Chapter 13
France

Antoine Colin, Holger Wernsdörfer, Alain Thivolle-Cazat, and Jean-Daniel Bontemps

Projections of wood resources have been needed for decades by both public authorities and public and private stakeholders. Projections are requested to formulate and assess forest policy and management strategies for the coming years to decades at regional, national, and international scales. The French NFI provides information for describing the forest resources and their spatio-temporal dynamics. These data contribute to initializing two large-scale dynamic models for forest resource projection that have been developed in France and implemented since the 1980s. The decision to use diameter-class or the age-class matrix models depends on the type of forest to be simulated. Both approaches provide robust projections from short to medium time scales and at spatial scales ranging from regional to national.

Recent projections carried out with these models have highlighted the potential for French forests to remain an important carbon sink until 2030, while fellings can be increased by two-thirds. This matrix-model approach is associated with interdisciplinary

A. Colin (✉)
IGN, Direction Interrégionale Nord-Est, Champigneulles, France
e-mail: antoine.colin@ign.fr

H. Wernsdörfer
UMR LERFOB, AgroParisTech, INRA, Nancy, France
e-mail: holger.wernsdorfer@agroparistech.fr

A. Thivolle-Cazat
Institut Technologique FCBA, Grenoble, France
e-mail: alain.thivollecazat@fcba.fr

J.-D. Bontemps
UMR LERFOB, AgroParisTech, INRA, Nancy, France

IGN, Laboratoire de l'Inventaire Forestier (LIF), Nancy, France
e-mail: jdbontemps.ign@gmail.com

© Springer International Publishing AG 2017
S. Barreiro et al. (eds.), *Forest Inventory-based Projection Systems for Wood and Biomass Availability*, Managing Forest Ecosystems 29,
DOI 10.1007/978-3-319-56201-8_13

research programs that aim at developing environment-dependent representations of forest dynamic processes such as growth, density-dependent mortality and forest regeneration, and also coupling of forest dynamics with forest sector models. Model validation is also essential, highlighting the major importance of current continuous forest inventory, and making forest inventory data comparable over time following changes in mensuration protocols.

13.1 Introduction

French forests are characterised by a high diversity in various aspects that must be considered when developing models for projecting wood resources and potential wood supply. We first provide this necessary background information and then present objectives, data and projection methods, and perspectives for further model development.

13.1.1 Key Figures on Forests and Forestry in France

Forests cover 16.8 million ha of the French metropolitan territory (30.8% of the area) and 8.2 million ha in oversea territories, mainly in French Guiana. Temperate and Mediterranean forests of the metropolitan territory thus represent two-thirds of the total national forested area. Intensive and systematic forest monitoring via the National Forest Inventory (NFI) has been carried out over the metropolitan territory since the late 1950s, enabling continuous analysis of forest features and wood resources. NFI-like monitoring is not conducted in the French tropical forests.

French metropolitan forests have developed in a variety of climates. Oceanic and sub-oceanic climates in western and north-central France favour the development of sessile (*Quercus petraea*) and pedunculate (*Quercus robur*) oaks. Maritime pine (*Pinus pinaster*) grows especially in the oceanic climate of the south-west. Semi-continental climate in the north-eastern and mountainous areas (Alps, Jura, Pyrenees, Massif Central and Vosges) are suitable for European beech (*Fagus sylvatica*), Norway spruce (*Picea abies*), silver fir (*Abies alba*), Scots pine (*Pinus sylvestris*) and European larch (*Larix decidua*). In the southern Mediterranean range, evergreen oak (*Quercus ilex*), Aleppo (*Pinus halepensis*) and Corsican (*Pinus nigra ssp laricio var Corsicana*) pines grow. As a consequence, French forests encompass all but the "boreal forests" type (13 types) according to the *European Forest Types* classification (EFT, Barbati et al. 2014), and rank first in Europe for the number of forest types covered. In addition, 18 tree species are found predominant over >200,000 ha (IFN 2010). Many other species are found in various locations, such as pubescent oak (*Quercus pubescens*), chestnut (*Castanea sativa*), hornbeam (C*arpinus betulus*), Douglas fir (*Pseudotsuga menziesii*), ashes (*Fraxinus spp.*), aspen (*Populus spp.*), etc. Mixed species forests hence form one half of the national resource, both in terms of forest area and growing stock (Morneau et al. 2008).

Stand structure also shows great variations, including pure even-aged high forests of broadleaved and coniferous species mainly in the northern plains and in the Aquitaine region, uneven-aged mixed species forests in the mountainous domain, and coppices and coppices with standards in the plains.

The heterogeneity in species and structure of French forests originates from ecological factors. Coniferous species are mainly located in the mountainous domain, broadleaved species are found in the plains, and Mediterranean species are located in southern France. It also results from historical socio-economic factors. In the plains, forests are dominated by broadleaved species, with sessile and pedunculate oak species ranking first for the growing stock (566 million m^3 representing 23% of the total national growing stock, IFN 2010). These species have been favoured since medieval and even Roman times, because of their ability to re-sprout from stumps after cutting. In the eighteenth and nineteenth century oak coppices with standards stands were managed to produce roundwood and fuelwood for domestic and industrial purposes. Later, following the introduction of coal and the need to produce timber, many of these forest types were either naturally or actively progressively converted into high forests, with high forests on stumps as a first structural step (IGN 2013).

Conifer plantations were promoted in the nineteenth century to drain the wetlands of Gascogne and Sologne and to protect fragile soils for purposes such as preventing erosion in the Alpine range or fixing dunes on the coast range. The National Forest Fund (Fonds Forestier National: FFN) policy framework was launched in 1947. It contributed to the development of a new conifer forest resource over marginal agricultural lands, and was instrumental in securing the wood supply for the country's industries (Gadant 1987). The FFN is estimated to have contributed 75% of the increase in coniferous forest plantation area, i.e. 1.5 million ha of new forests with Norway spruce (*Picea abies*), Douglas fir (*Pseudotsuga menziesii*), pines (*Pinus sylvestris*, *Pinus nigra*) and European larch (*Larix decidua*) as the main afforestation species (Pardé 1966; Dodane 2012).

The area of forests available for wood supply is 15.7 million ha in 2013, of which 11.8 million ha (74.8%) are private forests, 1.4 million ha (9%) are state-owned forests and 2.5 million ha (16.2%) are other public forests including forests owned by territorial communities and public authorities (IGN 2014a). Over the past decades, the decline of agricultural activity in low productive areas has led to further natural afforestation by pioneer species which may, however, neither correspond to demand on the wood market nor be situated in easily harvestable locations (IGN 2012). As a result of both afforestation and natural colonization, the French Forest area has more than doubled since 1788 (Brénac 1984). This reflects the typical pattern of 'forest transition' (Mather 1992) that has been experienced by most developed European countries following the industrial revolution and urbanization processes.

Concern for nature and biodiversity conservation has produced legal constraints (e.g. Natura 2000 network) that partially exclude some French forest areas from traditional forest management and harvest schemes. The impact on wood supply can be locally significant. In the Vosges Mountains and on the Lorraine plateau, 4% of the total forest area is not available for wood supply, and 8% of the forests available for wood supply are subject to management for species conservation (Colin and Lambert 2012; Thivolle-Cazat et al. 2012). Physical constraints also significantly hamper forest management in France, and cause a decrease in the profitability of harvest operations. One-third of the forest area available for wood supply is estimated to be very difficult to access, and 1 million ha of the forested area has a forwarding distance greater than 1 km, mainly in south-eastern France (IFN 2010).

Total annual fellings amount to 64 million m^3 of total aboveground volume over bark (IFN 2011c). Industrial roundwood removals (sawlogs, pulpwood, etc.) represent about 36 million m^3 over bark per year (Agreste 2011) and fuelwood about 20 million m^3 over bark per year (FAO 2011), while the remaining part corresponds to harvest residues. Total removals have increased slowly over the last 20 years and result from both an increase of removals from coniferous stands afforested between 1950 and 1980 (FFN) and a regular decrease in hardwood removals. Forest chip removals for energy have increased rapidly in recent years; the removed volumes have doubled every year since 2006, and reached 1.8 million m^3 in 2013 (round wood equivalent).

For several decades, French forests have experienced an increasing gap between total drain and increment. Hence, growing stock, assessed as bole volume up to a top-end diameter of 7 cm, has increased by about 25 million m^3 per year over a 26-year period. This increase represents an additional 650 million m^3 (IFN 2011b) for a total of 2.52 billion m^3. There is no sign of a future shift in this structural trend. Recent and severe damages caused by storms *Lothar* and *Martin* in 1999 (140 million m^3 of damage, Doll 2000 and IFN 2003) and *Klaus* in 2009 (43 million m^3 of damage, IFN 2009) represent anecdotal drains compared to the trend in growing stock on a national scale. The current expansion of the French forest area will further contribute to an increase in the growing stock in future decades. Thus, the French forest is far from a stationary state of development.

13.1.2 Motives and Objectives for Projection

The needs for projections on forest resources arise from two categories of stakeholders:

- **Public authorities,** at both national and regional levels, require projections to formulate and assess public policies, for strategic guidance and planning of the industrial roundwood and fuelwood sectors, and to report the contribution of forests to carbon sequestration as required by international policy processes on Green House Gases (GHG) emissions reduction.
- **Public or private stakeholders of the forest-wood sector**, including the French Forest Service (Office National des Forêts, ONF) that manages the public forests, saw and veneer-mills, pulp and paper, panel and fuelwood companies, and professional organisations (e.g. associations of wood producers and processers, interbranch organisations) require estimates for the wood availability and quality of a given species in a given area to formulate or support their economic strategies.

Inventory, assessment, analysis and projection of the forest resource, including wood volume, biomass or carbon, form the missions of the French NFI which is carried out by the French National Institute for Geographic and Forest Information (Institut national de l'information géographique et forestière: IGN). The French NFI consists of a repeated and spatially-systematic inventory of metropolitan forests with the objective of providing statistics at the regional and national levels (Vidal et al. 2005). It is thus well-suited for contributing to decision making and policy formulation at these scales. By contrast, it is not suitable for supporting forest management at a local scale.

Illustrations of recent wood resource projection studies based on NFI data follow:

- 2009, national level: potential wood availability for industrial and energy uses (study funded by the national renewable energy agency and the ministry of agriculture, Colin et al. 2009; Ginisty et al. 2011);
- 2010, intra-regional level: impact of the 2009 storm on the wood resource of the Landes de Gascogne maritime pine forest (study funded by the ministry of agriculture, Colin et al. 2010).
- 2012, regional level: potential wood availability in Lorraine and Aquitaine until 2025 (studies co-funded by regional and infra-regional public bodies, as well as professional organizations for pulp, paper and fuelwood, Colin and Lambert 2012; Thivolle-Cazat et al. 2012; Colin et al. 2012).
- 2014, national level: GHG emissions of the French forest until 2030 in the context of the development of renewable energies (study funded by the ministry of environment, Colin 2014).

13.2 Data Sources

13.2.1 NFI Data Used for Wood Resource Projections

Each year, the French NFI inventories the entire metropolitan forested area. The NFI is carried out in public and private forests, regardless of whether they are available for wood supply. Since 2004, the NFI design has featured a systematic sampling grid with a 10% systematic sample of the grid measured each year. Each year sampling is conducted in two phases. In the first phase, approximately 80,000 photo plots are interpreted to assess land cover and land use. In the second phase, approximately 7000 temporary ground plots are established at a subsample of first phase photo plot locations that have forest land use. All living trees on the sample plots are cored at 1.30 m height to measure radial increment over the past 5 years. Trees with diameters less than 7.5 cm are not measured. NFI statistics are calculated using a post-stratification process using the French forest map (IFN 2008) and aerial photo-interpretation of land cover/land use for the 80,000 photo plots for a given year. Typically five annual NFI samples are combined to calculate statistics for the forest resource.

NFI data used for projections include:

- Contextual data: a biophysical classification of the forest area into "sylvo-eco-regions" (IFN 2011a), administrative regions, forest land ownership, availability of forests for wood supply, topographic position, elevation, physical accessibility, soil characteristics, etc.;
- Plot level data: species composition and forest structure, stand age, number of stems, top height and site index (Seynave et al. 2005), etc.;
- Tree level data: tree species, circumference at 1.30 m height, height, wood quality classes, radial increment, bark thickness, growing stock, mortality, fellings, etc.

13.2.2 Additional Data for Spatial Contextualization of the Forest Resource

When projecting wood resources, the territory is usually divided into strata, often derived from GIS information. Both the wood resource and silvicultural scenarios are described at this level. In such studies, potential wood availability estimates and actual fellings often show a gap, due to repeatedly acknowledged physical, socio-economic, and environmental constraints (Puech 2009). Physical restrictions such as slope, presence of forwarding tracks and forwarding distance, prevail in mountain areas. Socio-economic restrictions result from the private ownership structure in France with a majority of small forest estates (Agreste 2013). Environmental restrictions arise from conservation and protection measures (soils, freshwater springs, etc.).

The initial state of the wood resource and projection scenarios can be refined using external GIS information to identify forest types with specific management features. For example, maps of large private forests with forest management plans allow identification of areas with more intensive management opportunities. Legal restrictions for environmental protection also have an impact on harvest costs or management regimes, and the areas where silviculture is legally not permitted (e.g. biological reserves with strong protective rules) are sometimes excluded from wood projections. Specific forest management practices are also implemented in areas with harvesting limitations for fauna/flora conservation. For example in the Vosges Mountains, silvicultural practices for the conservation of the Western Capercaillie (*Tetrao urogallus major*) habitat are encouraged (MEDDE 2012).

13.2.3 Newer NFI Data to Quantify Felling Regimes

Since 2010, the French NFI has provided direct measurements of fellings based on a partial re-inventory of temporary plots inventoried 5 years earlier. These estimates are much more accurate than previous estimates based on consumption surveys or stump inventories (IFN 2003). Productivity, mortality and felling statistics are now fully consistent with variations in the growing stock (IFN 2011c). These new data can contribute to the calibration of silvicultural and mortality scenarios used for projections, and especially the Business-As-Usual (BAU) scenario (Colin 2014). The silvicultural scenario derived from these measurements is relevant for BAU projections, because it takes into account implicitly all the current management and harvest opportunities and constraints (physical, economic, environmental and social).

These new data can also contribute to virtually doubling the number of NFI sample plots available for estimating the forest resource for a given year, because they can be used to update the wood resource of the forest plots inventoried 5 years ago. This practice leads to more precise NFI estimates, which finally allows more spatially accurate NFI results or more detailed results for a given spatial domain (Colin et al. 2012).

13.2.4 Data on Wood Assortments of Standing Trees and Removals

The French NFI identifies three classes of roundwood quality for each standing tree, according to potential uses such as veneer, sawn timber, pulpwood and fuelwood. In addition, market fluctuations and changes in transformation practices lead to implementation of a complementary expert-driven approach, based on analysis of data such as historical removals data.

Removal assortments are estimated from two surveys for which representativeness and statistical accuracy/bias are not assessed: (1) Since 1948, the national annual survey on commercialized wood removals (Agreste 2011) has provided harvested volumes over bark by species and assortment, at administrative-department level; and (2) the national survey on energy consumption by households (CEREN 2008) provides a raw estimate for fuelwood volume at regional level. The survey is carried out every 5 years. Finally, estimates of historical removals can be compared to wood availability estimates.

13.2.5 NFI Data on Extreme Climatic Disasters

The flexibility granted by the NFI design makes it possible to quickly update the state of forest resources for purposes including estimation of the extent of damages caused by severe windstorms such as *Klaus* in 2009 (IFN 2009). Every NFI plot was remeasured just after the storm to evaluate both volume of windthrows and remaining standing volumes. Regularly updated initial states of forest resources can hence be made available for wood projection studies as was done in Aquitaine (Colin et al. 2012).

13.2.6 Auxiliary Data on Technical/Economic Factors of Production

With respect to wood availability assessment and scenario simulation, independent economic data and specific expertise can also be used. Some examples are: harvesting system costs as a function of accessibility, cut types and stand characteristics, stumpage prices as a function of species and stand characteristics, and roadside wood prices as a function of species and assortments.

13.3 Tools and Simulators

13.3.1 Main Purposes and Specification of Projections

Five main forest policy issues are raised at national and regional levels: (1) the match between wood supply and demand by industries, (2) the opportunity for the development of new energy-wood industries, (3) the trends in the national timber sector, (4) the contribution of the French forest sector to GHG emissions reduction, and (5) as a matter of increasing concern, the impact of climate change on future forest patterns under different economic and climate scenarios.

Fundamental target variables for estimation include future quantity and quality of growing stock, the availability of wood for different uses, and projections of forest carbon stocks and fluxes.

The typical temporal horizon for forest resource projections ranges between 10 and 30 years with a usual simulation time-step of 5 years. Three spatial scales are typical: (1) a given tree species in a given regional domain, (2) all the broadleaved/coniferous species in a given regional domain, and (3) a comprehensive approach including the entire forest resource of a regional or national territory.

13.3.2 Types of Models and Their Implementation

In France, specific growth models are not available for many tree species (Pérot and Ginisty 2004), and when these models do exist (typically stand-scale models such as for abundant species including sessile oak, beech or maritime pine), they are usually not appropriate for large-scale projections due to French forest diversity in forest types and ecological conditions, and their non-stationary state. This context has fostered the development of large-scale forest resource models and simulators, as well as a specific expertise based on forest inventory data (Pignard 1993; Buongiorno et al. 1995; Houllier 1995; Wernsdörfer et al. 2012). The description of the current state of forest resources (area, growing stock, etc. distributed by tree species etc.)

and estimation of model parameters associated with forest dynamic processes (growth increment, natural mortality and recruitment) are based on NFI data.

Two types of large-scale forest dynamics models are currently used in France for forest resource projections: an age-class based approach for forests where stand age can be assessed, and a diameter-class approach for forests where this is not the case, or not meaningful. Both are currently developed at IGN in close association with the French NFI program, and both are used to address public and private needs (Sect. 13.1.2). The diameter-class approach is also associated with research programs (Wernsdörfer et al. 2012).

Diameter and age-class models are used in projection studies depending on the types of forests to be simulated. The age-class model applies to even-aged forests only (e.g. mono-species conifer plantations, poplar plantation, oak or beech high forests, managed coppices) while the diameter-class model can be used regardless of whether the stand is even-aged or uneven-aged, pure or mixed. Both models are implemented in specific simulation tools after being calibrated and initialised interactively on data extracted from the NFI database. They are run by an expert user.

13.4 Model Description

13.4.1 Forest Stratification

Forests are usually partitioned into homogenous subsets or 'strata' (Wernsdörfer et al. 2012), and projections are independently performed for each stratum. Stratification factors usually include geographic region or a categorization of the study area (biophysical classifications based on soil and climate such as the 'sylvo-eco-regions', IFN 2011a) with a view to encompass variations in growth conditions. Tree species composition is another mandatory stratification factor (e.g. single species, broadleaf-dominated, conifer-dominated and broadleaf-conifer mixed stands). Forest ownership category may be used as a stratification factor because management practices often differ between public and private forests and potentially lead to quite different stand characteristics for the different categories. Stand structure (high forest, coppice forest and high-forest with coppice) can also be used as a stratification factor when the available information is sufficiently accurate. Many other environmental factors can also be taken into account, depending on the context of the study. The number of strata is subject to statistical constraints including a minimum number of NFI plots per stratum to ensure an acceptable sampling error for within-stratum estimates of forest attributes.

13.4.2 Consideration for Environmental and Silvicultural Factors

In both the age-class and the diameter-class models, forest dynamics are not currently explicitly linked to environmental conditions such as site fertility. Spatial variations in growth conditions are implicitly accommodated in strata-specific estimates of model parameters. In addition, the models do not consider the impacts of climate and environmental changes. Last, density-dependence of forest dynamic processes is also implicit in forest stratification which may be sensitive to non-stationary contexts. This becomes very important when alternative silvicultural scenarios differing from the BAU scenario (Sect. 13.2.3) are simulated. For these reasons, the projection length should be limited to about 30 years.

13.4.3 Diameter-Class Model

13.4.3.1 Aim of Model Development

The tree diameter-class model was originally developed to assess future growing stock and wood availability for the medium-term (up to 30 years) within heterogeneous forested areas, i.e., uneven-aged and/or mixed-species stands. The model is also relevant for pure even-aged stands so that, unlike the age-class model, it allows for comprehensive projections for an entire territory (region, country) with various stand types. This model is particularly well-adapted to project forest resources in contexts of valuation of new afforested areas which are rarely even-aged, or where the forests are often heterogeneous such as in mountainous and Mediterranean regions. The diameter-class model is called MARGOT (MAtrix model of forest Resource Growth and dynamics On the Territory scale) and is described in Wernsdörfer et al. (2012). The next model development steps will be to incorporate competition and site as factors affecting forest dynamics.

13.4.3.2 Modelling Approach

Forest dynamics over time are described by within-stratum tree-diameter distribution and are governed by a Markov transition matrix with constant recruitment. The lower limit of the first diameter class is usually equal to the minimum diameter threshold (7.5 cm) of the French NFI. Three stratum-specific groups of parameters are defined: (1) the proportion of trees within a given diameter class that move up to the next larger diameter class (growth parameter), (2) the proportion of trees within a given diameter class that are removed through felling and natural mortality (felling and mortality parameters), and (3) the number of new trees that grow into the lowest diameter class (recruitment parameter) over a time-step. Further output variables such as merchantable tree volume, biomass or carbon content can be provided by multiplying the number of trees in each diameter class by the respective output variable value estimated for the tree of mean size (i.e. mean merchantable tree volume, biomass or carbon content, respectively).

13.4.3.3 Assumptions

The current model relies on four assumptions: (1) diameter distributions within different strata change over time independently of each other; (2) forest area, site and competition conditions are constant over time within each stratum; (3) the state of a tree at the end of one time-step depends only on its state at the beginning of that time-step (Markov hypothesis); and (4) no tree can move up more than one diameter class during a time-step, or regress towards a lower diameter class (Usher hypothesis, Vanclay 1994). Some of these assumptions such as constancy of site and competition will be relaxed in the near future.

13.4.4 Age-Class Model

13.4.4.1 Aim of Model Development

The stand age-class model applies to even-aged forests, mostly single-species conifer and poplar plantations, high forests of broadleaved species in the plains regions, and managed coppices where intensive management practices are usually implemented. In such homogeneous stands, age is an efficient proxy to estimate growth and to apply forest management practices. The model was described for the first time by Alvarez-Marty (1989).

13.4.4.2 Modelling Approach

Forest dynamics over time are described by a within-stratum age distribution of the forested area. Each stand cohort is represented by an age class and its associated area, growing stock per hectare, and volume production per hectare. The model simulates the lifespan of each cohort, from its birth (i.e., natural seedlings or plantation) to its death (i.e., clear cut of the last area). The growing stock per hectare of each cohort is recalculated at the end of each time-step of the simulation by subtracting the total volume of thinnings over the period from the initial growing stock per hectare. The mean production per hectare of the age class is finally added to this new growing stock. The area of a given cohort remains the same during the simulation, until it reaches the final cut age. From there, it is progressively reduced over time until zero, thus representing the variety in forest management practices within the stratum, and also the variety in site conditions. Silvicultural operations are defined by two parameters: for age classes up to the final cut age, a thinning rate is applied as a percentage of the growing stock per hectare; for age classes corresponding to the final cut age and beyond, a clear-cut rate is applied as a percentage of the surface area of the age-class. Importantly, reforestation and afforestation within a given stratum are represented by a net influx of new areas in the first age-class.

13.4.4.3 Assumptions

The model relies on two assumptions: (1) the site and density conditions are constant over time within each age class; and (2) the state of a cohort at the end of one time-step depends only on its state at the beginning of that time-step and not on any previous state. Contrary to the previous approach, the total forest area under study is not fixed and afforestation and land-use issues can be addressed.

13.4.5 Model Evaluation

Both the diameter-class and the age-class models provide projections that are consistent with historical trends observed in NFI data. A first sensitivity analysis based on NFI data for the years 2006–2008 was carried out by Wernsdörfer et al. (2012) for the diameter-class model. It focused on the sensitivity of forest dynamics to various stratification factors, showing that both varying growth conditions represented by nine large forest regions, tree-species composition (broadleaf-dominated, conifer-dominated and broadleaf-conifer mixed stands) and stand structure (high forest, coppice forest and high-coppice forest mixture) clearly affect forest dynamics at the larger-scale. Additional analyses on model evaluation are part of the future work envisaged in the frame of further model development.

13.5 Conclusions and Perspectives

Both large-scale age-class and diameter-class forest dynamics models are used for projecting wood resources in France, and they primarily target forest structures associated with specific silvicultural systems. While age-class models are of immediate advantage for simulation of forest areas of homogeneous stands and mapping their age-structure, diameter-class models encompass forest heterogeneity. However, the use of age as a proxy for developmental stage is questioned, because any historical factor may be confounded in this temporal proxy, including forest management practices, and environmental changes that affect soil fertility over time and create a shift in age-size relationships (Bontemps et al. 2009).

Diameter-class models also directly facilitate volume and biomass prediction using volume and biomass models. Quantification of available roundwood for different uses such as fuelwood, pulpwood and timber still requires further refinement.

Recent developments include total aboveground volume models for the main tree species in France (Vallet et al. 2006; Loustau 2010). A new generation of adaptive volume and biomass models has also been developed in the recently completed research project *Emerge*, funded by the French Research Agency (e.g. Genet et al. 2011; Dassot et al. 2012; Longuetaud et al. 2013).

Accurate projections of wood resources over time require that BAU felling regimes and initial state conditions are correctly quantified. In the past, this was difficult due to only approximate estimates of felled tree volumes resulting from the temporary-plot approach, and the occurrence of major disturbances caused by severe windstorms (e.g. *Lothar* and *Martin* in 1999). The forest inventory design implemented since 2004 (Hervé et al. 2014) is a source of major improvements: (1) plots in forest areas affected by severe storms can be quickly remeasured (e.g. in 2009), and (2) felling levels can be accurately estimated by remeasuring plots that were measured 5 years ago (IFN 2011c). Responsiveness in forest resource projections after major disturbances highlights the major role of a continuous and flexible inventory design.

Newer information sources such as aerial images and laser data should also be combined with NFI data in the near future. Multi-source inventory using maps of forest attributes as auxiliary information can improve the precision of forest resource estimates, and finally of wood availability and forest resource projections.

There is increasing demand to account for changes in the socio-economic environment in forest resource projection studies, for instance, to include a cost-approach to account for the feasibility of harvesting operations. This suggests an approach whereby forest characterisation with respect to physical and socio-economic factors is included as an input to such simulations. Additional GIS data sources may contribute to better assessments of the socio-economic context, e.g. the cadastral (ownership) data may be used to stratify projections according to ownership structure (IGN 2014b), and maps of harvest costs based on physical conditions may help to better identify the economic constraints (Clouet et al. 2010).

All models implicitly take growth conditions into account by varying growth estimates according to geographic domain or strata. In the face of ongoing environmental change impact onto forest growth as assessed from the French NFI (Charru et al. 2014), including climatic change, a future challenge will be to include environmental forcing into forest dynamics models using impact models of growth, mortality, and regeneration. Explicit approaches should rely on the environmental monitoring conducted on NFI plots (e.g. soil pH prediction using plant bioindication, Gégout et al. 2003, or mapping of soil water capacity, Piedallu et al. 2011), highlighting the interplay between forest inventory and environmental monitoring (FAO 2011).

Projections of wood resources are often conducted on a medium-term scale (about 20–30 years), either for regional strategic planning, or for national carbon accounting. In the context of global change, demand is increasing to perform simulations over the longer-term, e.g. 2050 up to 2100. Such applications should, however, not be encouraged as long as slow-developing processes such as changes in the forested area, in the growing stock, in tree species composition and site conditions are not covered at a minimum. Incorporating forest area dynamics into the diameter-class model approach is therefore needed. This also points to the importance of making forest inventory data comparable over time following changes in mensuration protocols.

References

Agreste (2011) La récolte de bois et la production de sciages en 2009. Un tiers des chablis de la tempête Klaus récoltés dès 2009. Agreste Primeur. Numéro 254. janvier 2011

Agreste (2013) Structure de la forêt privée en 2012. Des objectifs de production pour un tiers des propriétaires. Agreste Primeur. Numéro 306. Décembre 2013

Alvarez-Marty S (1989) La méthode des générations dans l'étude de la ressource d'une forêt équienne : le cas du massif landais. AFOCEL-ARMEF 3:135–146

Barbati A, Marchetti M, Chirici G, Corona P (2014) European forest types and Forest Europe SFM indicators: tools for monitoring progress on forest biodiversity conservation. For Ecol Manag 321:145–157

Bontemps J-D, Hervé J-C, Dhôte J-F (2009) Long-term changes in forest productivity: a consistent assessment in even-aged stands. For Sci 55:549–564

Brénac L (1984) Connaissance statistique des forêts françaises avant 1984. Revue Forestière Française 36:77–90

Buongiorno J, Peyron J-L, Houllier F, Bruciamacchie M (1995) Growth and management of mixed-species, uneven-aged forests in the French Jura: implications for economic returns and tree diversity. For Sci 41:397–429

CEREN (2008) Bilan national du bois de chauffage en 2006. CEREN

Charru M, Seynave I, Hervé J-C, Bontemps J-D (2014) Spatial patterns of historical growth changes in Norway spruce across western European mountains and the key effect of climate warming. Trees 28:205–221

Clouet N, Berger F, Monnet JM, Descroix L (2010) CARTUVI: un modèle sous SIG pour la cartographie des surfaces débardables en zone de montagne. Revue Forestière Française 62(2):155–170

Colin A (2014) Emissions et absorptions de gaz à effet de serre liées au secteur forestier dans le contexte d'un accroissement possible de la récolte aux horizons 2020 et 2030. Contribution de l'IGN aux projections du puits de CO2 dans la biomasse des forêts gérées de France métropolitaine en 2020 et 2030, selon différents scénarios d'offre de bois. Rapport final, mars 2014. Convention MEDDE.DGEC / IGN n°2200682886 (IGN n°10998)

Colin A, Lambert P (2012) Analyse de la ressource forestière actuelle en Lorraine. Résultats statistiques et représentations cartographiques. Rapport final de convention. Tome 2. Contrat IGN/DRAAF Lorraine n°ETU-2011-11

Colin A, Thivolle-Cazat A, Coulon F et al (2009) Biomasse forestière, populicole et bocagère disponible pour l'énergie à l'horizon 2020. Rapport final de convention. Contrat IFN/ADEME n°0601C0134, avec FCBA et SOLAGRO, 105 p. http://www.dispo-boisenergie.fr

Colin A, Meredieu C, Labbé T, Bélouard T (2010) Etude rétrospective et mise à jour de la ressource en pin maritime du massif des Landes de Gascogne après la tempête Klaus du 24 janvier 2009. Rapport final de la convention IFN/MAAP n°E18/2010 du 21 juin 2010. Décembre 2010

Colin A, Drouineau S, Cavaignac S et al (2012) Analyse prospective de la ressource forestière et des disponibilités en bois de la région Aquitaine à l'horizon 2025. Etat des lieux des forêts aquitaines à l'automne 2011. Version 1.0 du 31 juillet 2012. Rapport de conventions

Dassot M, Colin A, Santenoise P et al (2012) Terrestrial laser scanning for measuring the solid wood volume, including branches, of adult standing trees in the forest environment. Comput Electron Agr 89:86–93

Dodane C (2012) Quelle est la part du FFN dans la transformation du visage des forêts françaises au cours de la seconde moitié du XXe siècle ? Geoconfluences, 4 octobre 2010. http://geoconfluences.ens-lyon.fr/doc/territ/FranceMut/popup/Dodane3.htm

Doll D (2000) Statistiques historiques des grands chablis éoliens en Europe occidentale depuis le milieu du XIXe siècle: analyse critique. Dossiers de l'Environnement de l'INRA 20: 28–42. http://www7.inra.fr/dpenv/pdf/DollD20.pdf

FAO (2011) State of the world's forests 2011. Food and Agricultural Organisation. ISBN:978-92-5-1067550-5

Gadant J (1987) Quarante ans au service de la forêt française. Revue Forestière Française 39:10–19

Gégout JC, Hervé JC, Houllier F, Pierrat JC (2003) Prediction of forest soil nutrient status using vegetation. J Veg Sci 14:55–62
Genet A, Wernsdörfer H, Jonard M et al (2011) Ontogeny partly explains the apparent heterogeneity of published biomass equations for Fagus sylvatica in central Europe. For Ecol Manag 261(7):1188–1202
Ginisty C, Vallet P, Chevalier H, Colin A (2011) Disponibilité en biomasse ligneuse en forêt, dans les peupleraies et dans les haies pour les différents usages du bois. Evaluation à l'échelle métropolitaine à partir des données de l'Inventaire forestier national et des statistiques de consommation de bois. Revue Forestière Française LXIII-2-2011:151–162
Hervé JC, Wurpillot S, Vidal C, Roman-Amat B (2014) L'inventaire des ressources forestières en France: un nouveau regard sur de nouvelles forêts. Revue Forestière Française XLVI-3-2014:247–260
Houllier F (1995) A propos des modèles de la dynamique des peuplements hétérogènes: structures, processus démographiques et mécanismes de régulation. Revue Ecologie (Terre Vie) 50:273–282
IFN (2003) Les tempêtes de décembre 1999. Bilan national et enseignements. L'IF n°2 décembre 2003. Editeur IFN
IFN (2008) Nouvelle cartographie forestière. De la production à l'utilisation. L'IF n°20. 3[ième] trimestre 2008. Editeur IFN
IFN (2009) Tempête Klaus du 24 janvier 2009: 234 000 ha de forêts affectées à plus de 40%. 42,5 millions de mètres cubes de dégâts. L'IF n°21 – 1[er] trimestre 2009. Editeur IFN
IFN (2010) La forêt française. Résultats des campagnes 2005 à 2009. Nogent-sur-Vernisson, France
IFN (2011a) Un nouveau cadre de référence géographique pour les forestiers français : les sylvoécorégions (SER)
IFN (2011b) Volume de bois sur pied dans les forêts françaises : 650 millions de mètres cubes supplémentaires en un quart de siècle. L'IF n°27 – 2[ième] trimestre 2011. Editeur IFN
IFN (2011c) Prélèvements de bois en forêt et production biologique: des estimations directes et compatibles. L'IF n°28 – 3[ième] et 4[ième] trimestres 2011. Editeur IFN
IGN (2012) Quelles sont les ressources exploitables ? Analyse spatiale et temporelle. L'IF n°30 (numéro double). Décembre 2012. Editeur IGN
IGN (2013) Un siècle d'expansion des forêts françaises. De la statistique Daubrée à l'inventaire forestier de l'IGN. L'IF n°31. Mai 2013. Editeur IGN
IGN (2014a) Résultats d'inventaire forestier. Résultats standard. Les résultats des campagnes d'inventaire 2008–2012. Le palmarès
IGN (2014b) Notice méthodologique pour la détermination d'indicateurs de morcellement de la forêt privée. Version 2.0. IGN Conseil. Rapport pour le CRPF Picardie. Juin 2014. D2SI/SAI/2014.0126
Longuetaud F, Santenoise P, Mothe F et al (2013) Modeling expansion factors for European tree species in France. Forest Ecol Manag 292:111–121
Loustau D (2010) Forests, carbon cycle and climate change. Ouvrage collectif issu du projet CARBOFOR, Editions QUAE, Versailles, collection Update Sciences and Technologies. ISBN:97827592038
Mather AS (1992) The forest transition. Area 24:367–379
MEDDE (2012) Stratégie nationale d'actions en faveur du grand tétras (Tetrao urogallus major) 2012-2021. Ministère de l'Ecologie, du Développement Durable, des Transport et du Logement
Morneau F, Duprez C, Hervé J-C (2008) Les forêts mélangées en France métropolitaine. Caractérisation à partir des résultats de l'Inventaire Forestier National. Revue Forestière Française 60:107–120
Pardé J (1966) Forêts et reboisements à haute productivité en France. Revue Forestière Française 11:718–724
Pérot T, Ginisty C (2004) Bilan et perspectives sur les modèles de croissance, de dynamique forestière, et de qualité du bois. Cemagref, Rapport pour le Ministère de l'Agriculture et de la Pêche, Nogent-sur-Vernisson
Piedallu C, Gégout J-C, Bruand A, Seynave I (2011) Mapping soil water holding capacity over large areas to predict potential production of forest stands. Geoderma 160:355–366

Pignard G (1993) Eléments pour l'élaboration d'un logiciel de simulation de l'évolution des peuplements irréguliers. IFN, Cellule d'Evaluation de la Ressource (CER), Montpellier, document interne

Puech J (2009) Mise ne valeur de la forêt française et développement de la filière bois. Mission confiée à Jean Puech ancien ministre. Rapport remis à Monsieur Nicolas Sarkozy, Président de la République. 6 avril 2009. Paris

Seynave I, Gégout J-C, Hervé J-C et al (2005) Picea abies site index prediction by environmental factors and understorey vegetation: a two-scale approach based on survey databases. Can J For Res 35:1669–1678

Thivolle-Cazat A, Colin A, Lambert P (2012) Analyse de la ressource forestière et évaluation de la disponibilité en bois en Lorraine en 2025. Rapport final de convention. Tome 1. Contrats FCBA/DRAAF Lorraine n°ETU-2011-10 et IGN/DRAAF Lorraine n°ETU-2011-11

Vallet P, Dhôte J-F, Le Moguédec G et al (2006) Development of total aboveground volume equations for seven important forest tree species in France. Forest Ecol Manag 229:98–110

Vanclay JK (1994) Modelling forest growth and yield. Applications to mixed tropical forests. CAB International, Wallingford

Vidal C, Bélouard T, Hervé J-C et al (2005) A new flexible forest inventory in France. In: Proceedings of the 7th annual forest inventory and analysis symposium; 2005 October 3-6; Portland ME, McRoberts RE, Reams GA, Van Deusen PC, McWilliams WH (eds) – General Technical Report WO-77. – Washington, DC: U.S. Department of Agriculture Forest Service, 2007. – 319 p. [Online]: http://fia.fs.fed.us/symposium/proceedings/pubs/FIA2005%5Bhi%5D.pdf

Wernsdörfer H, Colin A, Bontemps J-D et al (2012) Large scale dynamics of a heterogeneous forest resource are driven jointly by geographically varying growth conditions, tree species composition and stand structure. Ann For Sci 69:829–844