Nha, Cg, Gha et Vha);
4) Caractéristiques dendrométriques du peuplement après éclaircie (Nha, Cg, Gha et Vha);
5) Divers indicateurs de croissance : accroissement courant en circonférence moyenne quadratique (ACC en cm/an), accroissement courant et moyen en surface terrière (ACG et ACM en m^2/an), accroissement courant et moyen en volume (ACV et AMV en m^3/an) et production totale en volume (PTV en m^3);
6) Evolution de l'indice de stabilité (h/d), proportion de tiges sur pied prélevées lors de l'éclaircie et distance moyenne entre les tiges après l'éclaircie.

Le second tableau (B) présente l'évolution de la distribution des volumes sur pied et prélevés par classe de grosseur :

1) Âge et hauteur dominante du peuplement;
2) Distribution par classe de grosseur des volumes sur pied avant éclaircie (m^3/ha);
3) Estimation de la valeur marchande (Valeur, en €/ha) du volume sur pied et actualisation de cette valeur à l'année de la plantation (VA, taux d'actualisation de 2%);
4) Distribution par classe de grosseur des volumes prélevés lors de l'éclaircie (m^3/ha);
5) Estimation de la valeur financière (Valeur, en €/ha) du volume prélevé vendu sur pied et actualisation de cette valeur à l'année de la plantation (VA, taux d'actualisation de 2%);
6) Somme des valeurs actualisées des prélèvements précédents et du volume sur pied, donnant ainsi une indication de la rentabilité en fonction de l'âge auquel on applique la coupe rase.



A

1		2				3				4				5						6		
		Avant éclaircie				Eclaircie				Après éclaircie				Accroissements								
Age	Hdom	Nha	Cg	Gha	Vha	Nha	Cg	Gha	Vha	Nha	Cg	Gha	Vha	ACC	ACG	AMG	ACV	AMV	PTV	h/d	% Ecl	Dist
17	13.5	1613	46	26.8	150	527	44	8.2	45	1086	46	18.6	104	2.5	2.27	1.57	22.8	8.8	150	92	32.6	3.3
23	18.1	1082	61	32.2	241	355	53	7.9	57	727	65	24.3	185	2.5	2.04	1.76	24.5	12.5	287	88	32.8	4.0
29	22.4	724	80	36.5	332	203	68	7.5	66	520	84	29.0	265	2.5	1.84	1.81	25.3	15.0	434	84	28.1	4.7
35	26.5	518	99	40.0	417	139	85	8.0	82	379	103	32.1	336	2.5	1.66	1.82	25.2	16.7	586	81	26.8	5.5
41	30.3	378	118	42.0	487	93	104	8.0	91	285	123	34.1	396	2.6	1.50	1.80	24.7	18.0	737	78	24.6	6.4
47	33.7	284	138	43.1	544	61	122	7.2	91	223	142	35.9	453	2.6	1.37	1.76	24.1	18.8	885	75	21.4	7.2
53	37.0	223	158	44.1	597	42	141	6.6	89	181	161	37.5	508	2.6	1.27	1.71	23.4	19.4	1 030	72	18.8	8.0
59	39.9	180	177	45.1	649	30	160	6.1	88	150	181	39.0	561	2.6	1.18	1.67	22.8	19.8	1 170	69	16.7	8.8
65	42.7	150	196	46.1	698	22	180	5.7	87	128	199	40.3	611	2.6	1.10	1.62	22.2	20.1	1 307	67	14.7	9.5
71	45.3	128	215	46.9	745	18	195	5.3	85	111	218	41.6	660	2.6	1.03	1.58	21.7	20.3	1 441	65	13.7	10.2
77	47.7	111	233	47.8	790	14	216	5.0	84	97	235	42.8	706	2.6	0.98	1.54	21.2	20.4	1 571	64	12.2	10.9
83	49.9	97	251	48.7	833	97	251	48.7	833	-	-	-	-	-	-	1.50	-	20.5	1 698	62	-	-

B

1		2								3		4								5		6
		Classes de grosseur - Volume sur pied								Valeur		Classes de grosseur - Volume prélevés								Recettes		VA totale
Age	Hdom	20-40	40-60	60-70	70-90	90-120	120-150	150-180	180+	€	VA	20-40	40-60	60-70	70-90	90-120	120-150	150-180	180+	€	VA	
17	13.5	29	89	27	5	0	0	0	0	2 211	1 579	10	26	8	2	0	0	0	0	591	422	1 579
23	18.1	8	71	56	89	17	0	0	0	6 914	4 385	5	26	10	13	2	0	0	0	1 151	730	4 807
29	22.4	1	26	37	124	143	0	0	0	13 867	7 809	1	14	14	19	18	0	0	0	2 064	1 162	8 960
35	26.5	0	7	14	75	220	102	0	0	21 719	10 860	0	5	8	25	31	12	0	0	3 388	1 694	13 174
41	30.3	0	1	3	26	180	227	49	0	29 344	13 029	0	1	2	14	43	23	7	0	4 543	2 017	17 037
47	33.7	0	0	0	6	76	257	198	6	36 912	14 553	0	0	0	4	31	35	19	0	5 098	2 010	20 579
53	37.0	0	0	0	1	21	165	288	122	44 590	15 611	0	0	0	1	12	42	25	9	5 533	1 937	23 646
59	39.9	0	0	0	0	3	54	276	315	51 842	16 117	0	0	0	0	2	24	42	19	5 957	1 852	26 089
65	42.7	0	0	0	0	0	12	140	545	58 051	16 025	0	0	0	0	0	5	42	39	6 270	1 731	27 849
71	45.3	0	0	0	0	0	2	38	704	63 057	15 457	0	0	0	0	0	2	18	64	6 328	1 551	29 012
77	47.7	0	0	0	0	0	0	6	783	67 210	14 629	0	0	0	0	0	0	4	79	6 370	1 387	29 736
83	49.9	0	0	0	0	0	0	0	833	71 050	13 732	0	0	0	0	0	0	0	833	71 050	13 732	30 225
Total	-	-	-	-	-	-	-	-	-	-	-	17	72	41	78	140	144	157	1043	-	30 225	-

Figure 5.6 Modèle des nouvelles tables de production qui synthétise dans deux tableaux l'évolution des caractéristiques du peuplement et des éclaircies (tableau A) et la distribution des volumes sur pied et prélevés par classe de grosseur (tableau B). Les tableaux représentés montrent l'application de la norme sur une plantation de douglas (écartement 2 x 2.5 m) de productivité moyenne (classe 2).

5. Conclusion

Les normes sylvicoles qui sont présentées pour l'épicéa et le douglas illustrent l’intérêt de disposer d’outils de simulation tels que GYMNOS. Elles répondent à un certain nombre d'objectifs de politique forestière qui sont de la responsabilité du DNF. Comme toutes normes, elles doivent évidemment s'appliquer avec discernement et bon sens. Elles ne peuvent par exemple par être mises en pratique dans certains peuplements qui ont déjà fait un long chemin sans éclaircie, ou qui sont instables du fait de la station ou du voisinage d’une coupe mise à blanc, etc. Cependant, ces normes sont censées donner le ton quant au type de sylviculture que le DNF souhaite mettre en place dans les forêts publiques pour les peuplements purs équiennes de ces deux essences.

Chapter 6

Forest modelling from NFI data

Adapted from

Perin J., Pitchugin M., Hébert J., Brostaux Y., Lejeune P., Ligot G. 2020. SIMREG, a tree-level distance-independent model to simulate forest dynamics and management from national forest inventory (NFI) data. *Currently submitted to Ecological Modelling*

1. Preamble

This chapter presents the development of a regional forest model based on the data from the Permanent Forest Inventory of Wallonia (IPRFW). This new model is intended to make it possible to overcome the shortcomings of permanent forest inventory data, forecast the future development of forest resources and estimate the effect of new forest management plans and policies. In particular, it is intended to account for and estimate the effect of methodological inconsistencies between sampling units and methodological changes between inventory cycles on the assessment of forest resources and their development. The need for such a model stems is also amplified by the low temporal resolution of the IPRFW: the first complete cycle was spread over a period of 14 years (1994-2008) and the second one is still ongoing. A model that can extrapolate the trends measured in the completed part of the second cycle to the totality of the first cycle data is thus required to update the information about the current forest resource.

2. Introduction

The importance of forests cannot be overstated as they provide many critical economic, ecologic and social services such as wood production, climate change mitigation, soil protection and biodiversity habitats. It is therefore essential to have accurate and up-to-date information on the state of our forest habitats and a good understanding of forest dynamics (growth, harvesting, regeneration, etc.) to help implement sustainable forest policy.

Permanent forest inventory data remain the reference to estimate forest resources and dynamics (Barreiro et al. 2017). National Forest Inventories (NFIs) use statistical sampling methods to provide unbiased and accurate forest resources estimates from extensive sample plots inventory data. NFIs methodology varies greatly from one country to another (Vidal et al. 2016). The main methodological differences concern the spatial and time resolution of the sampling design, the sampling pattern (random vs systematic, single phase vs multi-phase), the plot characteristics (temporary vs permanent, angle gauged vs. circular, threshold diameter, etc), the data collected and the measurement techniques. While there is an increasing need for global reporting about forest resources (MacDicken 2015), much progress has yet to be made toward international NFIs harmonisation (Vidal et al. 2008; Baker et al. 2010).

At the European level, one of the most significant works in this direction is the recent implementation of the European Forestry Dynamics Model (EFDM) to harmonize forest resources projections until 2040 in 23 countries based on their respective NFIs data (Vauhkonen et al. 2018). EFDM is a stand level Markov chain model that simulates the development of forest area units defined by a collection of classifying factors according to probabilities of transitions (Vauhkonen and Packalen 2017).

Forest simulation models are increasingly being used to simulate forest dynamics and assess the likely impact of management choices (Taylor et al. 2008; Muys et al. 2010; Weiskittel et al. 2011; Burkhart and Tomé, 2012; Blanco et al. 2015; Blanco et al. 2020). Various modelling methods have been used which are usually categorized as empirical or mechanistic depending on whether the model components depict simple correlation or causal relationships (Twery and Weiskittel, 2013; Pretzsch et al. 2015). Empirical models are generally simpler to develop and apply than mechanistic models but their high dependency on the data used for parameterisation makes them mostly unsuitable for extrapolation to other systems or conditions (Vanclay 1994; Porté and Bartelink 2002; Taylor et al. 2008).

Models can also be classified depending on the spatial explicitness (distance independent vs distance dependent) and level (stand vs tree) at which the forest is modelled (Porté and Bartelink 2002; Pretzsch et al. 2015). Over the years, whole stand models have been successfully used in numerous studies to simulate forest succession and forest management on a large scale (e.g. Sallnäs 1990; Nabuurs et al. 2000; Vauhkonen et al. 2018). Their main appeal is their relative simplicity, making their calibration and operating much easier than for more data-intensive models. However, they lead to an evident loss of information about forest composition and structure which can be a relevant concern in the case of very diverse and heterogeneous mixed forests. On the other hand, generic large scale application of tree-level modelling approaches (e.g. Pretzsch 2002; Chertov et al., 2006; Huber et al. 2013; Stadelmann 2019) are generally very demanding in terms of data and computing power.

Tree level models are thus often highly specialized and aimed to assist understanding of natural processes and/or decision-making about local silvicultural management in specific forest compositions and structures (e.g. Valsta 1992; Courbaud et al. 2001; Le Moguédec 2011). A major interest of tree-level forest models is to allow the accurate simulation of the selective removal of trees (i.e. thinning). The significant impact of thinning on tree growth and forest stability, growing stock, carbon sequestration, etc. is well documented (e.g. Cameron 2002; Roberts and Harrington 2008; Schütz et al. 2015; Ruiz-Peinado et al. 2017). In temperate forests, selective thinning is broadly used as a tree-selection method to promote the growth response and stability of the remaining trees and is increasingly being promoted as an alternative harvesting strategy to shift from even-aged management to less intensive and more multifunctional forestry (Gamborg and Larsen 2002, Sterba and Ledermann 2006), As a results, it is critical to integrate detailed selective tree thinning procedures in forest models (Söderbergh and Ledermann 2003; Schmid et al. 2006; Petritsch et al. 2007, Mina et al. 2017).

In Belgium, forest management is a regional competence and each of the 3 regions (Wallonia, Flanders and Brussels-Capital) is responsible for its own forest inventory. About 77% of the total forest area is located in the southern region of Wallonia (Rondeux et al. 2010) and is monitored by the Permanent Regional Forest Inventory of Wallonia (IPRFW). The Walloon forests could be described as highly fragmented, heterogenous and intensively managed (Alderweireld et al. 2015). They are also undergoing rapid composition and structure changes to deal with recent forest disturbances, new environmental regulations and economic opportunities (Latte et al. 2016). As a result, questions are being raised about the sustainability of Walloon forest management and the future of sectors that depend on its wood supply. Moreover, available estimates of current growing stocks, yield and harvested volumes are often incomplete or even inconsistent because of several methodological discrepancies that have only recently been addressed (UNFCCC, 2020). For example, the last official IPRFW report (Alderweireld et al. 2015) provides regional estimates of harvested volumes exceeding production, which seems to contradict the increase in growing stocks observed over the same period.

Thus, there is a real interest in the development of a Walloon forest model to support IPRFW estimates and forecast the effect of changing forest management practices on the future of its wood stock, yield and supply in order to provide guidelines for policy makers, help improve our management plans and fulfil our internationals commitments (Global Forest Resources Assessment, National Forest Accounting Plan, Forest Reference Level, etc.). Such a model is also desired to help synchronise the IPRFW estimates with remote sensing data which would require that it operate with an annual step: a very convenient yet rather uncommon feature (Barreiro et al. 2017).

Moreover, the great diversity of composition, structure and management found in Walloon forests makes them an ideal case study to help develop and test a generic forest simulation tool. In view of the renewed interest for continuous cover forestry (Pommerening and Murphy 2004, Vitkova and Dhubháin 2013), it is of particular interest that such silvicultural approach is already well established in southern Belgium.

This study presents the forest model SIMREG and its application to assess the sustainability of the forest management currently applied in Wallonia. It focuses on the use of national forest inventories data to model forest management and its effect on the development of forest resources. SIMREG is designed as a multifunctional forest model to support research, assessment and management of forests at scales ranging from single forest stands to entire country. We intend to demonstrate that empirical tree-level distance-independent forest modelling approach based on NFIs data allow for an excellent compromise between usability, precision and performance by taking advantage of widely available data to achieve an optimal level of details while remaining applicable on a large scale. We also expect that it should help identify the main controlled factors that influence silvicultural practices such as selective thinning and thus enable accurate modelling of forest management at the tree level. With regard to our case study, we expect to confirm that the management of Norway spruce plantations is currently unsustainable, that the current reforestation trends are the main driver of forest change in Wallonia and that there are very significant management differences depending on the forest composition, structure and owner.

3. Material and methods

3.1. Study area

The study concerns Wallonia, the southern Region of the Kingdom of Belgium neighbouring France, Germany and Luxemburg. The Region is characterized by a Subatlantic climate, well-distributed rainfall throughout the year and altitudes ranging from 20 m in the western part (Western-Hainaut) to 700 m in the eastern part (Ardenne). Annual rainfall and mean annual temperature varies mostly according to the altitudinal gradient: from 800 mm and 10.5 °C in the west to 1400 mm and 7.5°C in the east (standards defined for the period 1981-2010 by the Royal Meteorology Institute).

Wallonia is divided in 5 contrasted ecoregions from north-west to south-east: Limoneuse region, Condroz, Famenne, Ardenne and Jurassic region. The Limoneuse region is a low-plateau (altitude of 100 to 200 m) of deep loess with a mild oceanic climate (annual rainfall of 850 mm, mean annual temperature of 10°C). The plateau of the Condroz alternate limestone and psammitic bedrock with a thinner loessic cover. The Famenne is a large depression with shallow and compact clay-shale soils. The former mountain range of the Ardennes is defined by its rough relief, up to an altitude of 700 m, on schisto-sandstone bedrock, rocky oligotrophic soils, with a submontane climate (1100 to 1400 mm, 8°C, the harshest climate of Wallonia). The Jurassic region presents a distinctive relief composed of cuestas, with relatively rich soils, and a more continental climate open to the south and protected by the Ardennes massif.

About one third (554 000 ha) of the Walloon Region is forest lands of which 479 500 ha are covered by productive forest area (Alderweireld et al. 2015). Most of Wallonia’s forests are located at the south of the river Meuse and in particular in the eastern natural region of the Ardenne where about 60% of the Walloon forest area is located.

The forest management applied in Walloon forest is generally rather intensive and most stands are regularly thinned. Significant differences in thinning intensities, rotations and reforestations are observed depending on forest composition, structure and the type of owner (Alderweireld et al. 2015; Latte et al. 2016). About half of the forest area is in the public domain and managed by the Department of Nature and Forests (DNF) of the Public Service of Wallonia (SPW). The other half is distributed among approximately 100 000 private owners, each of whom is responsible for the management of their own forest property.

Norway spruce (Picea abies (L.) H. Karst.) plantations are the dominant forest type in Wallonia: they represented around 34% of the total productive forest area, 41% of the standing stock and 53% of the total wood production in 2001 but have been in continuous decline since. Other softwoods stands represented around 12% of the total productive area and are mainly composed of pure plantations of douglas-fir

(Pseudotsuga menziesii (Mirb.) Franco) and larches (Larix decidua Mill., Larix kaempferi (Lamb.) Carr. and Larix x eurolepis), mixed plantation of douglas-fir with Norway spruce and various forest stands dominated by scots pine (Pinus sylvestris L.).

About 54% of the productive forest area is occupied by hardwood stands dominated mainly by native oaks (Quercus robur L. and Quercus petraea (Matt.) Liebl.) and beech (Fagus sylvatica L.). In 2001, these two species represented respectively around 40 and 25% of the total hardwood standing stock. These two main species are often found mixed with various secondary species such as birch (Betula pendula Roth), ash (Fraxinus excelsior L.), hornbeam (Carpinus betulus L.) and maple (Acer pseudoplatanus L. and Acer platanoides L.) in a wide range of forest structures and compositions.

3.2. IPRFW data

Permanent sample plots (PSP) data were obtained from the Permanent Regional Forest Inventory of Wallonia (IPRFW) database. The sampling method applied by the IPRFW is presented in Rondeux et al. (2010), it is a single-phase, non-stratified inventory using a systematic sampling design with permanent sample plots at the intersections of a 1000 m (east-west) by 500 m (north-south) grid (each PSP thus represents 50 hectares or 0.5 km²). The PSP consists of three main concentric circular plots: trees with girth at breast height (Gbh) $\geq$ 120 cm are measured on the largest concentric plot (18 m radius), trees with 70 cm $\leq$ Gbh $<$ 120 cm on the intermediate concentric plot (9 m radius) and trees with 20 cm $\leq$ Gbh $<$ 70 cm on the smallest concentric plot (4.5 m radius). Therefore, the measured trees can represent different numbers of trees per hectare (called extension factor or Fext) depending on their Gbh.

A complete inventory cycle is divided into 10 equal independent shares called “tranche” according to a predefined scheme, ensuring that the whole territory is uniformly covered almost annually and that all site conditions and forest characteristics of Southern Belgium are represented. The first cycle of inventory was carried out between 1994 and 2008, the second is ongoing. We selected all data measured in permanent plots sampled between 1994 and 2015 that were representative of productive forest stands. This represent at total of 9 590 PSP of which half (= 5 tranches) were monitored twice at 6 to 16 years interval.

During this period, about 100 000 trees of 48 different species were measured. Most of these species are very marginally represented and have therefore been grouped in 3 miscellaneous classes, other very similar species of the same genus have also been grouped together (Table 6.1). This results in 11 broadleaves (hardwood, Hw) species groups: Native oaks, Beech, Birch, Ash, hybrid poplar (Populus spp.), Maple, Hornbeam, Black alder (Alnus glutinosa (L.) Gaertn.), Red oak (Quercus rubra L.), miscellaneous commercial hardwood (e.g. Prunus avium L. and Robinia pseudoacacia

L.) and non-commercial broadleaves (e.g. Sorbus aucuparia L., Populus tremula L. and Salix sp.) and 6 conifers (softwood, Sw) species groups: Norway spruce, Douglas-fir, Scots pine, Larch, Black pine (Pinus nigra J.F. Arnold) and miscellaneous softwood (e.g. Picea sitchensis (Bong.) Carr. and Abies sp.).

The data needed to model growth, thinning and recruitment were selected from 3145 PSP monitored twice where at least one shared tree was measured in both sampling (to exclude clearcuts, new reforestations and displaced PSP). This represents 26 930 increments records from the trees that were measured twice, 7425 tree removals data from the trees measured in the first inventory but absent or dead at the second and 1429 tree recruitment data from trees that have exceeded the measurement threshold in the smallest concentric plot. The number and main characteristics of the measured data per species group are presented in Table 6.1.

Table 6.1 Number and main attributes by species group of the tree measurement data obtained from the IPRFW. Cycle1 and Cycle2: number of trees measured during the first (complete, 1994-2008) and the second (in progress, 2008-2015) monitoring cycle. Surviv, Remov and Recruit: number of surviving, removed and recruited trees selected to model growth, thinning and recruitment.

		Number of data					**Girth at breast height (cm)**			
Species group	**Code**	**Cycle1**	**Cycle2**	**Surviv**	**Remov**	**Recruit**	**min**	**mean**	**max**	**StDev**
Broadleaves (hardwood)										
Native oak	Oak	18420	9545	7230	956	56	20	130.2	391	50.5
Beech	Bee	10568	5957	3958	1135	423	20	120.5	552	65.9
Birch	Bir	4318	2523	1042	310	173	20	56.4	212	33.9
Ash	Ash	2729	1699	960	211	115	20	100.9	336	54.2
Hybrid poplar	Pop	2287	1014	617	160	4	20	117.3	440	49.5
Maple	Map	2541	1612	597	101	134	20	66.3	276	45.5
Hornbeam	Hor	4427	2231	283	64	144	20	38.8	193	22.8
Black alder	Ald	1033	666	221	53	32	20	55.1	200	33.5
Red oak	Rok	773	534	284	44	15	20	109.3	442	61.3
Misc. commercial	Hwc	1053	652	289	59	28	20	73.0	354	48.5
Non-commercial	Hwx	2994	2126	229	115	93	20	36.2	298	26.0
Conifers (softwood)										
Norway spruce	Spr	37393	16046	8498	3339	173	20	95.6	290	37.7
Douglas-fir	Dou	3270	2266	920	392	20	20	104.5	336	43.1
Scots pine	Spi	2616	1209	861	232	5	20	111.3	252	34.3
Larch	Lar	1883	943	563	130	13	20	110.0	248	34.1
Black Pine	Bpi	597	271	192	65	0	20	105.4	257	42.4
Misc.	Swx	733	361	186	59	1	20	101.6	326	41.0
Total		97635	49655	26930	7425	1429	20	98.8	552	52.1

3.3. Description of SIMREG

We developed a tree-level distance-independent forest simulation software (FSS) in the open software CAPSIS (Computer-Aided Projection of Strategies In Silviculture) simulation platform (Dufour-Kowalski et al. 2012). Each simulated forest stands is represented by a set of trees each with their own species and girth (circumference) at breast height (Cbh) and by a list of stand variables: simulated area, elevation, natural region, type of owner, etc. Various computation method are integrated to estimate the individual tree solid wood volume (volume of the stem and branches with a circumference exceeding 22 cm at smaller end) using the corresponding species-dependent taper models of Dagnelie et al. (1985) and calculate usual stand characteristics such as density, total basal area, volume and biomass per ha (Nha, Gha, Vha and BMha, respectively), mean and dominant Cbh (Cg and Cdom), etc. as well as continuous indicator of the stand composition and structure such as the proportion of each species group and the standard deviation of trees girth. The development of each virtual forest stands is simulated annually by applying stand-level clearcut and reforestation models and tree-level removal, growth and recruitment models (Figure 6.1). SIMREG currently does not account for any changing environmental factors as sub-models to estimate such effect on tree growth are still in development. Anyway, the present applications of our simulator focus on relatively short time scales (2000-2050) for which we assume that the influence of global changes should remain small compared to that of management.

We made it possible to directly use non-synchronized forest inventory data as input in our forest simulation software to easily generate a virtual forest stand. The inventory data are formatted in two input files: stands.inv and trees.inv. In stands.inv, each line represents a measured sample plot with its ID, type of owner, elevation, natural region, number and area (in ha) of virtual forests stands to be generated, simulation start and end year, rotation length and forest status at the start year (stocked forest stand or clearcut). In trees.inv, each line represents a measured tree with its corresponding sample plot ID, measurement year, species, Cbh and the number of trees it represent per hectare (Fext).

Each measured tree is then used to generate a number of virtual trees equal to Fext x stand area in hectare. In order to avoid generating thousands of identical trees, the girth of the generated trees follows a lognormal distribution of mean equal to the measured Cbh and of standard deviation equal to 5 cm. This amount of added noise was selected to be without consequences on the total standard deviation of the tree girth distribution in the virtual forest stand as it is roughly equivalent to the Bessel’s correction (So, 2008). This process can automatically be repeated any number of time so that 1) each sample plot can be used iteratively to generate several virtual forest stands and 2) the FSS can handle thousands of different sample plot inventories in sequence to generate a life-size forest resources representation at a regional scale.

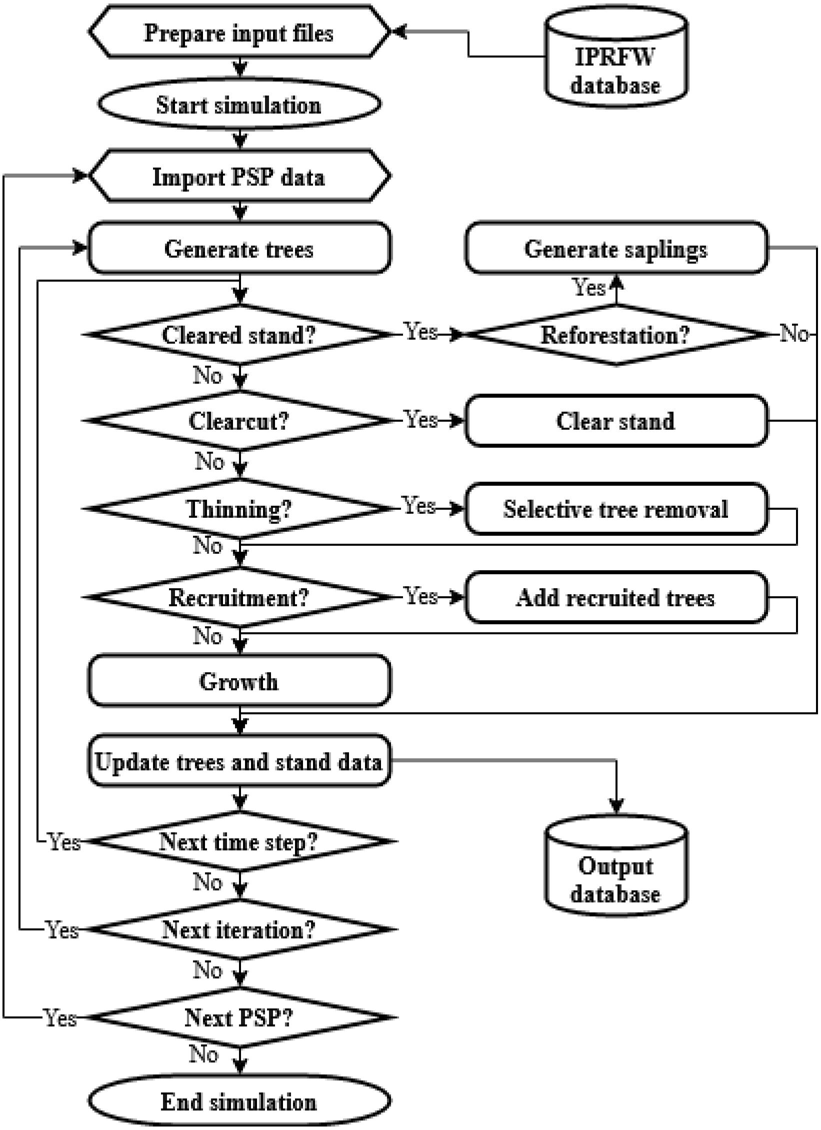


Figure 6.1 Conceptual diagram of the forest model SIMREG.

The calibrated models are then applied sequentially each simulated years from the generation of a stand. First removal if in a rotation year (clearcut or thinning), then recruitment and finally growth which marks the transition to the following simulated year. Reforestation is a parallel process that is only applied in cleared (i.e. non-stocked) stands.

All of the necessary models were fitted in R (R Core Team, 2019) using stepwise methods, general linear and nonlinear regression procedure from the "nlme" package (Pinheiro et al., 2019) and survey-weighted general linear regression procedure from the “survey” package (Lumley et al., 2017). These models were then validated using a 5-fold cross-validation procedure (Kohavi, 1995). Models were fitted on 4 of the 5 tranches (training dataset) and then applied for the prediction of the remaining tranche (validation dataset). This was repeated 5 times to ensure that every tranche is used as validation dataset. This way, the validation mean error and validation root mean square error (or validation Brier score for logistic models) can respectively be used as estimator of the accuracy (unbiasedness) and precision (overall predictive performance) of the model when applied on an independent dataset. The direct comparison of the training and validation fitting statistics can also be used to assess the model adequacy as large differences would indicate under or overfitting.

The codes used in R to fit each model are presented in the supplementary material with the resulting fitting statistics, including the parameters t-tables. Only significant predictors variables were kept in these models but not all parameter values were significant at the factor-level. We decided not to arbitrarily restructure our level of factors (especially species groups) based on the significance of their parameter values.

3.4. Growth

The methodology used to model tree girth growth is based on the previous works of Deleuze et al. (2004) and Perin et al (2016). The original model is a distance-independent model that predict tree basal area annual increment using dominant height, dominant height annual increment, total basal area and tree girth as explanatory variable. However, significant adjustments had to be made to allow this model to be compatible with mixed irregular stands using only simple variables that are recoverable from most NFIs data. In particular, the use of age, dominant height and dominant height growth did not appear appropriate in uneven aged stands. Moreover, these variables were simply not always available in the IPRFW data and therefore needed to be substituted.

We found that the dominant girth was a suitable substitute for the dominant height and that most of the site effect on growth could be estimated from altitude alone in Wallonia. The resulting model is a 6 parameters (Aa, Ab, Pa, Pb, ma, mb) tree-level distance-independent species-dependent non-linear model that uses altitude (Alt), total basal area (Gha), dominant Cbh (Cdom) and individual tree Cbh (Ci) as explanatory variables to predict mean annual basal area growth (dGi):

$$\mathrm{dG_i} = 0.5 * \mathrm{P} * (\mathrm{C_i} - \mathrm{m} * \mathrm{A} + \sqrt{(\mathrm{m} * \mathrm{A} + \mathrm{C_i})^2 - 4 * \mathrm{A} * \mathrm{C_i}}) \qquad \text{(Eq 1)}$$

Where:

$$A = Aa * Cdom^{Ab} \quad \text{(Eq 1.1)}$$

$$P = Pa * exp(1 - Pb * Alt) \quad \text{(Eq 1.2)}$$

$$m = 1 + exp(ma - mb * Gha) \quad \text{(Eq 1.3)}$$

The explanatory variables used (Gha, Cdom and Ci) are the averages between the first and the second inventory in order to represent the characteristics of trees and forest stands in the middle of the measurement period. In addition, the model was fitted on the mean annual girth increment value (dCi) rather than tree basal area growth segments (dGi) to avoid heteroscedasticity of residuals. To this end, the dGi estimated by the tree basal area growth model (Eq 3) were transformed in dCi using the following formula:

$$dC_i = \left(\sqrt{C_i^2 + 4\pi dG_i} - C_i\right) \quad \text{(Eq 2)}$$

We observed that the values of the parameters Ab and Pa were highly dependent on the species while the value of Aa, Pb, ma and mb varied very little within the hardwood and softwood division. We thus only fitted a division-dependent value for those five parameters to ensure the robust behavior of the model and ease the fitting convergence for the least represented species groups.

Annual growth is simulated by increasing the current girth value of each tree by its estimated increment. Stochastic effect is accounted for with random noise around the growth model estimates calibrated from the growth model residual distribution.

3.5. Removal

Removals refer to the trees that were removed by selective thinning or that died between two time frames (in our data, natural mortality account for about 5% of the total volume removed from the growing stock).

In a previous iteration of SIMREG, removals were simulated using a 2 steps process. The removal intensity was first estimated from stand characteristics and then trees were selected according to an individual score computed at the tree level. However, this method proved to be very compute intensive because of the large list of numbers that had to be sorted and difficult to calibrate for mixed stands. We thus decided to predict removal at the tree-level using a logit-function which make it much easier to account for the various stand composition and reduce total computation times by about

30%. This method has been used in few other forest models such as PrognAus (Ledermann 2006).

We used the data from the surviving and removed trees and formatted them in an Event/Trial format. The event is the removal and is either equal to 0 if the tree was still there and alive at the second monitoring or 1 if it was removed. The trial is the number of years that the tree existed between the two monitoring. For the surviving trees, it is simply equal to the duration in years between the two measurements (Period). However, we have to take into account that trees do not exist anymore after being removed. We assumed that on average, the removal took place exactly between the two inventories so that the number of trials is equal to Period/2 for removed trees.

We then calculated for each tree its annual proportion of event (= Event/Trial) and its weight corresponding to the number of “annual trees” it represent (= Trial x Fext). A survey-weighted generalised logistic procedure was applied using the svyglm() function (Lumley et al., 2017) on these formatted data to model the annual probability of removal. The variables considered were the species, girth and relative girth at the tree-level and the dominant girth, total basal area, standard deviation of the girth, proportion of each species, type of forest manager (private or public), elevation and natural region at the stand-level as well as their interaction up to the 3rd level.

The probability of removal was strongly related to the species and social status (relative size) of the tree and to the stand development stage and type of management (type of owner, density, structure). We identified and selected a subset of 7 relevant variables that had a significant influence on the probability of removals (Premovi), the formulation of the resulting logistic regression model is:

$$Premov_i = exp\,(Yremov_i)/\big(1 + exp(Yremov_i)\big) \qquad \text{(Eq 3)}$$

Where:

$$Yremov_i = f(Sp_i * Crel_i + Owner * Crel_i + Div * CV * Crel_i + Div * Gha + pcgha_{sp}) \qquad \text{(Eq 3.1)}$$

Where: Spi is the tree species group and Div is the corresponding division (broadleaves or conifers); Owner is the type of owner (public or private); Creli is the relative girth (Ci/Cdom) of the tree; CV is the coefficient of variation of the tree girth distribution in the stand; Gha is the stand total basal area in m²/ha; pcghasp the proportion of the stand total basal area represented by the tree species group.

3.6. Recruitment

We modelled the recruitment density using a quasibinomial logistic regression approach to account for the singular distribution of the observed annual recruitment density value which range from 0 (80% of the PSP) to 304 trees per hectare. The recruitment data were formatted by dividing the observed annual recruitment density by 400 so that the recruitment model estimates the annual probability that a tree will exceed the inventory threshold in a 1/400th ha forest area. The variables considered were the dominant girth, total basal area, standard deviation of the girth, proportion of each species, type of forest manager (private or public), elevation and natural region as well as their interaction up to the 3rd level.

We determined that the annual density of recruitment varied mostly with the structure and the density of the stand as well as some site related factors that appeared to be captured by the natural region. We identified and selected a subset of 4 relevant variables that had a significant influence on the annual recruitment density per hectare (Nharecrut), the formulation of the resulting model is:

$$Nha_{recrut} = 400 * exp\,(Yrecrut)/\big(1 + exp(Yrecrut)\big) \qquad \text{(Eq 4)}$$

Where:

$$Yrecrut = f(RN * Gha + Cg + Cg^2 + CV) \qquad \text{(Eq 4.1)}$$

Where: RN is the natural region; Gha is the stand total basal area in m^2/ha; Cg and CV are the quadratic mean and the coefficient of variation of the tree girth distribution in the stand.

We then modelled the recruitment composition according to the stand composition by averaging the recruitment composition observed in each PSP weighted by the corresponding total basal area proportion of each species-group found in the stand. First, we calculated for each PSP a recruitment vector (VRj) and a composition vector (VCj). The recruitment vector (VRj) is a row vector of length 17 where each value represents the recruitment density proportion (between 0 and 100 %) for each species group. The composition vector (VCj) is a column vector of length 17 where each value represents the stand basal area proportion (between 0 and 100 %) for each species group. We then multiplied the composition vector by the recruitment vector for each PSP, summed the matrixes obtained for all the PSP and divided the resulting matrix by the sum of the composition vectors (Eq 5):

$$\sum(VCj\ x\ VRj)/\sum VCj \qquad \text{(Eq 5)}$$

This results in a 17 x 17 matrix where each line represents the average composition of the recruitment density found below one species group. The vector of recruitment composition for a given stand composition can then be obtained by multiplying this 17 x 17 matrix by the column 1 x 17 stands composition vector.

In SIMREG, the recruitment density models is first applied to compute the total number of recruited trees in a virtual forest stand. The species of each recruited trees are then randomly selected according to the probability estimated using the recruitment composition model. The newly recruited trees are all generated in the virtual stand with a girth equal to the measurement threshold (20 cm).

3.7. Clearcut

We used aerial photographic interpretation to update the status of all the PSP in order to provide a more accurate assessment of the current resources of Wallonia (about 25 % of the sampled plots of the IPRFW were not monitored since 2000). Aerial photograph data (orthoimage) covering the whole Walloon Region territory were obtained from the Public Service of Wallonia (SPW) geoportal (http://geoportail.wallonie.be). These multispectral images (4 spectral bands: red, green, blue, and infrared) are characterized by a resolution of 25 cm and are available for the years 2006, 2009, 2012 and 2015. We then identified all the sample plots which have undergone a major transformation between their monitoring by the IPRFW and 2015 (e.g. clearcut and reforestation) using a specific application developed in the QGIS environment (GIS Opensource) and presented in Latte et al. (2015).

We modelled the probability of clearcutting using a binary logistic regression approach on the data obtained by photointerpretation. We selected the 6429 forest stands that were still standing on the orthophotos of 2006 from the 6921 productive forest stands sampled by the IPRFW before 2007. In this selection, 603 clearcuts were identified between 2006 and 2015. The data were ordered so that the status of every selected stand is represented each year from 2007 to 2015 by a 0 when the forest stand is standing and by a 1 when a clearcut was performed. A logistic binary regression was then performed on these data to estimate the yearly probability that a forest stand will be harvested depending on its characteristics. The variables considered were the dominant girth, total basal area, standard deviation of the girth, proportion of each species, type of forest manager (private or public), elevation and natural region as well as their interaction up to the 3rd level.

We identified the species composition, the development stage and the type of owner as the main predictors of the clearcut probability. We identified and selected 4 relevant combined variables that had a significant influence on the clearcut probability (Pcc), the formulation of the resulting logistic model is:

$$P_{cc} = exp\,(Ycc)/\big(1 + exp(Ycc)\big) \qquad \text{(Eq 6)}$$

Where:

$$Ycc = f(Owner + CdomxSW^2 + CdomxSpr^2 + CdomxPop^2) \qquad \text{(Eq 6.1)}$$

Where the Owner is the type of owner (public or private); $CdomxSW^2$, $CdomxSpr^2$ and $CdomxPop^2$ are variables obtained by multiplying the stand dominant girth (mean girth of the 100 biggest trees per hectare in cm) by the square of the proportion of the total basal area represented by respectively softwood, Norway spruce and hybrid poplar.

3.8. Reforestation

The data used to model reforestation were collected from the 475 newly reforested stand (212 in private forest and 263 in public forest) identified in this previous study. We worked in collaboration with the forest service of Wallonia (DNF) in public forest and with the IPRFW in private forest to retrieve more accurate information about the current species composition, structure and silvicultural objectives in the corresponding forest stands.

We assume the reforestation rate to be 100% in Wallonia as the total productive forest area is considered stable, with no significant change observed since the first inventory cycle. We analysed the data collected from 475 newly reforested stands to identify which variables had an influence on the composition of the reforestation and then model the probability of each type of reforestation depending on the characteristics of the previous forest stand.

Our simulator allows the configuration of a waiting period during which cleared stands stay non-stocked and no model is applied to account for the fact that reforestation are usually carried out several years after clearcuts. Once this period is completed, a simple random process is applied each simulated year to decide if any reforestation happens or if the stand stays non-stocked one more year. The composition and density of the reforestation is then randomly selected according to the probability defined in the reforestation model.

After analysis of the available data and consultation with forest experts, we have established the following elements: a) the waiting period and the subsequent annual probability of reforestation were set to 3 years and 50%, b) the girth assigned to each newly generated sapling follow a lognormal distribution of mean 1 and 0.5 of standard deviation and c) no removals and no recruitment happen until the dominant girth of the newly reforested trees first exceeds 40 cm. These parameters ensure that the average density and girth distribution obtained after 20 years of growth is equivalent to that measured in comparable stands by the IPRFW.

3.9. *Simulation of Wallonia's forest development*

We initiated a simulation by generating virtual stands from the data of the first cycle of the IPRFW. While each PSP represents an area of 50 hectares, Southern Belgium forest stands are generally substantially smaller and we have chosen to use each PSP inventory to generate 10 virtual stands of 5 hectares (0.05 km²). The development of each virtual stand was simulated from the year its corresponding PSP was inventoried (1994-2008) until 2050. This means that the life-size representation of the Walloon forest is only achieved from the end of the first cycle of the IPRFW in 2008. We assumed that the total area of the Walloon productive forest and the type of owner of each virtual stand remained fixed during this period.

We have integrated thinning cycles into our simulator to take into account the resulting cyclical fluctuation of stand density. The first thinning year from the generation of each virtual stand is determined by an integer randomly generated between 0 and the rotation length minus 1, thinning and clearcut models are then applied every thinning cycle from this first date. The rotation length was set at 6 years for the following simulations. The annual probability are transformed into rotation probability using the following equation:

$$P_{Rotation} = 1 - (1 - P_{Annual})^{Rotation} \quad \text{(Eq 7)}$$

4. Results

4.1. *Growth models*

The calibrated model explains respectively 41% and 58% of the total variance on the annual girth and basal area increment. The performance of the model at the species-level is highly variable (Table 6.2) and the adjusted R² on the estimation of girth increment range from 9% for the miscellaneous commercial hardwood group to 41% for douglas-fir (respectively 30% and 72% on the basal area increment estimation). It appears to generally explain a larger part of the growth variability of faster growing species such as hybrid poplar, Norway spruce and douglas-fir. It seems reasonable to assume that a higher growth rate reduce the share in the total variance of the uncertainty caused by measurement inaccuracy and errors. These species are also found more often in even-aged plantations where the spatial distribution of trees is generally more homogenous and the effect of competition is therefore probably easier to estimate with a non-spatialized model.

Table 6.2 Observed mean annual growth and fitting statistics (RMSE = Root Mean Square Error, ME = Mean Error) of the parameterized growth model for each species groups; all statistics are presented for the annual tree girth increment estimation (cm/yr) and for the annual tree basal area increment estimation (cm²/yr, between parenthesis).

Sp	Mean Increment	Training RMSE	Adjusted R²	Validation RMSE	Validation ME
Oak	1.00 (23.64)	0.51 (12.62)	0.12 (0.39)	0.51 (12.65)	0.00 (0.03)
Bee	1.36 (29.73)	0.69 (16.09)	0.15 (0.50)	0.69 (16.12)	0.00 (0.58)
Bir	0.78 (9.33)	0.59 (7.59)	0.12 (0.40)	0.59 (7.60)	-0.02 (-0.09)
Ash	1.34 (26.97)	0.67 (14.14)	0.19 (0.54)	0.68 (14.22)	-0.01 (-0.39)
Pop	2.78 (58.54)	1.49 (32.49)	0.33 (0.32)	1.56 (33.86)	-0.04 (-0.17)
Map	1.23 (18.98)	0.70 (11.14)	0.14 (0.50)	0.70 (11.16)	0.00 (0.24)
Hor	0.89 (10.93)	0.54 (7.45)	0.10 (0.44)	0.55 (7.68)	-0.02 (-0.10)
Ald	0.89 (11.53)	0.59 (7.52)	0.24 (0.38)	0.60 (7.62)	0.01 (0.41)
Rok	2.19 (49.39)	0.91 (21.73)	0.20 (0.58)	0.92 (21.78)	-0.01 (-0.94)
Hwt	1.08 (18.27)	0.80 (15.69)	0.09 (0.30)	0.85 (16.26)	0.00 (0.44)
Hwx	1.04 (13.38)	0.82 (12.26)	0.29 (0.57)	0.84 (12.42)	0.02 (-0.46)
Spr	1.44 (24.65)	0.54 (9.94)	0.31 (0.59)	0.54 (9.99)	0.00 (0.15)
Dou	2.36 (47.45)	0.77 (15.80)	0.41 (0.72)	0.77 (15.94)	0.01 (-0.63)
Spi	0.83 (16.25)	0.47 (9.49)	0.16 (0.29)	0.47 (9.62)	0.00 (0.16)
Lar	1.52 (30.58)	0.61 (13.12)	0.21 (0.40)	0.61 (13.26)	-0.01 (0.00)
Bpi	1.08 (21.04)	0.57 (12.11)	0.15 (0.36)	0.65 (13.67)	-0.08 (-0.89)
Swx	2.09 (40.10)	0.82 (18.44)	0.37 (0.64)	0.85 (19.29)	0.01 (-0.08)
Total	**1.31 (25.83)**	**0.63 (13.28)**	**0.41 (0.58)**	**0.63 (13.43)**	**0.00 (0.09)**

The analysis of the distribution of the validation residuals showed no evidence of bias over the entire range of each explanatory variable (individual tree girth, elevation, dominant girth and total basal area). We can also rule out under and overfitting as the training and validation RMSE values are also very similar for all the species group considered except black pine (Table 6.2). The relatively poor performance of the model for black pine is most certainly explained by its presence in only 21 different PSPs in our dataset.

4.2. Removals

The model shows that dominant trees (high Creli) generally have a lower probability of removals than dominated ones (low Creli), especially in private owned stands. However, the strong interaction between Crel and the standard deviation shows that this trend decreases in more irregular stands (high CV). This underlines that, in even-aged plantations, selective thinning is mostly applied to favor the growth of larger trees in preparation of the final harvest (clearcut) while in more irregular stands, trees that reach their logging dimension are regularly harvested to favor the natural regeneration (continuous cover forestry).

The calibrated parameters values reveal significantly different trends and removal rates between species (Table 6.3). For example, all other variables being equal, short rotation planted species such as douglas-fir and Norway spruce generally have a higher estimated removals probability than long revolution naturally regenerated species such as native oaks which are characterized by the lowest overall probability of removal. A notable exception to this rule is hybrid poplar that is generally planted at a very wide spacing and rarely thinned before the final harvest.

Table 6.3 Observed mean annual removal probability and fitting statistics (BS = Brier Score, ME = Mean Error) of the parameterized removal model for each species groups.

Species	Mean Premoval	Training BS	Validation BS	Validation ME
Oak	0.0172	0.0168	0.0169	-0.0001
Bee	0.0237	0.0231	0.0232	0.0001
Bir	0.0275	0.0267	0.0267	0.0003
Ash	0.0221	0.0215	0.0216	0.0007
Pop	0.0246	0.0238	0.0239	-0.0008
Map	0.0212	0.0206	0.0207	0.0003
Hor	0.0237	0.0231	0.0232	-0.0007
Ald	0.0335	0.0320	0.0324	0.0008
Rok	0.0201	0.0195	0.0199	0.0002
Hwc	0.0243	0.0237	0.0238	0.0003
Hwx	0.0386	0.0371	0.0372	0.0000
Spr	0.0458	0.0427	0.0427	0.0000
Dou	0.0541	0.0499	0.0501	0.0004
Spi	0.0302	0.0291	0.0292	0.0004
Lar	0.0322	0.0305	0.0307	-0.0009
Bpi	0.0491	0.0453	0.0454	-0.0041
Swx	0.0336	0.0316	0.0322	0.0024
Total	**0.0340**	**0.0322**	**0.0323**	**0.0001**

Our model also shows an overall increase of the removal probability in denser stands (higher total basal area). However, this trend appears to be significantly weaker for coniferous species (for which a higher competition level is often recommended to avoid the formation of large branches).

The pcghasp variable makes it possible to differentiate in a stand between the dominant species (high pcghasp value) that generally are the main production objective and the dominated ones (low pcghasp value) that usually mostly have an accompanying role. Unsurprisingly, this variable shows that the main species generally have a higher probability of removals than accompanying ones also leading to a higher removal rate in monospecific forests.

Validation mean error (bias) are insignificant for all species group (Table 6.3) and the comparison between training and validation Brier score do not highlight any evidence of under or overfitting. The poor performance of the model for Black pine and miscellaneous softwood is probably due to the low number of PSPs in which these species are found in our data as well as the heterogeneity of the latter group of species.

4.3. Recruitment models

Recruitment data shows a large variability of which a significant part is likely random noise related to the small size (4.5 m radius) of the plot on which they are measured. Consequently, only a small part (Table 6.4) of this variability could be explained by our calibrated model even at it highlight some very significant relationships.

First, the polynomial relationship with the average tree girth (Cg) shows that the recruitment density decreases until around 120 cm of Cg and then increases again. It makes sense that the recruitment density is higher in very young forest stands that are more likely to already contain some trees whose girth is just below the measurement threshold and in very old forests where natural regeneration can sprout and develop. The parameterized model also indicates that the annual density of recruitment decreases with the total basal area (Gha) and increases with the dispersion of the tree girth (CV). This evidently shows that saplings thrive better in open irregular forest stands than in dense even-aged ones. We also found an interaction between the total basal area and the natural region. In particular, the negative effect of the Gha on the recruitment density appears considerably higher in the harshest region of the Ardenne, probably due to greater competition for resources.

Validation mean error are insignificant for each natural region (Table 6.4) and the graphical analysis of the distribution of the validation residuals over the entire range of each continuous explanatory variable (Cg, Gha and CV) showed no evidence of bias. The comparison of the training and validation RMSE again shows no evidence of under or overfitting.

Table 6.4 Observed mean annual recruitment density and fitting statistics (RMSE = Root Mean Square Error, ME = Mean Error) of the parameterized recruitment model in each natural region.

Natural region	Plot number	Mean Nharecrut	Training RMSE	Adjusted R^2	Valid RMSE	Valid ME
Limoneuse	263	7.39	20.32	0.14	21.18	-0.28
Condroz	556	6.67	17.47	0.04	17.72	0.07
Famenne	432	5.76	14.48	0.09	14.70	-0.15
Ardenne	1662	6.81	21.31	0.21	21.81	0.04
Jurassique	232	11.85	23.18	0.14	23.57	-0.08
Total	**3145**	**7.06**	**19.92**	**0.17**	**20.37**	**-0.02**

The recruitment composition model (Table 6.5) highlight some interesting trends that likely results from the very contrasted natural regeneration potential under continuous cover of the considered species groups. In particular, recruitments of native oaks appear very rare (except under scots pine), even in forest stands that it dominates where it is more likely to find recruitment of beech, hornbeam or birch. On the contrary, recruitments of beech appear very common under most forest composition but recruitment of other species is very rare under beech. Birch and beech are the only two deciduous species that recruit well under Norway spruce and douglas fir. Recruitments of ash and maple are often found together, sometimes in association with alder, hornbeam, poplar and/or miscellaneous hardwood. Norway spruce recruitments are common under itself, douglas-fir and larch with which it is often associated.

Table 6.5 Average recruitment composition (rounded to the nearest percent) according to the stand composition.

Recruitment composition

Stand composition

%	Oak	Bee	Bir	Ash	Pop	Map	Hor	Ald	Rok	Hwc	Hwx	Spr	Dou	Spi	Lar	Bpi	Swx
Oak	7	28	11	5	0	9	22	0	1	2	8	7	0	0	0	0	0
Bee	1	74	1	1	0	5	7	1	0	1	3	6	0	0	0	0	0
Bir	9	12	28	5	0	6	6	4	1	2	16	9	0	0	2	0	0
Ash	3	5	6	25	3	31	11	4	0	2	6	2	2	0	0	0	0
Pop	7	4	1	28	0	19	0	20	0	7	11	4	0	0	0	0	0
Map	2	12	2	15	0	44	7	2	1	4	7	2	1	1	0	0	0
Hor	0	9	0	15	0	15	57	0	2	0	2	0	0	0	0	0	0
Ald	0	10	3	28	0	23	0	21	0	0	3	12	0	0	0	0	0
Rok	0	12	16	0	0	34	0	0	26	2	10	0	0	0	0	0	0
Hwc	1	9	0	18	0	31	6	0	1	7	19	0	7	0	0	0	0
Hwx	4	12	13	14	0	13	9	1	4	1	28	2	0	0	0	0	0
Spr	5	10	10	0	0	3	3	0	0	0	6	59	4	0	0	0	0
Dou	0	20	35	0	0	2	2	0	0	0	0	25	17	0	0	0	0
Spi	23	8	20	6	0	0	2	0	2	3	16	11	0	11	0	0	0
Lar	8	5	11	1	0	6	4	0	0	5	7	24	13	0	15	0	0
Bpi	12	0	0	7	0	0	0	0	0	0	81	0	0	0	0	0	0
Swx	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60

4.4. *Clearcut probability models*

The parameterized model shows that the probability of clearcutting is significantly higher in private owned stands than in public ones and increases with the dominant girth in forest stands composed of hybrid poplar and softwood and is consequently at its lowest in forests that contain neither (Figure 6.2). For a given dominant girth at breast height, the probability of clearcutting is the highest when Norway spruce is the dominant species, followed by hybrid poplar, then by the other softwood species (e.g. douglas-fir, pine, larch) and finally by other hardwood species where clearcuts are extremely rare.

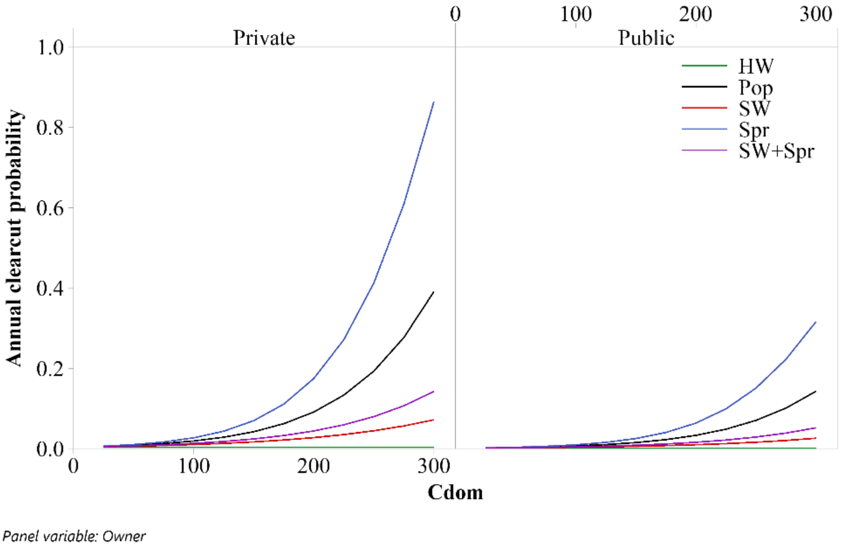


Figure 6.2 Prediction in private and public forests of the annual probability of clearcutting as a function of the dominant circumference for 5 typical forest compositions: pure spruce (Spr), pure hybrid poplar (Pop); broadleaves without poplar (HW); conifers without Norway spruce (SW); mixed conifers with 50% of Norway spruce (SW+Spr).

4.5. *Reforestation models*

The reforestation data showed that the most important predictor of the reforestation composition and structure is the type of owner. In public and private forest, respectively 26% and 40% of all reforestations are achieved from natural regeneration. We observed that the composition of forest stands resulting from natural regeneration depended on the composition of the previous forest stand and appeared to follow the same pattern as the recruitment composition (Table 6.5). In the case of plantation, no relationship was found with the previous composition of the stand or any characteristics other than the type of owner. We identified 20 different plantation types and estimated their probability of implementation for each owner type (Table 6.6).

Table 6.6 Probability (in percent) associated with each observed type of reforestation depending on the owner type (PR = private and PB = public) and sorted in descending order of importance considering the total probability. The corresponding density per species group generated by the reforestation model are presented in the last column.

Reforestation type	Prob PB	Prob PR	Composition per ha
Natural regeneration	26.24	40.09	2000 * recruit
Spruce	14.83	19.81	2250 * Spr
Spruce + douglas	22.43	9.91	1500 * Spr + 750 * Dou
Douglas	9.13	18.4	2000 * Dou
Larch	7.98	1.89	2000 * Lar
Beech	3.04	2.83	2250 * Bee
Native oak	4.18	0	2000 * Oak
Hybrid poplar	0.38	3.3	120 * Pop
Douglas + larch	2.28	0.5	1500 * Dou + 750 * Lar
Red oak	1.14	0.94	2000 * Rok
Misc. hardwood	0.76	0.94	1100 * Hwc
Spruce + larch	1.52	0	1500 * Spr + 750 * Lar
Maple	0.76	0.47	2000 * Map
Misc. softwood	0.76	0.47	2000 * Swx
Birch	1.14	0	2000 * Bir
Beech + oak	1.14	0	1000 * Bee + 1000 * Oak
Ash	0.76	0	2000 * Ash
Beech + douglas	0.76	0	1500 * Bee + 750 * Dou
Black alder	0	0.47	2000 * Ald
Beech + larch	0.38	0	1500 * Bee + 750 * Lar
Scot pine	0.38	0	2000 * Spi

While the composition and density of natural regeneration is initially very variable, we found that it is generally quickly controlled by early silvicultural interventions in southern Belgium. We have observed that after about twenty years, the density and dimensions of trees in stands of similar compositions are usually comparable whether they are the result of natural regeneration or planting. Natural regeneration can therefore be effectively simulated by considering that it leads to reforestation densities equivalent to those of plantation (2000 trees per hectare on average) and that its composition follow the recruitment composition vector calculated just before the final harvest of the previous forest stand.

4.6. *Simulation of Wallonia's forest development*

The entire productive forest resource of Wallonia generated from the first permanent inventory cycle made between 1994 and 2008 represent 479 500 ha of forest and about 465 million simulated trees distributed in 95 900 forest stands. Its simulation until 2050 required 54 minutes to complete on a computer equipped with an i9 7900x CPU (10 x 4.3 GHz) and 64 Go of RAM. The simulation outputs were stored in a 1,40 GB text file. We found that, given the large number of simulated trees (465 millions) and forest stands (95 900), no further replication was needed for the output values to converge.

As the entire Walloon productive forest area is only simulated from the end of the first cycle of the permanent inventory (2008), the total solid wood stock estimates presented hereafter for the years 2000 to 2007 are extrapolated to the total surface area.

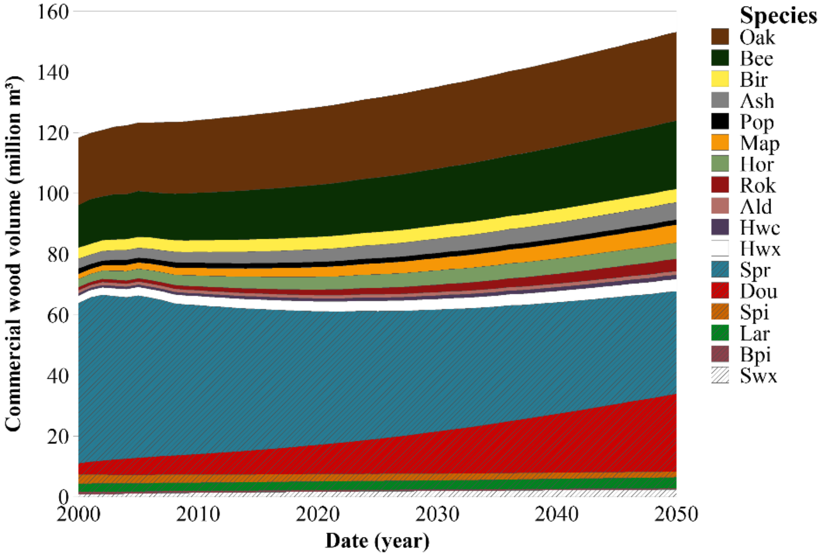


Figure 6.3 Simulated development between 2000 and 2050 of the total growing solid wood stock (in millions m³) by species group.

Our simulation shows a continuous hardwood stock increase of about 600 000 m³/year. Softwood stock would decrease until around 2020 and then would slowly recover: from around -300,000 m³/year in 2010 to +350,000 m³/year in 2050. There would be a substantial decrease in standing stock of Norway spruce and pines in favour of douglas-fir, larch and various hardwood species (Figure 6.3).

We plan an overall increase in the total wood production of the Walloon forest (Figure 6.4) mainly due to the gradual maturation of new plantations of fast growing species such as douglas-fir and larch. The hardwood production would also significantly rise because of a net increase of the share of hardwood dominated forest stands.

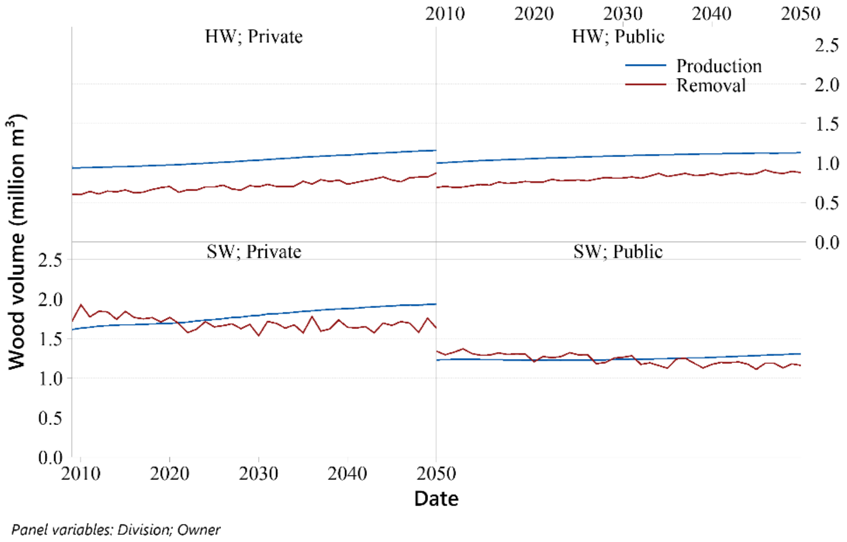


Figure 6.4 Simulated development between 2009 and 2050 of the total annual wood production and removal (in millions m³) by division (SW = softwood, HW = hardwood) and by type of owner.

We observe (Figure 6.4) that the hardwood removal rate would remain relatively constant at respectively around 65% and 75% of the total annual hardwood production of private and public owned forests. Conversely, the current softwood management appears to be unsustainable (particularly in private owned forests) and we project that its removal rate should decrease in the coming decades. This is largely explained by the gradual replacement of Norway spruce which has a highly unsustainable removal rate of over 120% by other tree species with higher exploitable girth and lower removal rates such as douglas-fir and various hardwoods. In our simulation, this leads to a significant decrease of the total removal rate from 93% in 2010 to 83% in 2050. It appears likely that the removal rate of douglas-fir will eventually increase as it becomes one of Wallonia's main wood production species but this trends is not yet observed in the available inventory data.

5. Discussion

The trends highlighted by our simulation are consistent with previous reports about the observed changes of Wallonia's forest resources. The most recent published estimates (UNFCCC, 2020) indicates an estimated solid wood stock increase of about 5 million m³ between 2001 and 2012 while our simulation estimated an increase of 5.01 million m³ over the same period. The current Norway spruce decline is also well documented (e.g. Hébert et al. 2002; Alderweireld et al. 2015) and is thought to have started following serious windfall damage in 1990 (Claessens 2006). In the same time, the better productivity, durability and resilience to windfall of douglas-fir and larches has made them the preferred alternative species (Pauwels 2003; Bievelet et al. 2007).

The total growing stocks per species predicted by SIMREG are reasonably close (within a one year variation) to the most recent estimates provided by the IPRFW (Table 6.7) except for a slight overestimation of douglas-fir growing stock. Although it may simply result from stochastic process, imprecision and the differences between the plots (whole network simulated vs half measured) and time periods (2012 vs 2008-2015) considered, it could also suggest that the current reforestation model is too optimistic in that it underestimates the share of douglas fir plantations that subsequently fail. It may therefore be worth collecting older data on reforestation in order to accurately estimate the success rate of plantations.

Table 6.7 Comparison of the estimates per species of the total growing stock from the first half of the second cycle of the IPRFW (2008-2015) with those of SIMREG for the year 2012.

Tree species	**Forest stock (10³ m³)** **IPRFW**	 **SIMREG**	**Difference (10³ m³)**
Native oak	24 656	24 292	-364
Beech	15 876	15 870	-6
Ash	3 857	3 666	-191
Birch	3 991	3 959	-32
Poplar	1 759	1 712	-47
Other hardwood	12 395	12 755	360
Total hardwood	**62 534**	**62 254**	**-280**
N. spruce	47 858	47 935	77
Douglas-fir	6 589	7 253	664
Larches	2 683	2 747	64
Pines	3 366	3 223	-143
Other softwood	1 116	1 442	326
Total softwood	**61 612**	**62 599**	**987**
Total	**124 145**	**124 853**	**708**

While individual tree models are generally considered more complex than stand-level ones, they are also more flexible (Pretzsch 2008) and streamline the representation of the potentially infinite range of forest stand compositions and structures (Pretzsch 2015). They also maximize the use of inventory data, both for model calibration and simulation initialization (Ledermann 2006; Stadelmann 2019). In SIMREG, the combination of this modelling approach with an annual simulation time-step makes it possible to directly use non-synchronized raw forest inventory data as input which should greatly facilitate its adaptation to other case studies. Moreover it also allows to synchronize IPRFW estimates with remote sensing and various survey data which opens interesting opportunities for forest assessment, management and research (Huang et al. 2018). We intend to continue to use this feature to regularly update the IPRFW data with external information such as those derived from the photointerpretation of clearcuts.

The performances of our growth model are comparable to those of other previously published empirical models (e.g. Monserud and Sterba 1996; Andreassen and Tomter 2003; Rohner et al. 2017). It is interesting to note that the validation RMSE on the estimated girth increment estimation for Norway spruce, douglas-fir and larches are almost identical to those obtained in a previous study (Perin et al, 2016) based on an entirely independent dataset: respectively 0.542 versus 0.545 cm/yr, 0.774 versus 0.771 cm/yr and 0.614 versus 0.627 cm/yr. However, the total annual girth increment variance in our dataset is comparatively lower for each of those species, leading to a lower adjusted coefficient of determination. This is certainly due to the over-representation in this previous study of data collected from several silvicultural field experiments representative of very unusual site condition and management practices.

Unsurprisingly, the explained share of the total annual girth increment variance is generally lower for species that are mainly found in mixed irregular stands. Modelling tree growth, removals and recruitment in mixed uneven-aged forests is undoubtedly complicated by the greater heterogeneity of local conditions (density, composition, structure…) compared to that of pure even-aged forests (Porté and Bartelink, 2002; Blanco et al. 2015). While distance-dependent approaches would have allowed to better account for local conditions (Pretzsch 2008), they require data that are not available in most forest inventory and would have been too compute-intensive for such large-scale applications. In the case of a regional forest management model, tree-level predictions need to be accurate (unbiased) but not overly precise so that we found it more efficient to simply emulate the local heterogeneity with a stochastic modelling approach.

The use of timber removal sub-models based on inventory data to emulate the behavior of forest owner is rather uncommon in large-scale forest models (Sterba et al. 2000; Söderbergh and Ledermann 2003; Thurnher et al. 2011; Barreiro et al. 2017). Nonetheless, the usefulness of analytical thinning algorithms to accurately reproduce stands dynamics has already been demonstrated (Sterba and Ledermann 2006; Mina et al. 2017). Our removal sub-model highlights many interesting trends depending on the composition, structure and type of owner which clearly demonstrates its interest in view of the current forest changes and shift towards more multifunctional forest management strategies (Gamborg and Larsen 2002, Vitkova and Dhubháin 2013). In particular, it appears essential to take into account the interactions between forest composition, structure and type of owner that can lead to very distinct forest management strategies. For example, thinning account for respectively 95% and 60% of the total volume of hardwood and softwood annually removed from Walloon public forests while those values drop to 75% and 30% in private forests. We therefore intend to regularly improve and update the removal sub-model to identify and account for potential behavioral responses to the ongoing forest resources changes.

Current reforestation trends are undoubtedly the main drivers of the ongoing composition changes in Walloon forests. In particular, the low replantation rate of Norway spruce combined with the very young age at which it is harvested in private forests are the obvious causes of its rapid decline. Consequently, the clearcut and reforestation sub-models are probably the most influential elements to accurately forecast the future characteristics of our forest resources. While our dataset did not allow us to identify any sites effect on these process, it appears probable that such relation exists. Particularly considering that some regulations were enacted (DNF, 1997) to prevent the plantation of some tree species in unsuitable sites (e.g. Norway spruce on white clays and peat soils) and help restore some natural habitat (e.g. Natura 2000 network). We will therefore continue to try to improve these sub-models as new data become available to improve the precision and accuracy of our simulations.

The main limitation of SIMREG stem from the empirical nature of its sub-models which currently constrains its application to the simulation of more original scenarios. We are currently working on the development of easily parameterizable removals, clearcut and reforestation sub-models to overcome these limitations and provide a flexible decision-support tool to assist forest management planning. In the near future, we also plan to improve SIMREG with several complementary sub-models to account for natural disturbances and changing environmental conditions.

6. Conclusion and perspectives

Our modelling approach proved appropriate to develop forest management models suitable for a wide range of forests characteristics using only variables that are available in the majority of forest inventories. Our growth, removals, recruitment, clearcut and reforestation sub-models account for the interactions between species composition, stand density, tree size, social status, some sites characteristics and the type of forest ownership to accurately predict forest management in a forest stand. Our forest model SIMREG was also optimized for large-scale applications and it allows the simulation of hundreds of millions of trees generated from generic national forest inventories (NFI) data. It is therefore an interesting tool for predicting forest resources changes on a regional scale in order to provide guidelines for policy makers and help improve forest management plans.

Chapter 7

Main results and general discussion

1. Site index modelling

Site-species suitability is an important driver of forest productivity and a major decision-making criterion for silvicultural management. In particular, spruce presence in unsuitable sites could be a determining factor to explain its low replanting level. Moreover, it is reasonable to assume that sites characteristics and productivity levels could influence the choice of reforested species.

Therefore, there is a need for detailed models to accurately estimate stand productivity from forest inventory data. Although such models already exist for the main production species in Wallonia, their integration into a simulation software is complicated by their formulation and lack of harmonization. Besides, some were based on data and modelling methods that are now considered outdated.

1.1. Data acquisition and modelling approach

The quality of models is limited by the quality of the information on which they are built. Consequently, the representativeness of the data set is the most critical element when fitting an empirical model.

In the case of a site index modelling, the dataset must equitably represent all sites and stages of development at which it is expected to be valid. In practise, finding the necessary data may be complicated by the near absence of certain combinations of variables. In particular, the planting of certain tree species in some sites conditions may be recent or, on the contrary, a thing of the past. This often means that certain uncommon occurrences should be over-represented directly in the dataset or using a weighting method.

Consequently, modelling site index from single height-age pair measurements is hazardous, as there is no guarantee that such data equitably represents site-development stage combinations. Therefore, long-term tracking of top-height growth are generally considered to be the best data for site index modelling (Spurr, 1952; Hägglund, 1981; Clutter et al., 1983). Unfortunately, such data require permanent sample plots monitored over the course of several years or even decades.

Stem analysis (SA) represents an interesting method to acquire long-term growth segments without the need for permanent forest inventory (Curtis, 1964; Herman, 1975). As such, they are increasingly being used to study historical growth pattern and response to global changes (e.g. LeBlanc et al., 1987; Spiecker et al., 2012; Latte et al., 2016) or gather dataset to fit growth and site index models (e.g. Curtis, 1964; Garcia, 2005; Bontemps & Duplat, 2012). While some studies question the use of SA to model site index as there is no guarantee that a tree has been dominant throughout its life (Dahms 1963; Raulier et al. 2003; Hu and Garcia 2010), we have demonstrated that these concerns do not apply to softwood plantations in Wallonia. We argue that dominant tree dynamics is probably a relevant concern in forests under low intensity management and where natural mortality is high (for example in boreal and montane forests) but less so in European temperate plantations where selective thinning is regularly applied to favour the most valuable trees ensuring that change in dominance status are quite rare.

Over the years, lots of models formulations have been used for site index modelling. The earliest models consisted of sets of top-height growth curves, requiring an iterative method or graphical analysis to estimate the index site from a height-age pair. Formulations compatible with a Generalized Algebraic Differential Approach (Cieszewski and Bailey 2000) are becoming the new standard as GADA models provide a simple algebraic solution to the estimation of top-height at any age (including the reference site index age) from any height-age pair.

We tested the fitting performances of 16 popular sigmoid growth equations compatible with a GADA approach on a dataset composed of 86 Norway spruce stem analysis (Figure 2.3). We found significant variation in fitting statistics between these models, even showing that some were poorly adapted for site index modelling as they provided aberrant predictions under certain conditions (non-zero height estimation at age 0, negative top-height growth, etc.). However, the most interesting result was that commonly used horizontal asymptote models were always underperforming compared to oblique asymptotic ones and non-asymptotic ones.

We argue that horizontal asymptotic models are probably mostly unsuitable for temperate tree species since height growth does not peak until a very old age which is almost never reached in our intensively managed forests. For example, the first site index models for douglas-fir forest stands in Wallonia (Rondeux et al., 1991) projected a 65 meters horizontal asymptote for the best productivity level, while the highest top-height in its training dataset was only 40 meters. Moreover, some 100 year-old douglas-fir under similar growing conditions in Germany, France and UK are already exceeding this asymptote and still growing steadily (www.monumentaltrees.com).

A generic and flexible GADA oblique asymptotic model formulation derived from the Duplat and Tran-Ha model (Duplat & Tran-Ha, 1986) was developed and successfully applied to model the top-height growth in pure even-aged stands of Norway spruce, douglas-fir and larches. It should be suitable for most temperate tree species as the model it is based on had originally been developed for oak, beech, Scots pine and silver fir (Duplat & Tran-Ha, 1986; 1997).

1.2. *Softwood site index changes in Wallonia*

Our stem analysis data and modelling methodology made it possible to highlight that previous Walloon site index models for Norway spruce and douglas-fir were biased and significantly underestimated annual top-height growth. These previous models were fitted using a guide curve method and single height-age pair as training data, thus confirming the risks of using such data. The validity and unbiasedness of the new models were confirmed using top-height increment data from the IPRFW (Figure 2.7).

An analysis of the current distribution of site index in Wallonia pure even-aged stands of Norway spruce highlighted a significant relationship between forests stands age and site index (Figure 7.1). These changes directly result from a combination of factors related to interaction between sites and forest management, genetic improvement and global changes.

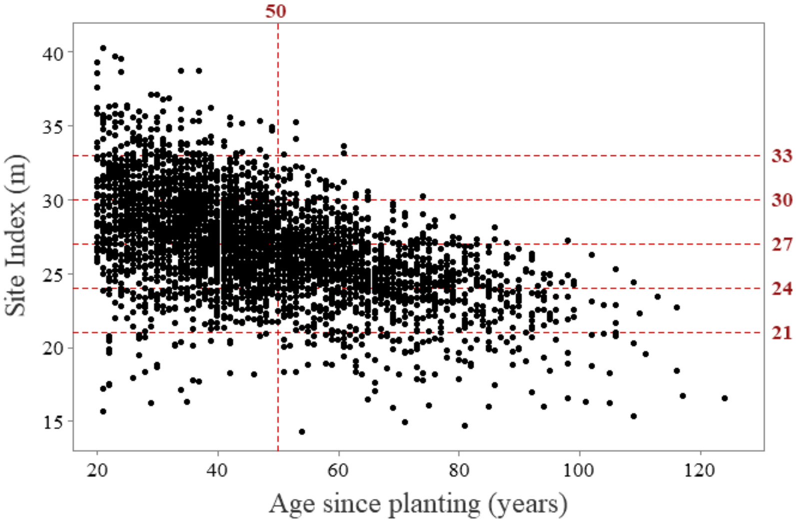


Figure 7.1 Site index distribution in relation to Norway spruce forest stands age from plantation.

Timber exploitation is apparently the main driver of this uneven distribution of the site index. Plantations are generally harvested when most standing trees reach the most profitable exploitable dimension (Figure 6.2), which for Norway spruce are around 120 cm GBH (40 cm DBH) and correspond to about 30 m top-height (Hébert et al., 2002). Such dimensions can be reached as early as 45 years in the most productive stands or as late as 80 in the less productive ones. Thus, the most productive stands are generally exploited at a younger age, leading to a truncated representation of productivity levels in older stands.

Several other factors are also contributing to this imbalance:

- Seed selection: research work initiated in 1968 following the EU directive (66/404/EC) led to the development of a recommended provenance dictionary (SPW, 2019) and the installation of seed orchards for the most important production tree species;
- Improving knowledge: numerous guides and tools have been produced (e.g. Balleux, 2009; SPW, 2017) to support decision making about new plantations (species-sites suitability, plants selection and handling, timing, etc.), leading to an overall increase of the productivity;
- New regulations: softwood plantations are now restricted in certain sites, especially peat-soil and riverbanks (DNF, 1997);
- Global change: numerous studies point to the influence of rising temperatures and atmospheric CO2, soil alteration, etc. on forest stand productivity (e.g. Boisvenue & Running, 2006; Weiskittel et al., 2011; Reyer et al., 2014; Latte et al., 2016).

As comparable trends are observed in other countries and other forest compositions (e.g. Spiecker et al., 1996; Bontemps & Duplat, 2012; Yue et al., 2014; Socha & Ochał, 2017; Mäkinen et al., 2017), all site index models based on single height-age pair could be similarly biased. We also suggest that the wide adoption of horizontal asymptotic site index model may have been misguided by such data imbalance that led to the belief that the top-height peaked faster than in reality.

2. Growth and yield modelling

Site index models are the base of important management tools such as yield tables that serve as reference to set the rhythm of the selective thinning and to determine the optimal rotation age. Thus, a biased perception of the decline of top-height growth with age likely had an influence on forest management by encouraging early final harvests. The development of new growth and yield management tools is therefore indicated to link the new site index models to actual growth and yield estimates in order to assess the adequacy of current silvicultural scenarios and eventually improve future forest management plans.

2.1. Data acquisition and modelling approach

In contrast to top-height growth, diameter growth is very sensitive to forest management and in particular planting spacing and thinning. As a result, growth and yield models require more extensive datasets representative of even broader conditions than site index models. In addition, the validity of our model under novel growth conditions must be ensured so that they can be used to improve current management scenarios.

We thus collected data from all known observation networks, field experiments and forest inventories relevant to our study (e.g. Hébert et al., 2002; Pauwels et al., 2007), ensuring that our dataset was representative of a wider diversity of conditions (sites, age, planting spacing, thinning intensity, etc.) that those generally encountered in pure even-aged coniferous forest stands managed for timber production in Wallonia.

The modelling approach follows the same principles that were detailed before: our model should be applicable to simple inventory data and provide the best level of detail possible while still being usable on a large scale. As such, a tree-level distance-independent modelling approach was again considered most appropriate. The resulting growth model is based on the formulation proposed by Deleuze et al., (2004) that had already been used for Norway spruce in neighbouring France.

This model presents really interesting features such as:

- a flexible yet biologically plausible constrained form that ensures consistent behaviour even outside of its area of validity;
- a segmented shape based on the premise that dominant trees are less affected by competition than dominated ones (Schütz et al., 2015);
- 3 parameters (A, P and m) that influence in very contrasted ways the shape of the relation between individual girth and tree basal area increment (Figure 4.2);
- only one tree-level variable (GBH), greatly simplifying the representation and understanding of the combined influence of explanatory variables on growth.

We also showed that simple methods were sufficient to adequately account for heteroscedasticity (1) and sampling heterogeneity (2): 1) the model was fitted on annual girth increment values rather than periodic basal area increment; 2) each growth segment data was weighted by its length (in years) divided by the number of growth segments measured at the same time in the PSP to even out the contribution of each PSP to the model calibration.

The fitting performances of our model (Table 4.5) are on the high end (e.g. Monserud & Sterba, 1996; Andreassen & Tomter, 2003; Monty et al., 2007, Pauwels et al., 2007) as it explains 61, 50 and 61% of the annual girth increment variance and 68, 73 and 67% of the annual basal area increment variance respectively for Norway spruce, douglas-fir and larch. This level of precision is probably close to the maximum attainable by using only simple non spatialized variables that are already collected in most forest inventory data.

2.2. Main variables affecting growth

Our model helped us identify 4 main effects that have a significant effect on the growth of Norway spruce, douglas-fir and Larches in pure even-aged plantations:

- Productivity level;
- Forest stand development stage;
- Tree vigour;
- Current intra-specific competition.

The effect of productivity level is simple to interpret: a higher site-index leads to a better growth rate. This effect appears to be linear and a 10% gain in index site is equivalent to about 7% in basal area growth rate.

The effect of forest stand development stage also follows the new site-index models: an increase or decline in annual top-height growth has a direct proportional effect on growth rate. Thus, all other tree and forest stands characteristics being equal, growth rate would theoretically increase until around 15, 15 and 7 years and then decrease slowly by about 1.2%, 0.6% and 1.5% per year over the next 50 years respectively for Norway spruce, douglas-fir and larches. Taking into account that other variables such as circumference and top-height obviously change with the stage of development show that the dominant tree basal area growth does not in fact peak until well after trees reach harvesting size. In terms of annual girth growth (Figure 4.5), this translates into an annual decline of about 0.7, 0.7 and 0.9% per year between 25 and 50 years respectively for Norway spruce, douglas-fir and larches.

In even-aged stands, a higher girth at a given age can be interpreted as a result of greater vigour (i.e. growth rate). Tree vigour is a combination of genetic, localised site and forest stands conditions and the cumulative effect of past intra-specific competition. In our model, the tree vigour is represented by the tree girth value relative to the top-height of the stands. This definitely reminds us of the ratio between the height and diameter of the tree (H/D) which is already a well-known indicator of individual tree stability (e.g. Bruchert et al., 2000; Wonn & O'Hara, 2001; Slodicak & Novak, 2006), crown dimension (Dyer & Burkhardt, 1987; Hasenauer & Monserud, 1996) and has already been investigated as a potential competition index (Opio et al., 2000; Bachofen & Zingg, 2001). In our model, a power function of the top-height is used to calculate a girth threshold value (A) under which the growth rate is very low or even nil. Therefore, we can expect that trees whose girth is close or below this threshold were probably heavily suppressed during a significant part of their lifetime resulting in a very small crown ratio and low potential vigour.

We found that the current intra-specific competition level in the stand was ideally expressed as a direct function of its total basal area. We also found a slight inverse relationship with top-height, suggesting that a given total basal area value accounts for a higher level of competition in younger forests stands than in older ones. In our model, a lower total basal area translates into a higher flexibility around the girth threshold value which strongly benefits supressed trees ($Gbh_i <= A$) but not so much dominant ones ($Gbh_i >> A$). This is consistent with the fact that dominant trees are less affected by competition than dominated ones (Schütz et al., 2015).

Theoretical applications of this model show that the girth growth rate of douglas-fir is about 1.5 times that of Norway spruce and Japanese larch (Figure 4.5) in similar growing conditions. They also confirm the high sensitivity of larch to stand density variation which led Pauwels et al. (2007) to recommended lower density in larch plantations than what is generally implemented for Norway spruce and douglas-fir.

2.3. Assessment of current softwood management

The new site-index and growth models were implemented into the simulation platform Capsis (Dufour-Kowalski et al., 2012) as part of the module Gymnos (Ligot et al., 2013): a tree-level distance-independent management-oriented forest simulation model for pure plantations of Norway-spruce, douglas-fir and larch. In addition, Gymnos also includes several tools to simulate customized selective thinning as well as optional self-thinning and stand generation models based on the lognormal GBH distribution observed in even-aged softwood plantations (Figure 7.2).

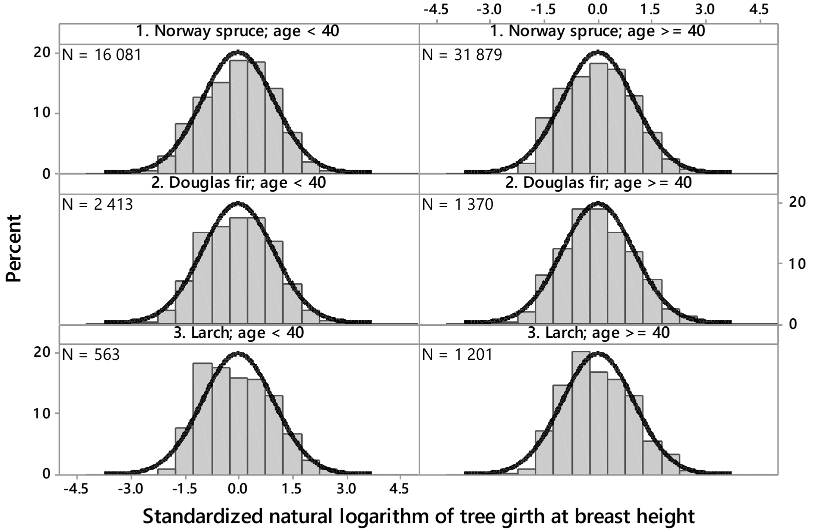


Figure 7.2 Distribution of the natural logarithm of the tree girth standardized for each PSP monitored by the IPRFW in Norway spruce, douglas-fir and Larch even-aged stands. Younger stands (< 40 years) are represented on the left and older ones (>= 40 years) on the right. The standard normal distribution is shown in bold in each panel for easy comparison.

Gymnos was applied to check the validity of current management tools and silvicultural guidelines for Norway spruce (Dagnelie et al., 1988, Hébert et al., 2002), douglas-fir (Rondeux et al., 1991) and larch (Pauwels et al., 2007) plantations. This revealed that the tools in use for Norway-spruce and douglas-fir were outdated because they were based on the same misguided assumption of a sharp decline in growth rate with age that we have discussed before.

Following these conclusions, a multidisciplinary taskforce was assembled at the initiative of the DNF to conceive new silvicultural guidelines that reflect current management objectives and practices and build the corresponding yield table for Norway spruce and douglas-fir using Gymnos. This also led to the development and integration into Gymnos of an economic model based on the public timber sales data of 2012-2014 to estimate the evolution of revenues and profitability depending on the age of the final cut.

An interesting conclusion of this work was that the average annual volume growth and theoretical profitability of Norway spruce and douglas-fir plantations continue to increase well beyond the generally recommended rotation (Figure 5.3). However, these do not account for the increased risks of windfalls and biotic attacks (bark beetles) which represent a major ongoing concern. In particular, windfall damage risks are known to increase rapidly once trees exceed 20 metres in height in sites that do not allow deep rooting (e.g. Renaud, 2005, Riou-Nivert et al., 2005, Colin et al., 2008, Colin and Riou-Nivert, 2009). A good compromise between maximizing production and stability was defined at 30 metres top-height for Norway spruce and 42 meters top-height for douglas-fir in suitable sites, corresponding to respectively around 140 and 190 cm dominant girth. Plantations in unsuitable sites present a higher risk and it is therefore recommended that they be harvested earlier.

An analysis of the dominant girth distribution of Norway spruce stands that were clearcut between 2006 and 2015 (Figure 7.3) shows that these recommendations are already being implemented in public forests but not in private ones. As a matter of fact, half of the private Norway spruce plantations are harvested before they reach 120 cm of dominant girth. This translates into a substantial loss of production (-5%) and profits (-20%) in private Norway spruce plantations compared to public ones.

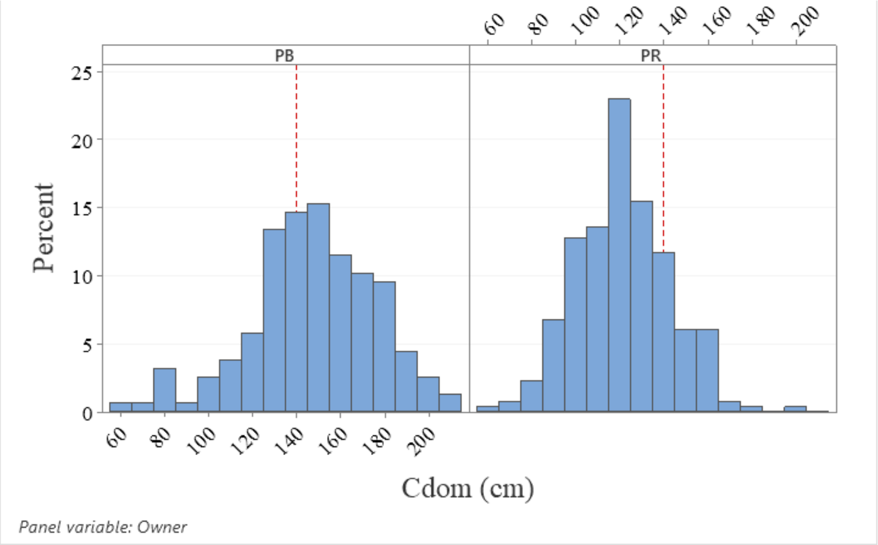


Figure 7.3 Distribution of the estimated dominant girth of Norway spruce plantations at the time of the final felling in public (left) and private (right) forests.

3. Regional forest resource modelling

We showed that the composition of Walloon forests is quickly changing. In particular, Norway spruce plantation area decreased by more than 20% between the first complete cycle and the first half of the second cycle of the IPRFW (corresponding to a period of about 11 years). Norway spruce being the main wood production species of the region, this leads to legitimate questions regarding the future of the region's wood supply.

We also concluded that some of the estimates reported by the Permanent Forest Inventory of Wallonia are incompatible. In particular, it seems absurd that a harvest rate above 100% (i.e. a volume harvested higher than the volume produced) would result in a growing stock increase over the same period. These discrepancies raise questions about the accuracy and representativeness of these estimates.

A forest model that can be applied to the whole measured resources was therefore needed to fill in the gap, provide an accurate assessment of the volume produced and harvested in Wallonia's forests, consistent with stock changes estimates and forecast the future development of forest resources. We thus developed SIMREG, a forest growth and management model calibrated on data from the IPRFW to simulate regional forest resource changes.

3.1. *Modelling approach*

SIMREG is an individual tree distance-independent forest gap model. The main interest of forest gap models is to allow local competition variables to be considered in distance-independent models (Bugmann, 2001; Taylor et al., 2009). Our work shows that this modelling approach can represent an ideal compromise as the data needed for its calibration are already available in most countries with permanent forest inventories and its large-scale operation is compatible with current computational capabilities.

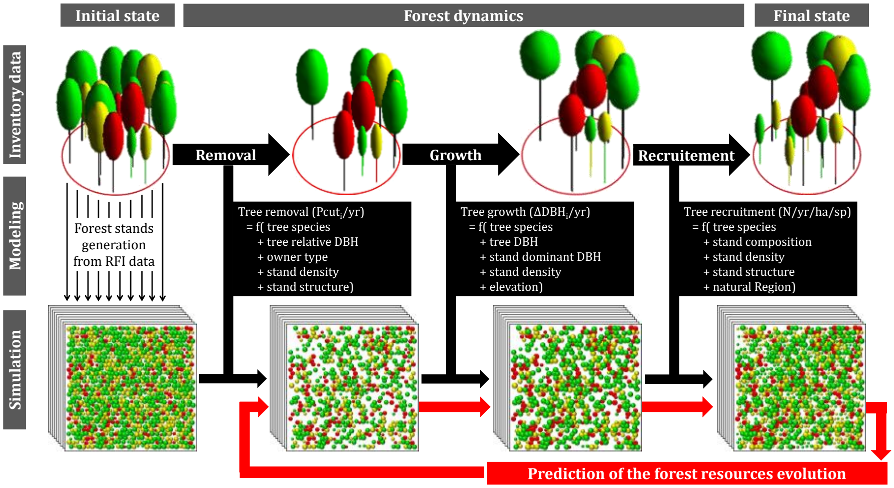


Figure 7.4 Illustration of our modelling methodology (Perin et al., 2019).

In SIMREG, a forest is represented by a list of virtual trees with each their own species and size. The development of the forest is then simulated by applying variations of three basic process that emulates what is observed in forest inventories (Figure 7.4):

- Removal: some trees are removed from the growing stock. This is currently handled by a stand-level clearcut model (final harvest) and a tree-level selective removal model (thinning and natural mortality);
- Growth: trees change size, marking the transition to the next simulated year;
- Recruitment: some new trees appear in the growing stock. This is currently handled by a reforestation model (reconstitution of a forest from a clearings) and a recruitment model (regeneration under cover).

Compared to other forest models based on NFI data (Barreiro et al., 2017), our model generally includes more detailed sub-models to improve the accuracy of the representation of silvicultural management and its effect on forest development. In particular, large scale forest projection systems often account for thinning using simple harvesting rules that assume fixed removal rates and standard distribution of size dependent tree selection probabilities (e.g. Söderbergh and Ledermann, 2003; Chertov et al., 2006; Stadelmann, 2019). In SIMREG, however, thinning sub-model takes into account the tree species and social status and their interaction with several variables representative of the forest composition, structure and ownership. This allows for a more accurate modelling of selective thinning and facilitates extrapolation to forest structures and compositions that are intermediate between those most represented in our dataset. An accurate modelling of thinning is especially critical in light of the current shift to less intensive and more multifunctional forest management (Gamborg and Larsen 2002, Sterba and Ledermann 2006) and the renewed popularity of continuous cover forestry (Pommerening and Murphy, 2004; Vitkova and Dhubháin, 2013).

Our growth model also attempts to depict the effect of tree competition on growth as accurately as it is possible with a distance-independent approach. Interestingly, although the growth model formulation that we use had initially been developed for even-aged pure stands (Dhôte, 1991; Deleuze et al., 2004; Perin et al., 2017), no major changes were required to adapt it to mixed and irregular stands. While our growth estimates are generally more precise in even-aged structure (Table 7.1) than in irregular or coppiced forests, this was expected as in even-aged stands, the tree relative size is not only an indicator of its social status but also a direct estimator of its past growth potential. In any case, the analysis of the residuals distribution (Figure 7.5) did not highlight any evidence of bias or unsuitability. This leads us to conclude that, no matter the structure of the forest, the total basal area is a good indicator of the overall level of competition in a forest stand and the tree relative size to the dominant girth represents well its level of competitiveness for limited resources.

Table 7.1 Fitting statistics of the parameterized growth model depending on the tree type (HW = hardwood and SW = softwood) and the forest structure (COP = coppice, IRR = irregular, REG = even-aged) defined by the IPRFW.

Type	Structure	Mean dCi	RMSE	Mean error	Median error	R² dCi	R² dGi
HW	COP	1.17	0.69	0.02	0.08	0.37	0.53
HW	IRR	1.24	0.72	-0.09	0.02	0.30	0.54
HW	REG	1.21	0.62	0.01	0.06	0.41	0.54
SW	COP	1.34	0.72	-0.04	-0.02	0.39	0.54
SW	IRR	1.33	0.70	-0.09	0.01	0.48	0.67
SW	REG	1.49	0.55	0.01	0.04	0.44	0.66

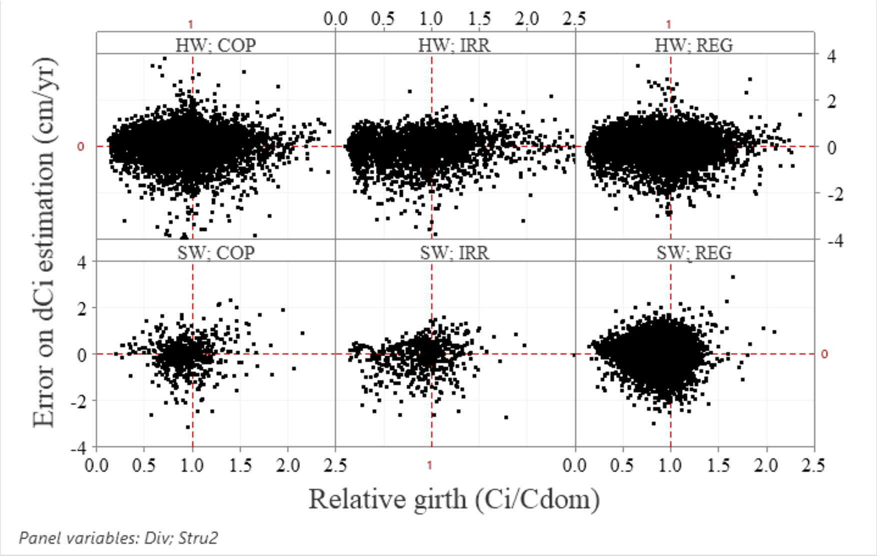


Figure 7.5 Distribution of the residuals (predicted - measured) on the annual girth increment estimation (in cm/yrs) depending on the corresponding forest structure (COP = coppice, IRR = irregular, REG = even-aged) defined by the IPRFW, the tree type (HW = hardwood and SW = softwood) and its social status (relative size in relation to the dominant girth).

At present, our model does not explicitly account for any interspecific effect of species mixing on growth. It does, however, take into account any effects related to the different sensitivities of species to competition and stand structure that can be likened to an intra-specific effect.

Like all models, SIMREG represents a simplified version of reality that will inevitably lead to a levelling of the specificities and diversity of forests. Thus, while maximising the level of detail by using a tree-level approach ensure a precise initial representation of the particularities of forests, it does not prevent them from converging as a result of the application of the model. Various random effects have therefore been added to account for the unexplained variability in our sub-models and limit this simplification effect. Currently, all of SIMREG procedures, from the generation of virtual stands to recruitment, growth and removal, integrate stochastic components calibrated according to the fitting statistics of the corresponding models. Fine-tuning the noise calibration and the way it is added around each sub-model is a major task and many tests are still underway to perfect it.

Conveniently, our modelling methodology allows the use of unsynchronized periodic inventory data to calibrate annual models and to initiate simulations. This is particularly useful to process national forest inventory data which are often collected over several years (Vidal et al., 2016), for example in Wallonia the first cycle of the IPRFW was carried out over a period of 14 years (1994-2008). It is a rather unusual approach as forest simulators based on NFI data (Barreiro et al., 2017) often consider the inventory data to be representative of the middle of the inventory period (i.e. 2001 for the first cycle of the IPRFW) which can be inaccurate in the case of asynchronous resources changes. SIMREG can thus be used to provide synchronized annual estimates from unsynchronized inventory data. This feature can also be used to synchronize inventory data with external information in order to, for example, facilitate the cross-checking, supplementing or updating of field data with remote sensing data.

These features make SIMREG a robust generic forest simulation tool that can be calibrated with raw tree-level permanent inventory data. This should greatly facilitate its application to different contexts and more particularly to other national inventory data. It also makes it possible to use it to identify and take into account inconsistencies in inventory data in order to provide more precise, accurate and consistent estimates of stock change, production and harvest.

3.2. Simulation of forest changes in Wallonia

We used SIMREG to simulate the regional forest resource development from the first IPRFW cycle (1994-2008) until 2050. This represents about 465 million simulated trees distributed in 119 875 forest stands of 5 ha for a total of 479 500 ha of productive forest.

A comparison of the distribution of the growing stock per species estimated from the second cycle of the IPRFW with the result of our simulation is presented in table 7.2. Differences were expected considering that:

- SIMREG is not a deterministic model;
- IPRFW estimates include only half of the PSP as the second inventory cycle is still underway;
- the correspondence between annual (SIMREG) and periodic (IPRFW) estimates is obviously not perfect;
- tree growth, removals and regeneration are simulated as sequential instantaneous processes whereas in reality they are not;
- SIMREG simulation considered a constant total productive forest area, dismissing the estimated 0.1%/year decrease as insignificant.

Table 7.2 Comparison of the estimates per species of the total growing stock from the first half of IPRFW cycle 2 with those of SIMREG for the year 2012.

	Forest stock (10^3 m^3)		**Difference**
Tree species	**IPRFW**	**SIMREG**	**(10^3 m^3)**
Native oak	24 656	24 292	-364
Beech	15 876	15 870	-6
Ash	3 857	3 666	-191
Birch	3 991	3 959	-32
Hornbeam	3 227	3 692	465
Mapple	2 883	2 648	-235
Poplar	1 759	1 712	-47
Misc. hardwood	6 285	6 415	130
Total hardwood	**62 534**	**62 254**	**-280**
N. spruce	47 858	47 935	77
Douglas-fir	6 589	7 253	664
Larches	2 683	2 747	64
Pines	3 366	3 223	-143
Misc. softwood	1 116	1 442	326
Total softwood	**61 612**	**62 599**	**987**
Total	**124 145**	**124 853**	**708**

Anyway, most growing stocks estimates appear reasonably close except maybe for those of Hornbeam and douglas-fir. We hypothesize that the hornbeam growing stocks could be overestimated because of an underestimation of its removal. Hornbeam is often found in coppice for which permanent data is lacking leading to uncertainty about the reliability of our sub-models in these forest structures. As for the overestimation of douglas-fir stocks, it could be caused by an overly favourable reforestation model. It now appears likely that a non-negligible portion of douglas fir reforestation fails, which should be accounted for in our models.

A comparison of the total annual solid wood production in Wallonia estimated using SIMREG with recent estimates provided by the IPRFW highlights some very significant differences (Table 7.3). SIMREG expects the total hardwood and softwood solid wood annual production to be underestimated by respectively 30% and 23% by the IPRFW.

Table 7.3 Comparison of IPRFW and SIMREG estimates of the total annual production of solid wood in Wallonia forests for a period centred on 2008.

Species	**Production (10^3 m^3)**		**Difference (10^3 m^3)**
	IPRFW	**SIMREG**	
Native oak	375	525	150
Beech	447	499	52
Ash	92	119	27
Birch	105	117	12
Poplar	64	62	-2
Misc. HW	229	561	332
Total HW	**1 313**	**1 884**	**571**
N. spruce	1 815	2 290	475
Douglas-fir	340	465	125
Larches	66	89	23
Pines	59	83	24
Misc. SW	52	116	64
Total SW	**2 332**	**3 043**	**711**
Total	**3 645**	**4 884**	**1 239**

Considering that the majority of unmeasured spruce stands are classified as impenetrable and are therefore unthinned, we can assume the spruce harvest estimates of the IPRFW to be mostly correct. Moreover, the spruce stock variation estimate is mostly accurate as no significant change in unmeasured spruce volumes was identified between the two cycles of the IPRFW. Therefore, we can use the estimates presented in figures 1.2 and 1.3 to estimate Norway spruce production has it should be equal to the sum of the variation in stock (-479 000 m³/year) with the removals (2 840 000 m³/year) i.e. 2 360 000 m³/year. This is very close to our own estimate of 2 290 000 m³/year. Applying this method to the other softwood species, we estimate the total softwood production at 2 950 000 m³/year, which is again similar to SIMREG's estimate. As a result, we can conclude that the softwood harvesting rate, while still unsustainable, has to be much lower than previously thought.

Unfortunately, no such hypothesis is applicable to allow the estimation of hardwood production from previous IPRFW estimates. Indeed, they most certainly significantly underestimated both hardwood production and harvest as they include neither coppice trees nor linear stands that represent about 15% of the total solid hardwood volume. Moreover, since coppice trees are generally much smaller than high forest ones (average girth of 33 cm vs 62 cm), it can probably be assumed that their production relative to their growing volume is higher. It is interesting to note that the most common coppice trees species groups are also those with the largest differences between the SIMREG and IPRFW estimates: respectively 67% and 14% of the coppices trees are miscellaneous hardwood (44% of the total volume of misc.

hardwood) and native oak (6% of the total volume of native oak). The IPRFW estimates indicate an average hardwood stand yield of about 5 m³/ha/year while SIMREG estimates it at about 7 m³/ha/year, which appear to be more consistent with growth and yield reference values for comparable temperate broadleaved forests (Schöber, 1975; Vannière & Decourt, 1984). SIMREG also extrapolate a similar increase of the harvested volume leading to a hardwood harvesting rate around 70% comparable with previous estimates.

Therefore, although improvements and validation with more complete inventory data remains desirable (in particular to validate our forest dynamics sub-models for coppice trees), we are fully confident that SIMREG currently provides the most accurate estimates about Walloon forest stock, stock changes, production and harvests.

These new figures show that, on the whole, the annual solid wood production is higher than what is harvested, which is a necessary condition for sustainable management. This results in an overall increase of the total solid wood stock (Table 7.4) of about 0.35% per year that is due to the low hardwood harvesting rate (70%). Indeed, hardwood stocks are currently increasing at a rate of 1% per year, while softwood stocks are declining by 0.30% per year. Norway spruce and pines harvesting rates are especially unsustainable leading to stock declining by about 1% per year while douglas-fir stock increase by 3.5% per year.

As the main production species of Wallonia, the decline of Norway spruce resource is especially worrying. It has already been well documented (Alderweireld et al., 2015) and results from its very low replanting rate (around 40%) leading to the gradual replacement of pure spruce forest stands with other compositions (Latte et al., 2016). This can be explained by a combination of factors related to the cost and risks associated with spruce plantations, its historical plantation in inadequate sites and the opportunity represented by other species (Claessens et al., 2001). In particular, Norway spruce is known to be sensitive to wind damage, bark beetle attacks and drought (Hébert et al., 2002) and the presence of ageing spruce stands on difficult sites (heavy clay, peat, irregular water-regime, etc.) has often amplified the perception of these vulnerabilities (Claessens, 2001).

While there is no guarantee that the wood industry will consider douglas-fir as a suitable substitute species for Norway spruce, douglas fir has now become the main plantation species in Wallonia’s forests and its future importance for the timber industry cannot be ignored (Balleux, 2009). Moreover, our simulation suggests (Table 7.4) that its significantly higher production level could eventually make it possible to compensate for the net reduction in softwood plantations area. Especially in light of the fact that while a significant proportion of old spruce forests were planted on unsuitable sites, douglas-fir is usually only planted on optimal sites (Claessens et al., 1996).

Table 7.4 Simulated stock and composition changes between 2010 and 2050.

Species	Stock (10^3 m^3)			Stock change (10^3 m^3/yr)	
	2010	2020	2050	2010-20	2020-50
Native oak	23 927	25 573	29 234	165	122
Beech	15 564	17 095	22 484	153	180
Ash	3 551	4 112	5 713	56	53
Birch	3 910	4 146	4 396	24	8
Hornbeam	3 549	4 183	5 306	63	37
Mapple	2 503	3 248	5 960	75	90
Poplar	1 717	1 711	1 655	-1	-2
Misc. HW	6 251	7 172	10 683	92	117
Total HW	**60 973**	**67 239**	**85 431**	**627**	**606**
N. spruce	49 005	43 962	33 744	-504	-341
Douglas-fir	6 757	9 621	25 616	286	533
Larches	2 734	2 843	3 647	11	27
Pines	3 281	2 985	2 257	-30	-24
misc. SW	1 374	1 719	2 460	34	25
Total SW	**63 152**	**61 130**	**67 723**	**-202**	**220**
Total	**124 124**	**128 369**	**153 154**	**424**	**826**

Anyway, these forecast are based on the assumption that the trends observed between 1994 and 2015 will be maintained, which is dubious at best. The main interest of such projections is not to give an unreliable prediction of the future but rather to show what would happen under certain well-defined conditions. In this way, these simulations are useful to assist forest managers and policy makers in making decisions to shape the future of our forest resources.

3.3. SIMREG applicability to other forest inventory

SIMREG was also used to prepare the National Forest Accounting plan and the Forest Reference Level of Belgium submitted under Regulation EU/2018/841 of the European Parliament and the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework (NFAP, 2019). This project gave us the opportunity to test the applicability of SIMREG on other forest inventory data provided by the Flemish Research Institute for Nature and Forest (INBO) and Brussels Environment (IBGE-BIM).

We found that Walloon growth and thinning sub-models were mostly applicable to the rest of the country despite very significant sites, composition and structures differences between the forests of its 3 regions. Nonetheless, we took advantage of these new data to recalibrate all SIMREG sub-models and thus increase their validity area to the entire Belgium forest. We also adapted SIMREG to estimate the carbon balance of our forests using harmonized allometric relationships for total volume and biomass (Longuetaud et al., 2013; Gschwantner et al., 2019).

We concluded that Belgian forests are net carbon sink (Figure 7.6) sequestering around 1.2 million tonnes of CO2 each year of which 1 million from Walloon forests alone. On a per hectare basis, Brussels forests leads with an annual sequestration of 3.2 tonnes of CO2 per hectare, followed by Walloon (2 t/ha/yr) and then Flemish (1.6 t/ha/yr) forests. The much higher CO2 sequestration in Brussels forests results from the large proportion of protected old "cathedral beech forests" where almost no removals take place.

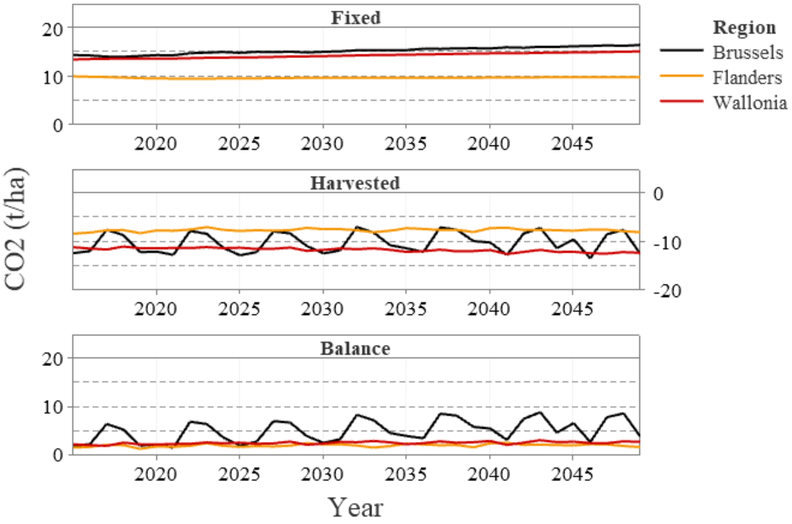


Figure 7.6 Projection of the CO2 balance of Brussels, Flanders and Wallonia forests.

Using SIMREG to simulate forest resources on a 1:1 scale is obviously not necessary, but it has made it possible to check the reliability and demonstrate the processing speed possible with this tool. Assuming a representation of the resources at the scale of the IPRFW sampling (1000 m² per 50 hectares or 1/500th), a 50 years simulation of the development of the 182 million hectares of forest in the European Union could be carried out in about 7 hours. Interestingly, the simulation time increases linearly with the number of simulated forest gaps but not with their size. For example raising the gap size from 1000 m² to 5000 m² (+400%) only increases the simulation time by about 40%.

4. Conclusion

Every stage of this work demonstrates the critical importance of permanent forest inventory data. Although indicators of sustainable forest management are still mostly based on stock-change estimates, we have shown that they are sensitive to the slightest methodological discrepancies. Permanent forest inventories are thus essential to account for the evolution of measurement methods and of basics definitions about forests that appears inevitable in the context of current scientific progress and global harmonisation. Moreover, we have shown that evident interactions between management and forest characteristics (sites, development stage, etc.) make it inadvisable to use temporary data to model forest dynamics.

We also highlighted the value of tree-level data to account for the potentially infinite combinations of composition and structure at the forest stand level and demonstrated that tree-level distance-independent models represented a good compromise between accuracy and applicability. In addition, the better accuracy and a wider area of validity that can be achieved with individual tree models facilitate their harmonization and extrapolation to conditions not covered by the original training dataset.

The models developed in this thesis were designed to answer current needs about forest resources assessment and assist in their management. They are functional, efficient, user-friendly, easily adaptable to other conditions and some of them are already being adopted by Belgian foresters. They highlight the benefits of combining the most recent data, statistical methods and technologies to modernise ageing forest assessment and management support tools. Moreover, the significant forest changes observed raise questions about the consistency over-time of some key allometric relationships, which should therefore be updated regularly.

5. Perspectives

This work presents many obvious perspectives related to the need to improve our models and management tools to account for new conditions related to global changes, changing forestry, etc.

Considering the importance of SI models to account for interactions between sites, growth and management, it would be appropriate to improve the consideration of sites characteristics into SIMREG. The relevance of top-height at a reference age as a productivity indicator is obviously questionable in uneven-aged forest stands so that a generalized Site Index would likely need to be based on individual tree height–age pairs or periodic height growth data. Interestingly, our SI models can already be assimilated to total height growth models as our SI modelling methodology is based on individual tree stem analysis data. Therefore, we think that a generalisation of our SI modelling methodology to mixed composition and uneven-aged structures is conceivable.

Anyway, it would seem more efficient to directly model species growth responses to sites characteristics. Such an approach would also make it easier to account for climate change by using models that estimate its effect over time on local sites characteristics. A first approach that is currently being considered is to model the growth response of each tree species to site characteristics based on their corresponding ecogram from the new species autecology file (SPW, 2017).

As elsewhere, Walloon forests are regularly affected by various disturbances (pests, drought, windfall, etc.). While the majority of these are only temporary, some can have a significant lasting impact on the production potential of certain tree species. The most serious phytosanitary problems currently identified (OWSF, 2018) are ash dieback (Hymenoscyphus fraxineus), spruce-bark beetle (Ips typographus), Swiss needle cast on douglas-fir (Phaeocryptopus gaeumannii) and beech dieback (caused by repeated drought). While the exact evolution of these threats remains unpredictable, SIMREG can be used to assess their effect on forest resources based on actual data and realistic scenarios. As an example: a recent photo-interpretation campaign carried out on the IPRFW sampled points has made it possible to identify the corresponding spruce stands affected by bark beetles in 2018-2019. We plan to cross-reference these data with SIMREG simulations to accurately estimate the solid wood volumes impacted, the resulting revenue shortfall and the effect of a possible further decline in the replanting rate of Norway spruce.

Although we initially developed SIMREG for regional simulations, its potential for management planning is evident. Nevertheless, the application of SIMREG to assist in the development of management plans requires that certain sub-models can be calibrated to the preferences of forest managers. For this purpose, configurable selective thinning procedures are currently developed for SIMREG based on those already available in Gymnos. In addition, several options to allow the customization at the forest stand level of final harvest trigger and reforestation characteristics are being added directly into the initialization file. This work in progress should be followed by the implementation in SIMREG of already existing libraries such as Economics2 to allow comparison of the economic return of different management choices.

As it has already been discussed, one important advantage of our modelling framework is that it is based on data that are already available or currently being acquired in many countries. We therefore hope that our models will be tested and successfully adapted to other national forest inventories data.

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Appendix

1. H50 online tool

H50 is an online tool that integrates, within an easy-to-use interface, the most recent site index (SI) models developed by scientists at Gembloux Agro-Bio Tech. As of 2020, it allow the estimation of the SI in pure even-aged stands of Norway spruce, douglas-fir, larch, alder, native oaks, birch, sycamore maple, wild cherry and black locust.

Permanent URL: http://hdl.handle.net/2268/167733

Additional URL: https://www.gembloux.ulg.ac.be/gestion-des-ressources-forestieres/estimation-si/

2. New yield tables for spruce and douglas

This document presents the yield tables for the new recommended silvicultural guidelines in even-aged pure stands of Norway spruce and Douglas-fir introduced in the chapter 5.

Permanent URL: http://hdl.handle.net/2268/198122

3. SIMREG models fitting summaries

The following tables present the R code, fitting statistics and coefficients tables for the growth, removal, recruitment and clearcut sub-models of SIMREG that are presented in chapter 6.

3.1. Growth model

```
ModIg <- function(Cm,A,P,m){P*(Cm-m*A+((m*A+Cm)^2-4*A*Cm)^0.5)/2}
ModIc <- function(Cm,A,P,m){((Cm^2+4*pi*ModIg(Cm,A,P,m))^0.5-Cm)}
Generalized nonlinear least squares fit
  Model: dC ~ ModIc(Cm, P = Pa * exp(1 - Pb * Elev), A = Aa * Cdomm^Ab,
m = 1 + exp(ma - mb * Gham))
  Data: DatadC
       AIC      BIC    logLik
  51214.22 51566.86 -25564.11

Coefficients:
                    Value  Std.Error   t-value p-value
Pa.(Intercept)  0.1133067 0.00231661  48.91065  0.0000
Pa.SpB_Bee      0.0210951 0.00254466   8.28998  0.0000
Pa.SpC_Bir     -0.0015119 0.00523783  -0.28866  0.7728
Pa.SpD_Ash      0.0286806 0.00453756   6.32071  0.0000
Pa.SpE_Pop      0.2953545 0.00840867  35.12500  0.0000
Pa.SpF_Map      0.0052467 0.00439003   1.19513  0.2320
Pa.SpG_Hor     -0.0179006 0.00716091  -2.49977  0.0124
Pa.SpH_Ald      0.0236325 0.01150450   2.05420  0.0400
Pa.SpI_Rok      0.1338862 0.00869664  15.39517  0.0000
Pa.SpJ_Hwc     -0.0075468 0.00620114  -1.21700  0.2236
Pa.SpK_Hwx      0.0495058 0.01017995   4.86307  0.0000
Pa.SpL_Spr      0.1022942 0.00569419  17.96466  0.0000
Pa.SpM_Dou      0.2404053 0.01097429  21.90622  0.0000
Pa.SpN_Spi      0.0137233 0.00997185   1.37620  0.1688
Pa.SpO_Lar      0.1164195 0.01352080   8.61040  0.0000
Pa.SpP_Bpi      0.0216904 0.01605241   1.35123  0.1766
Pa.SpQ_Swx      0.1439357 0.01766796   8.14671  0.0000
Pb.(Intercept)  0.0007591 0.00003864  19.64344  0.0000
Pb.DivRES      -0.0005693 0.00005246 -10.85346  0.0000
Aa.(Intercept)  0.2100732 0.03633146   5.78213  0.0000
Aa.DivRES       0.1354134 0.04580812   2.95610  0.0031
Ab.(Intercept)  1.1205397 0.03493027  32.07933  0.0000
Ab.SpB_Bee     -0.1760684 0.01129444 -15.58894  0.0000
Ab.SpC_Bir      0.0093179 0.01595503   0.58401  0.5592
Ab.SpD_Ash     -0.0566711 0.01517380  -3.73480  0.0002
Ab.SpE_Pop      0.1062056 0.00739644  14.35902  0.0000
Ab.SpF_Map     -0.1711763 0.02056718  -8.32279  0.0000
Ab.SpG_Hor     -0.1714247 0.03381975  -5.06877  0.0000
Ab.SpH_Ald      0.0412650 0.02371926   1.73972  0.0819
Ab.SpI_Rok      0.0039356 0.01320271   0.29809  0.7656
Ab.SpJ_Hwc     -0.1293810 0.03075354  -4.20703  0.0000
Ab.SpK_Hwx     -0.0229574 0.02186133  -1.05014  0.2937
Ab.SpL_Spr     -0.0364415 0.03862890  -0.94337  0.3455
Ab.SpM_Dou     -0.0262111 0.03848513  -0.68107  0.4958
Ab.SpN_Spi      0.0123044 0.04127433   0.29811  0.7656
Ab.SpO_Lar      0.0090278 0.03997569   0.22583  0.8213
Ab.SpP_Bpi     -0.0603806 0.04715654  -1.28043  0.2004
Ab.SpQ_Swx     -0.0946620 0.04310326  -2.19617  0.0281
ma.(Intercept)  1.8475879 0.20127178   9.17957  0.0000
ma.DivRES      -2.0463140 0.27469826  -7.44932  0.0000
mb.(Intercept)  0.1587627 0.00938731  16.91247  0.0000
mb.DivRES      -0.0921052 0.01125777  -8.18147  0.0000

Standardized residuals:
         Min          Q1         Med          Q3         Max 
-12.46833485  -0.61792183  -0.08136976   0.52189956  10.39430505 

Residual standard error: 0.6257038 
Degrees of freedom: 26930 total; 26888 residual
```

3.2. Removal model

```
svyglm(formula = Premov ~ Sp * Crel + Owner * Crel + Div * Gha +
    pcghasp + Div * CV * Crel, design = Thin_dsgn, family = quasibinomial,
    na.action = na.omit)

Survey design:
svydesign(id = ~1, strata = NULL, weights = DataEcl$Trial, data = DataEcl)

Coefficients: (2 not defined because of singularities)
                Estimate Std. Error t value Pr(>|t|)    
(Intercept)    -2.240249   0.260133  -8.612  < 2e-16 ***
SpB_Bee        -0.829099   0.178213  -4.652 3.29e-06 ***
SpC_Bir         0.163110   0.227201   0.718 0.472817    
SpD_Ash        -0.132709   0.274818  -0.483 0.629172    
SpE_Pop         0.882087   0.599687   1.471 0.141324    
SpF_Map         0.518080   0.289945   1.787 0.073975 .  
SpG_Hor        -0.424399   0.351889  -1.206 0.227803    
SpH_Ald         1.253891   0.415662   3.017 0.002558 ** 
SpI_Rok         0.591676   0.565851   1.046 0.295735    
SpJ_Hwt         0.259750   0.350256   0.742 0.458334    
SpK_Hwx         0.133758   0.279403   0.479 0.632135    
SpL_Spr         5.036552   0.328795  15.318  < 2e-16 ***
SpM_Dou         4.851100   0.387365  12.523  < 2e-16 ***
SpN_Spi         4.229362   0.535963   7.891 3.08e-15 ***
SpO_Lar         5.287871   0.582623   9.076  < 2e-16 ***
SpP_Bpi         4.670584   0.486751   9.595  < 2e-16 ***
SpQ_Swx         4.604051   0.601284   7.657 1.95e-14 ***
Crel           -2.580626   0.278782  -9.257  < 2e-16 ***
OwnerPR         0.143179   0.092058   1.555 0.119881    
Gha             0.009822   0.002670   3.679 0.000234 ***
pcghasp         0.246203   0.076998   3.198 0.001387 ** 
CV             -2.057649   0.350963  -5.863 4.59e-09 ***
SpB_Bee:Crel    1.590573   0.210544   7.555 4.31e-14 ***
SpC_Bir:Crel    0.176256   0.341174   0.517 0.605426    
SpD_Ash:Crel    0.474645   0.377735   1.257 0.208924    
SpE_Pop:Crel    0.016280   0.665981   0.024 0.980498    
SpF_Map:Crel   -1.515988   0.577600  -2.625 0.008678 ** 
SpG_Hor:Crel    0.967172   0.654945   1.477 0.139759    
SpH_Ald:Crel   -1.307988   0.707902  -1.848 0.064655 .  
SpI_Rok:Crel   -0.768953   0.829989  -0.926 0.354213    
SpJ_Hwt:Crel   -0.299282   0.577301  -0.518 0.604172    
SpK_Hwx:Crel    0.932834   0.504243   1.850 0.064326 .  
SpL_Spr:Crel   -4.562646   0.377393 -12.090  < 2e-16 ***
SpM_Dou:Crel   -3.902406   0.486518  -8.021 1.08e-15 ***
SpN_Spi:Crel   -3.344765   0.650521  -5.142 2.74e-07 ***
SpO_Lar:Crel   -4.815391   0.739664  -6.510 7.61e-11 ***
SpP_Bpi:Crel   -3.837060   0.708873  -5.413 6.24e-08 ***
SpQ_Swx:Crel   -4.016483   0.841394  -4.774 1.82e-06 ***
Crel:OwnerPR   -0.615048   0.135016  -4.555 5.25e-06 ***
DivRES:Gha     -0.013837   0.003148  -4.396 1.11e-05 ***
DivRES:CV      -9.083870   0.766857 -11.846  < 2e-16 ***
Crel:CV         1.955457   0.420020   4.656 3.24e-06 ***
Crel:DivRES:CV  8.842787   0.977732   9.044  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for quasibinomial family taken to be 0.1625331)

Number of Fisher Scoring iterations: 7
```

3.3. Recruitment model

```
glm(formula = Event/Trial ~ RFOR * Gha + Cg + Cg2 + CV, family = quasibinom
ial, data = DataRecrut, na.action = na.omit)

Deviance Residuals: 
     Min        1Q    Median        3Q       Max  
-0.66415  -0.17955  -0.11898  -0.04852   1.58396  

Coefficients:
              Estimate Std. Error t value Pr(>|t|)    
(Intercept) -6.139e-01  2.526e-01  -2.430 0.015138 *  
RFORCon     -1.648e+00  3.178e-01  -5.186 2.29e-07 ***
RFORFam     -1.462e+00  3.846e-01  -3.802 0.000146 ***
RFORJur     -9.376e-01  3.538e-01  -2.650 0.008092 ** 
RFORLim     -1.128e+00  3.865e-01  -2.918 0.003546 ** 
Gha         -1.166e-01  8.062e-03 -14.461  < 2e-16 ***
Cg          -2.509e-02  3.954e-03  -6.345 2.55e-10 ***
Cg2          1.074e-04  1.664e-05   6.451 1.28e-10 ***
CV           9.239e-01  2.074e-01   4.454 8.72e-06 ***
RFORCon:Gha  6.552e-02  1.532e-02   4.276 1.96e-05 ***
RFORFam:Gha  4.718e-02  1.982e-02   2.380 0.017376 *  
RFORJur:Gha  5.370e-02  1.869e-02   2.874 0.004086 ** 
RFORLim:Gha  4.495e-02  1.903e-02   2.362 0.018261 *  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 

(Dispersion parameter for quasibinomial family taken to be 0.1216247)

    Null deviance: 232.03  on 3144  degrees of freedom
Residual deviance: 175.31  on 3132  degrees of freedom
AIC: NA

Number of Fisher Scoring iterations: 8
```

3.4. Clearcut model

```
glm(formula = Bin_CR ~ Owner + CdomxPop2 + CdomxSpr2 + CdomxSW2, 
    family = binomial, data = DataClearcut, na.action = na.omit)

Deviance Residuals: 
    Min       1Q   Median       3Q      Max  
-0.5833  -0.1500  -0.0904  -0.0548   3.6066  

Coefficients:
             Estimate Std. Error z value Pr(>|z|)    
(Intercept) -6.502260   0.114272 -56.902  < 2e-16 ***
OwnerPR      1.004733   0.088539  11.348  < 2e-16 ***
CdomxPop2    0.015712   0.001459  10.771  < 2e-16 ***
CdomxSpr2    0.009450   0.001214   7.783 7.09e-15 ***
CdomxSW2     0.009654   0.001334   7.238 4.56e-13 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 6772.0  on 61211  degrees of freedom
Residual deviance: 5937.5  on 61207  degrees of freedom
AIC: 5947.5

Number of Fisher Scoring iterations: 8
```