Forests **2014**, *5*, 784-801; doi:10.3390/f5040784

OPEN ACCESS

forests

ISSN 1999-4907

www.mdpi.com/journal/forests

Article

The Impact of Windstorm Damage in the Assessment of the Carbon Balance in Even-Aged *Fagus sylvatica* L. Stands

Mathieu Fortin [1,*], Axel Albrecht [2], Ulrich Kohnle [2] and François Ningre [3]

[1] AgroParisTech, Centre de Nancy, 14 rue Girardet, Nancy Cedex 54042, France

[2] Forest Research Institute Baden-Württemberg, Wonnhaldestr. 4, Freiburg 79100, Germany; E-Mails: axel.albrecht@forst.bwl.de (A.A.); ulrich.kohnle@forst.bwl.de (U.K.)

[3] INRA, Centre de Nancy-Lorraine, 1 rue de l'Arboretum, Champenoux 54280, France; E-Mail: ningre@nancy.inra.fr

* Author to whom correspondence should be addressed; E-Mail: mathieu.fortin@agroparistech.fr; Tel.: +33-0-383-396-871; Fax: +33-0-383-396-847.

Received: 8 February 2014; in revised form: 18 March 2014 / Accepted: 9 April 2014 / Published: 21 April 2014

Abstract: Due to the fact that forest ecosystems can potentially mitigate the impact of climate change, the carbon balance of managed forests has caught the attention of a large scientific community. Some authors conclude that extending rotation lengths would actually favour the climate change mitigation effect since more carbon would be stored in the biomass on the average. However, when the occurrence of catastrophic disturbances such as windstorms is not considered, the advantage of extending the rotation length might be overestimated for some species. In this study, we addressed this issue by coupling a growth model, a windstorm damage model and a carbon assessment tool. The evolution of an even-aged European beech (*Fagus sylvatica* L.) stand was simulated under three different rotation lengths. Simulations including stochastic windstorm events were run and compared with deterministic simulations with no catastrophic disturbance. Our results indicate that when disturbances caused by storms were not taken into account, the carbon balance was actually overestimated in some cases and that this overestimation increased with the rotation length. In our case study, omitting windstorm damage resulted in an overestimation as large as 8% for the longer rotation length. Nevertheless, when windstorm damage was taken into account in the simulation, the longer rotation length still stored more carbon on the average than shorter rotation lengths. However, the marginal gain in carbon storage induced by the increase of the rotation length was reduced.

Keywords: carbon balance assessment; windstorm damage; Monte Carlo simulation; growth predictions; harvested wood products; forest carbon pool

1. Introduction

Since the commitment of most countries included in Annex B to the Kyoto Protocol, the potential of forest ecosystems as a means to mitigate climate change has caught the attention of a broad research community. In the last two decades, carbon accounting of forests has emerged as a new field of study and some reviews and reports now give a broad overview of the methods and issues in this field (e.g., [1–3]). Even though forests were not given much importance in the first 2008–2012 commitment period [4], it is expected that they will play a larger role in the second period according to recent international negotiations [5].

In a context of climate change mitigation, an important issue for forest managers and decision makers is the implementation of management strategies that improve the carbon balance of forest ecosystems. Forests can offset a part of the carbon dioxyde (CO_2) emissions due to human activities through photosynthesis and biomass growth [1]. They also provide harvested wood products (HWPs) which keep the carbon sequestered for a given period of time [6]. Using forest biomass for energy production might also contribute to reduce fossil fuel consumption [7].

For a proper assessment of the carbon balance at the stand level, carbon has to be accounted for not only in the forest but also in HWPs that are extracted from the forest (e.g., [8]). The forest and the HWPs can be considered as two closely related carbon pools, with the first one feeding into the second one. In order to assess these carbon pools in more detail, they are broken down into different compartments, including aboveground biomass and soil in the forest carbon pool [1], and long, medium and short lifetime HWPs (e.g., [6]). Although carbon accounting of forest ecosystems has greatly improved over the last decade, it is still tainted by many uncertainties, such as soil carbon dynamics and decay rate of coarse woody debris [9]. Moreover, not all aspects of this forest-wood product chain are well documented and the carbon balance assessment may suffer from leakage if some parts of the chain, such as HWP disposal and recycling, are omitted, or if they rely on simplistic assumptions.

In spite of all these uncertainties, some studies have attempted to report the carbon balance of typical forest stands under different management scenarios and harvest patterns (e.g., [8,10–14]). Most of these authors concluded that longer rotation lengths result in larger rotation-averaged carbon stocks in forest vegetation. Even though the trend might be different for the HWP carbon pool [8], the total carbon stock in both pools still tends to increase with longer rotation lengths. As a consequence, it may be tempting for forest managers to let forest stands grow older in order to store carbon in the vegetation for a longer period of time.

Considering the impact of a long-rotation management policy, it is surprising to find that the effects of large-scale disturbances are often overlooked in these stand-level studies. While some authors have reported the effects of fires and insect outbreaks at both the landscape and stand levels (e.g., [15–18]), the effects of catastrophic windstorms have not been incorporated in stand-level carbon accounting. In Europe, windstorms are considered as the major disturbance to forest ecosystems [19]. For some species, and European beech (*Fagus sylvatica* L.) in particular, it is also well known that older stands are more vulnerable to windstorm damage than younger ones due to greater stand heights [20,21]. Consequently, it can reasonably be assumed that management scenarios based on longer rotation lengths are overoptimistic in the sense that the stand may be at least partially blown down before the scheduled final cut.

Testing this hypothesis requires the coupling of a growth model and a windstorm damage model. Moreover, both need to be compatible with a carbon assessment tool (CAT). The lack of availability of these three compatible components-a growth model, a windstorm damage model and a CAT-may explain why this issue has not been thoroughly addressed as of this time.

Our motivation was to assess the impact of windstorm damage on the carbon balance. Basically, we wanted to test the following two hypotheses: (i) omitting the windstorm damage in the growth simulations results in an overestimation of the carbon balance; and (ii) the longer the rotation length is, the larger this overestimation will be. The first hypothesis relied on the fact that windstorms may arbitrarily shorten the rotation length or decrease the standing volume and, therefore, reduce the carbon stock that would be observed on average on the whole rotation. The second hypothesis is based on the increasing vulnerability with age, which increases the probability of disturbance before the final cut.

Because European beech is a major component of both French and German forests [22,23] and is vulnerable to windstorms, we selected this species for our study. Starting with an even-aged beech stand that was deemed to be typical, we ran stochastic simulations of windstorm damage under three different management scenarios with increasing rotation lengths.

The simulations were all run within CAPSIS, a Java platform that already hosts more than 50 growth models [24] as well as a CAT [13]. For this study, Albrecht *et al.*'s [20] windstorm damage model was also implemented in CAPSIS in order to obtain all the models required for our simulations. The stochastic simulations including windstorm damage were compared with simulations without windstorm damage to test our two hypotheses.

This paper is structured as follows. The growth model, the CAT and the windstorm damage model that defined our framework for carbon accounting under windstorm damage are first described. The characteristics of our typical stand, the management scenarios and the details of the stochastic simulations are then presented. The results section contains the carbon balance of the different management scenarios with and without windstorm damage. Our discussion focuses on the impacts of windstorms on the stand-level carbon balance in the forest and the HWP carbon pools and the interactions with forest management.

2. Methods

2.1. Growth model

The FAGACEES growth model is currently the reference model for pure even-aged stands of either European beech or sessile oak. The model was designed in the 1990s [25,26] and was largely described by Le Moguédec and Dhôte [27]. In brief, the model uses a top-down approach to predict forest growth over three-year growth intervals. Stand-level basal area growth is first predicted using current dominant height, dominant height growth and a relative density index (RDI) as predictors. Note that dominant features are based on the average of the 100 thickest trees per hectare. Growth of individual trees is then derived from these stand-level basal area growth predictions. The competition-induced mortality is simulated through a simple algorithm that relies on the RDI. The model uses some other allometric relationships such as a stem taper model, a crown length model, an aboveground volume model [28] and a root biomass model [29] to obtain some additional tree features.

FAGACEES also implements a harvest algorithm based on a target RDI, a tolerance around the target, a minimum period between successive thinnings and a target dominant diameter. The algorithm performs the different thinnings in such a way that the stand RDI is kept close to the target until the dominant diameter is reached. For further details about this algorithm, readers can refer to Le Moguédec and Dhôte [28] Section 3.3.

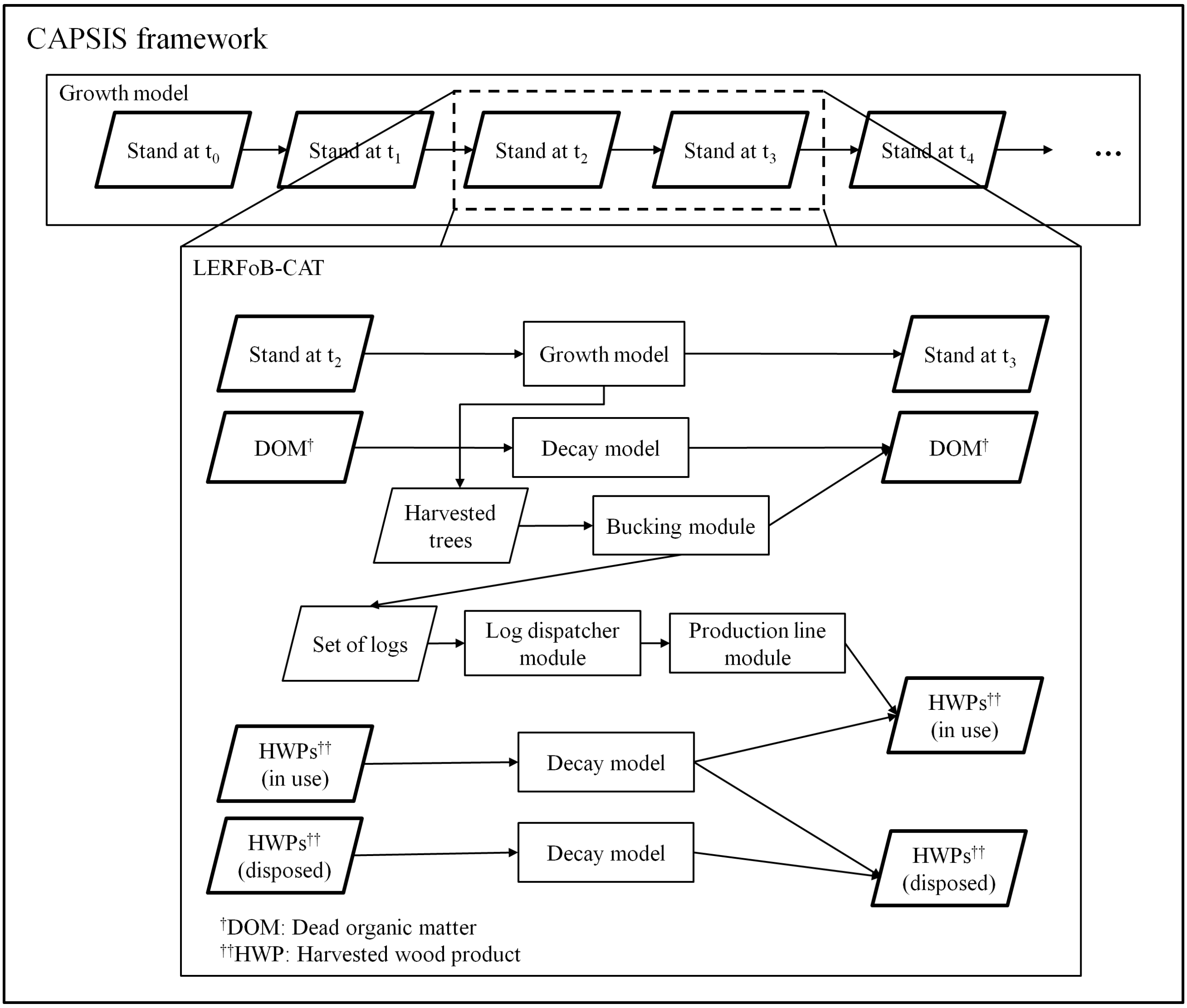
2.2. Carbon Assessment Tool (CAT)

Since 2010, the *Laboratoire d'Etude des Ressources Forêt-Bois* (LERFoB) has been developing a CAT, which we will refer to as LERFoB-CAT in the following sections. It is specifically designed to assess the carbon balance of the complete forest-wood product chain. It provides estimates of the carbon stocks in different compartments of the forest and the HWP carbon pools. The boundaries of the system considered in this tool have been extended as much as possible to cover the entire life cycle of the HWPs, from their production to their disposal including methane (CH_4) emissions from the landfill site or an eventual recycling into energy wood.

LERFoB-CAT has been implemented in the CAPSIS platform, which makes it fully compatible with all the growth models in this platform, such as FAGACEES. It follows the IPCC Good Practice Guidance for the Land Use, Land-Use Change and Forestry (LULUCF) sector [1]. For the forest pool, the carbon stocks are evaluated in the aboveground and belowground compartments as well as in dead organic matter. These carbon stocks are derived from volume estimates that are converted into carbon using species-dependent basic density factors and carbon content ratios. Considering the complexity related to estimating the litter and the soil organic carbon, these two compartments are assumed to have a constant carbon stock, which is actually the default procedure suggested in the IPCC Good Practice Guidance [1].

LERFoB-CAT handles the HWP carbon pool through three modules (Figure 1): a tree bucking module, a production line module and a log dispatcher module. The tree bucking module processes all the harvested trees from the growth model into a list of logs of different grades. In addition to a default bucking algorithm, there is also the possibility of using other bucking algorithms whenever they are available. For example, the GEOLOG bucking module was specifically designed to work with FAGACEES [30], and we used it in our study. GEOLOG allows the user to define some log grade requirements in terms of minimum length, small-end diameter and juvenile wood diameter. Each log grade is given a priority by the user. Subsequently, when partitioning a tree into logs, the bucking algorithm starts at stump height and first tries to produce the log with the highest priority grade. If the first tree section does not meet the requirements, the algorithm tries with the second highest priority until a log can be produced. Whenever this happens, the algorithm starts again at the top of the section that was just extracted until it reaches the tree tip. In this study, we defined the six following log grades from the highest to the lowest priority: slicing, furniture, peeling, sawing, particle and firewood. With these specifications, we assumed a traditional harvest pattern in which the fine wood debris (branches with small-end diameter <7 cm) and the stumps are left on the forest floor.

Figure 1. Coupling of a growth model and the carbon assessment tool (LERFoB-CAT) within the CAPSIS framework (adapted from Fortin *et al.* [13]).



After the bucking module is done with the list of harvested trees, useless tree parts such as the root system, the stump and the top are considered to be dead organic matter. A decay model that is based on an exponential distribution ([31], p. 17) accounts for the degradation of dead organic matter (Figure 1).

The production line module makes it possible to define the way the logs are processed into HWPs (Figure 2). The user is free to create specific production lines that may include many different processes in a hierarchical order. Whenever a log enters a production line, it goes through the first process that splits its volume and sends it to secondary processes, just as a primary saw mill supplies some secondary saw mills. In the end, either HWPs are obtained or the volume is sent to another production line. The production lines we used in this study are detailed in Figure 2.

Figure 2. Production lines module in the carbon assessment tool.

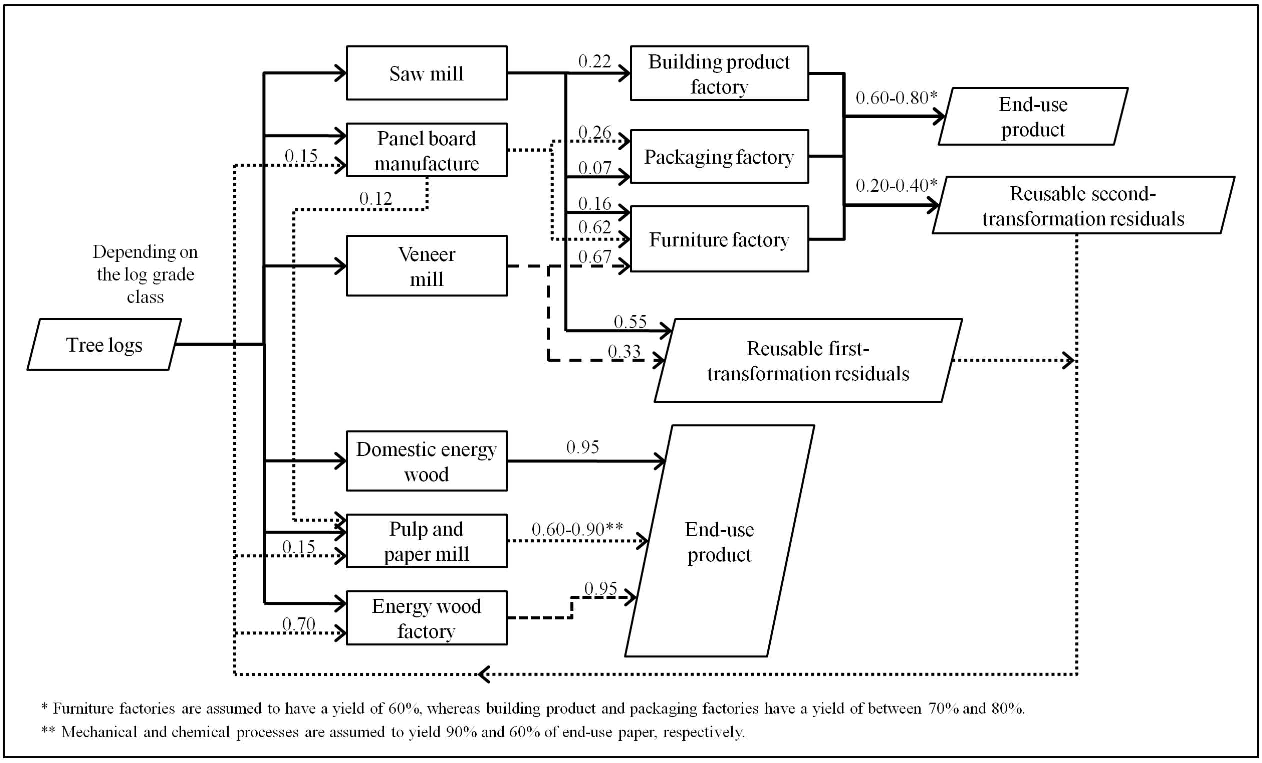


Table 1. Average lifetimes of the different end-use products (adapted from Fortin *et al.* [13]).

Factory and end-use product	Lifetime (years)
Building product factory	
Flooring	40.0
Exterior cladding	20.0
Interior coverings	15.0
Other end-use products	10.0
Furniture factory	
Office furniture	10.0
Kitchen furniture	25.0
Home furniture	20.0
Chairs	13.0
Beds	13.0
Packaging factory	
Heavy packaging	6.3
Pulp and paper mill	
Paper (mechanical)	2.8
Paper (chemical)	2.8
Domestic energy wood	
Firewood	1.7
Energy wood factory	
Wood pellets	1.7

In addition to handling all the fluxes within and between the production lines, this module also updates the amount of HWPs after each growth step. The update is based on user-specified average lifetimes and a decay model that follows an exponential distribution. The proportion of the HWPs that is no longer in use is sent to the landfill site and a user-specified proportion can be recycled. A degradable carbon organic fraction has to be provided for the HWPs that are not recycled. The degradation of these HWPs is also accounted for in the carbon balance. The average lifetimes we used in our simulations can be found in Table 1. The degradable organic carbon fraction and average lifetime as well as the average lifetime of dead organic matter are shown in Table 2.

Table 2. Additional parameters that were specified in LERFoB-CAT for the simulations of the carbon balance.

Parameter	**Value**
Basic density (Mg m^{-3} of dry biomass)	0.578
Carbon content ratio (Mg of C/Mg of dry biomass)	0.4841
Degradable organic carbon fraction	0.4
Degradable carbon average lifetime (years)	25
Dead organic matter average lifetime (years)	10

The log dispatcher is a third module that allows the user to choose the production line to which the different logs will be sent as a function of their grades. Different scenarios of HWPs can be tested this way. In this study, we assumed a business-as-usual dispatch scenario: slicing and peeling logs are sent to the veneer mill, furniture and sawing logs are sent to the saw mill, firewood logs are sent to domestic energy wood outlet, and particle logs are sent to the panel board manufacture, to the pulp and paper mill and to the energy wood factory in proportions of 15%, 15% and 70%, respectively.

After a particular simulation, LERFoB-CAT produces two different reports. The first report concerns the evolution of the carbon stocks in the different compartments of the forest and HWP carbon pools during the entire rotation. The second report provides the average carbon stocks throughout the rotation. The first report is not sufficient to compare different management scenarios because the rotation lengths will probably be different. In the second report, the annual carbon stocks are summed throughout the rotation and divided by the rotation length, which yields a rotation-averaged carbon stock that would be observed if the scenario was repeated indefinitely. These rotation-averaged carbon stocks are the usual way to compare management scenarios with different rotation lengths [8,12,13].

2.3. Windstorm Damage Model

Windstorm damage is predicted using Albrecht *et al.*'s [20] model. The model includes four sub-models that are conditional on each other. The first three apply to the stand level. The first sub-model predicts the occurrence of damage in a binary mode (yes/no). Conditional on this occurrence of damage, a second sub-model predicts whether or not the damage is total, *i.e.*, all trees are blown down. Conditional on non-total damage, the third sub-model predicts which proportion of the basal area is blown down. Finally, the fourth sub-model applies to the tree level and predicts the probability that a particular tree is blown down conditional on the proportion of the basal area predicted in the third sub-model. Stand dominant diameter, stand dominant height and the relative ratio between these two are included in the array of stand-level predictors for these four sub-models.

The model predicts the storm damage for six species groups, one of which is European beech. This model was fitted to long-term monitoring data, which included more than 80,000 observations on beech trees. The study region was Baden-Württemberg (south-western Germany), which shares a border with Eastern France. To our knowledge, there was no other windstorm damage model that better matched the context of this study.

It is worth mentioning that the probability of windstorm occurrence is thus implicitly included in the first sub-model. In other words, there is no need to specify a probability of recurrence for extreme windstorms. The model implicitly represents this recurrence by reproducing average storm damage caused by several storm events over the second half of the 20th century. For more details about this model, readers are referred to Albrecht *et al*. [20].

2.4. Simulations

Beech is one of the most abundant species in Europe [32]. In 2010, pure beech stands covered an estimated area of 600,000 ha just in France [23]. For this study, we generated a pure even-aged beech stand that was deemed to be typical in the French and German conditions. This initial stand was fully stocked, 15 years old and covered an area of 1 ha. The site index was set to 30 m for a reference age of 100 years which is an average fertility for this kind of forests [33]. The growth of this stand was then simulated under three different management scenarios. All of the scenarios targeted a 60-cm dominant diameter, but differed in terms of target RDI. The first one was a low-density scenario with a target RDI of 0.3. The second scenario was a standard scenario with a target RDI of 0.5. Finally, the last scenario was based on an RDI of 0.7, which implies a higher density than the previous two. The first two scenarios roughly correspond to current practices on public lands in France.

Without windstorm damage, it can be assumed that the lower the RDI is, the shorter the rotation will be. Because the trees grow in a low density environment, their radial growth is larger and the stand reaches the target dominant diameter sooner than with high densities [34,35]. Henceforth, the three scenarios will be referred to as the low-density, the standard and the high-density scenarios. According to the current standards of beech silviculture in France (cf. [36,37]), we also assumed that a pre-commercial thinning would be carried out as soon as the dominant height reached 5 m.

For the purpose of this study, Albrecht *et al*.'s model was also implemented in the CAPSIS platform. Because windstorm damage is a highly stochastic phenomenon, Monte Carlo techniques were used. For each realization within a particular management scenario, a growth simulation was run. Every time a five-year period was completed, a first random deviate from a uniform distribution $U(0, 1)$ was drawn. If the deviate was smaller than the predicted probability of damage, a second deviate from $U(0, 1)$ was drawn. If this second deviate was smaller than the probability of total damage, the stand was considered to be blown down. If not, the third sub-model in Albrecth *et al*.'s model provided the proportion of basal area that was damaged. Then, based on the individual probabilities predicted by the fourth sub-model, a series of uniform random deviates was drawn again in order to determine which trees were blown down. Given the number of observations that served to fit the model, we assumed that the parameter estimates were error free.

The growth simulation stopped whenever the target dominant diameter of 60 cm was reached or when all of the trees were blown down. Once the simulation stopped, LERFoB-CAT was used to provide its carbon balance. Because of the computational burden, we ran a 1000-realization Monte Carlo simulation for each one of the three aforementioned scenarios. Note that we did not consider any breakage or windfall damage during the processing of tree logs into HWPs. This assumption was necessary because we had no data on this potential wind damage-induced downgrading of the logs.

In addition to the stochastic simulations with windstorm damage, we also ran a deterministic simulation without windstorm damage for each scenario. The comparison between the deterministic simulation and the average of the stochastic realizations provides an estimate of the potential overestimation in the carbon balance assessment when windstorm damage is not taken into account.

3. Results

The deterministic simulations yielded estimated rotation lengths of 105, 138, and 168 years for the low-density, the standard and the high-density scenarios, respectively. In practice, the rotation lengths for the low-density and standard scenarios are estimated to 100 and 140 years, respectively [33]. The first major windstorm damage occurred between 100 and 120 years of age, depending on the scenario (Figure 3). As the dominant height increases, the stand becomes more and more vulnerable to major windthrow. Because the final cut occurred at an earlier age in the low-density scenario, namely between 100 and 110 years of age, there was little windstorm damage and the variability across the realizations was rather small (Figure 3a). There was actually no realization with a major blow-down in this scenario. On the other hand, this variability increased with the rotation lengths, as shown in the standard and the high-density scenarios (Figure 3b,c). The percentage of realizations with a major blow-down increased to 4% and 61% for the standard and the high-density scenarios, respectively. In some realizations, partial storm damage was observed, as indicated by a partial drop in the carbon stock. It is worth mentioning that the thinning schedule was affected by partial damage, with some thinnings being delayed. As a result, the carbon stock could be punctually larger in some realizations affected by partial damage. Compared with the standard scenario, this partial damage occurred earlier and induced larger drops in the carbon stock in the high-density scenario.

The stocks in the HWP carbon pool are shown in Figure 4. The final cut in the deterministic simulations resulted in a sharp increase of the stock in this pool since a large volume was harvested and then processed into end-use wood products. In each scenario, some stochastic realizations also showed sharp increases that occurred earlier than in the deterministic simulation, indicating that a major blow-down had occurred and that the volume was salvaged after the disturbance. These sharp increases in the HWP carbon pool actually correspond to the sharp decreases in the forest carbon pool, as shown in Figure 3. In accordance with the forest carbon pool, fewer increases due to major blow-downs were observed in the low-density scenario (Figure 4a). These increases became more frequent in the standard and the high-density scenarios (Figure 4b,c).

Figure 3. Evolution of the carbon stocks in the forest carbon pool for three different management scenarios (black: without wind damage; gray: realizations with stochastic wind damage).

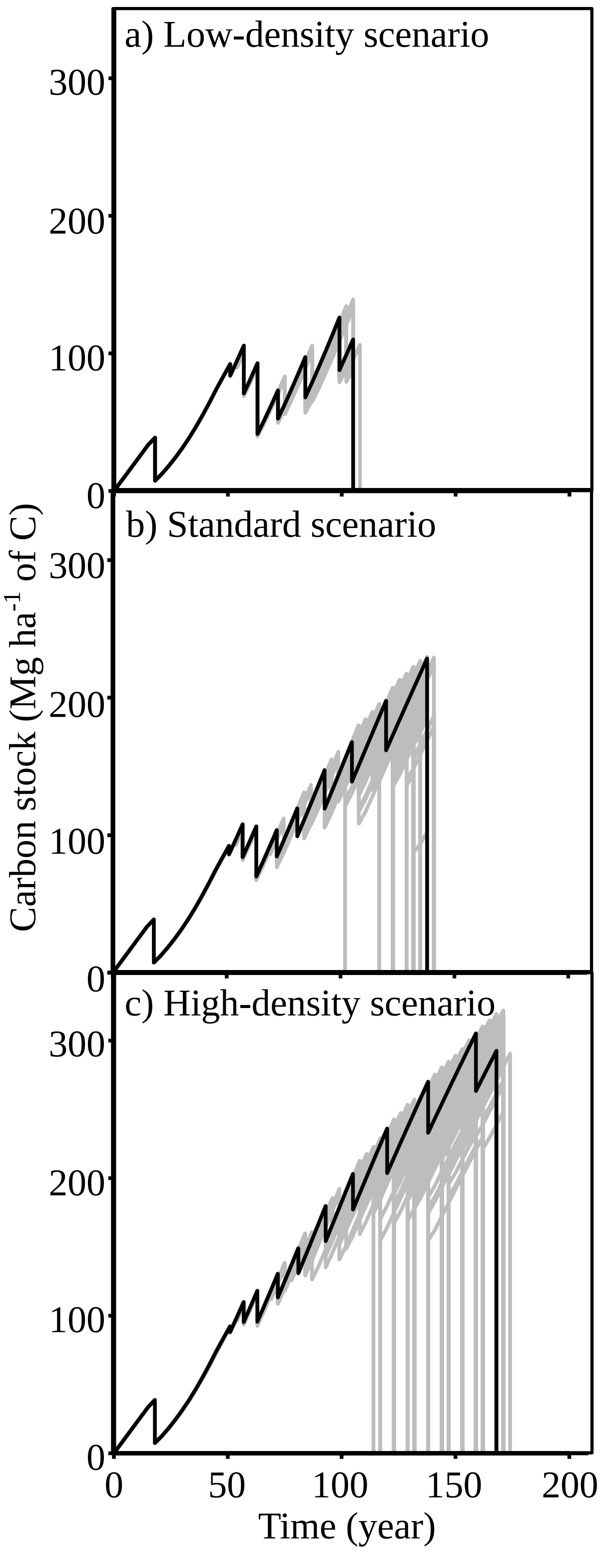
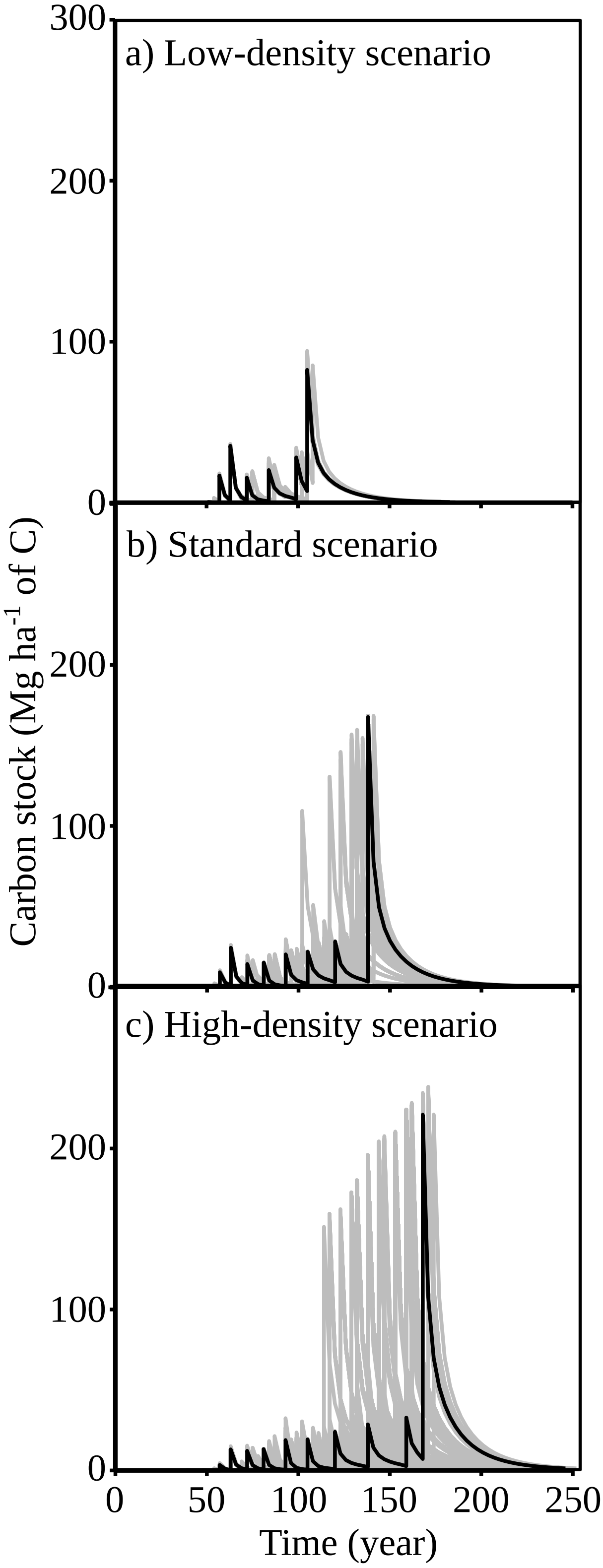
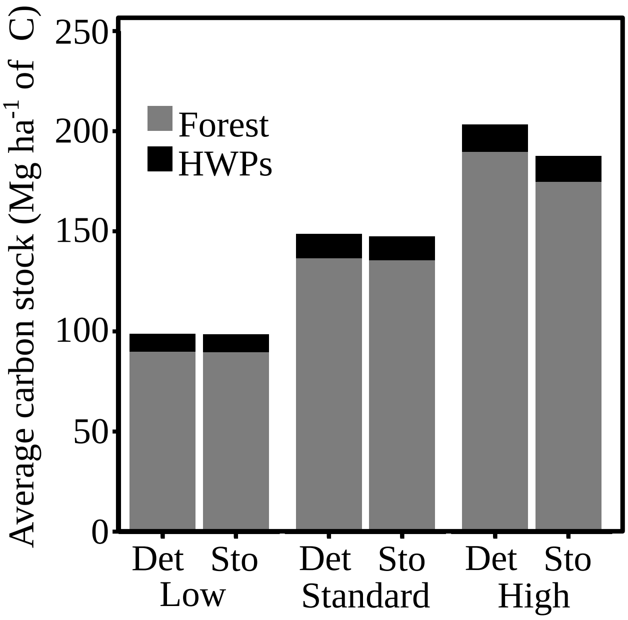


Figure 4. Evolution of the carbon stocks in the HWP carbon pool for three different management scenarios (black: without wind damage; gray: realizations with stochastic wind damage).



The rotation-averaged carbon stocks, *i.e.*, the sum of the carbon stocks all along the rotation divided by its length, are shown in Figure 5. In terms of proportions, the stock in the HWP carbon pool accounted for 5% to 7% of the total stock in the two pools combined. For the low-density scenario, both the deterministic and stochastic simulations yielded a total average carbon stock of 98 Mg ha^{-1} of C, indicating that windstorm damage was rather negligible. The average carbon stock decreased by 1 Mg ha^{-1} of C when windstorm damage was taken into account in the simulations of the standard scenario. Finally, the largest drop was observed for the high-density scenario. The average carbon stock decreased from 203 to 188 Mg ha^{-1} of C.

Figure 5. Rotation-averaged carbon stocks in the forest and the HWP carbon pools under deterministic (Det) simulations without storm damage considered, and stochastic (Sto) simulations including storm damage for the three forest management scenarios (Low, Standard and High densities). For stochastic simulations, the values are the averages of the 1000 realizations.



4. Discussion

As in previous studies [8,10,12,13], our deterministic simulations showed that the rotation-averaged carbon stock tended to increase with the rotation length (Figure 5) when windstorm damage was not taken into account. Liski *et al.* [8] reported that a decrease of the carbon stock in the soil may offset the gain of longer rotation lengths for some species. Because we assumed a constant carbon stock in the soil, we cannot test whether the gain due to longer rotation lengths might eventually be smaller for European beech. This remains to be investigated.

At the stand level, the low proportion of the HWP pool compared to the forest pool (Figure 5) in all scenarios is not new either (e.g., [8,11–13]). The processing of the logs of broadleaved species has a low yield and, consequently, only a small amount of the initial volume ends up in long-lived HWPs [13]. Even with coniferous species, the HWP carbon pool only represents a small fraction of the total carbon (e.g., [8]). Unless the proportion of long-lived wood products increases in the future, the impact of HWPs on the stand-level carbon balance remains limited, especially for broadleaved species. Green *et al.* [38] reported that the uncertainty around the average lifetimes of the HWPs was one of the major sources of variability in the assessment of the HWP pool at the national level. In some preliminary trials, we obtained stocks that were 50% larger in the HWP carbon pool with average lifetimes that were 10 years longer for construction and furniture products. If these lifetimes were to increase in the future, the HWP carbon pool might get more importance with respect to the forest carbon pool.

The impacts of windstorms on the HWP pool were similar to those on the forest pool. We observed an overestimation for the longest rotation length. However, given that the HWP pool contained a small fraction of the total carbon, this overestimation was almost negligible in absolute value. Harmon [39] pointed out that the scale issue may lead to seemingly divergent responses in terms of carbon sequestration. At the landscape level, a windstorm event may punctually increase the HWP carbon pool through the large amount of salvaged wood. The offer in beech wood greatly increased in France after the 1999 Lothar storm [33]. However, such a situation is occasional and the new stands resulting from major windthrows will not produce any HWPs until they reach at least 50 years of age as shown in Figure 4. That a windstorm may cause some fluctuations in the HWP carbon pool is obvious. However, in the long term, our results show that there is no net increase in this pool at the stand level.

It could be argued that storm damage was not taken into account in the processing of logs into HWPs in this study. In fact, the major effect of this downgrading would be to increase the proportion of short-lived HWPs and, as a result, the rotation-averaged carbon stock would be expected to slightly decrease. However, considering the limited impact of the HWP carbon pool mentioned above, it would hardly change the global pattern that we observed in our simulations.

Storm damage occurred at an earlier age when extending the rotation length (Figure 3c). Since terrain and other risk factors were intentionally kept constant, this change in vulnerability is exclusively caused by the changing stand characteristics. Because height growth was identical at the same ages for the three scenarios, it is most likely that the difference in storm damage was triggered by the relative stand dominant height/dominant diameter (h/d) ratio predictor [20]. This ratio describes the slenderness or taper of trees and is thus an indicator of stem stability. In the high-density scenario, the stand reached a higher h/d ratio and, consequently, was less stable, which may explain the increase in an earlier occurrence of storm damage. Other authors have also found the slenderness to be a good indicator of stem stability-especially against snow breakage [40–45]—but also against storm damage [46–48].

As shown in Figure 5, not considering wind damage in the carbon balance assessment may result in overestimated average carbon stocks in some cases, but cannot be considered as a general rule for European beech. The overestimation was clearly dependent on the scenario and proved to increase with rotation length. Given that 188 Mg ha^{-1} of C is the expected average carbon stock in the high-density scenario including windstorm damage, the omission of these disturbances leads to the overestimation of the carbon balance by 8%. On the other hand, the carbon balance of the low-density scenario remained almost unaffected by wind damage, mainly because this stand did not develop characteristics that made it vulnerable to windstorm damage.

In beech stands, Bock *et al.* [21] identified a threshold of 23–24 m in dominant height beyond which windstorm damage becomes more important. They also pointed out the age of 90 years as a lower boundary for major windstorm damage. The stand we simulated in this study reached this dominant height threshold at around 90 years of age. Although we observed some partial damage at that age, Albrecht *et al*.'s [20] model seems to trigger the damage later, though the damage is greater than that reported in Bock *et al*. [21]. Some differences between these two models may be caused by the different modeling approaches, namely that Albrecht *et al*. included several storm events and, as such, it can be assumed to represent "average" risks, whereas Bock *et al*. analyzed the impact of a single event, namely the catastrophic 1999 storm, Lothar, in Eastern France. The further comparison of both models in the context of carbon balance assessment is beyond the scope of this study, but clearly deserves to be investigated in future studies.

Regardless of the thresholds in terms of age and dominant height, the global trend remains the same: beyond 130 years of age, major windthrows are expected to occur more and more frequently as forest stands grow older and taller. For the standard and the high-density scenarios, the rotation lengths exceeded 130 years. For the high-density scenario, in particular, the final cut occurred almost 40 years past this age (Figure 3), which means that almost a quarter of the planned rotation length is in the "danger zone". Furthermore, as red heart proportion increases with age in beech [35], a decreasing yield of long-lived HWPs can be assumed, further reducing the carbon storage balance of the high-density scenario with its long rotation.

However, even when windstorm damage is taken into account in the simulations, the high-density scenario still stores more carbon on the average than the other two (Figure 5). Actually, we expected the existence of an asymptotic trend: at some point, increasing the rotation length would result in no gain in terms of carbon balance. Identifying this threshold would provide forest managers with a useful guideline if their objective was to maximize the carbon balance in managed forest stands. Although the trend was clearly linear when windstorm damage was not considered, a slight quadratic trend appeared when it was taken into account. The gain from the low-density scenario to the standard scenario was estimated at 49 Mg ha^{-1} of C for an increase of 33 years in rotation length. The gain from the standard to the high-density scenario was 40 Mg ha^{-1} for an increase of 30 years in rotation length.

Even though a slight quadratic trend was observed as expected, our simulations were still far from the expected asymptotic trend. Clearly, at the stand level, identifying the rotation lengths beyond which there is no gain in terms of carbon balance implies simulating rotation lengths longer than 168 years for beech. From a practical standpoint, such long rotation lengths are neither common management nor are they considered as state-of-the-art silviculture. However, even though there is a gain associated with longer rotation lengths, the marginal gain is likely to decrease. If improving the carbon balance of this stand was the sole objective, the results of our study indicate that the high-density scenario is still advantageous.

In this study, coupling a growth model, a CAT and a windstorm damage model was not straightforward, and some assumptions had to be made. The growth model we used, FAGACEES, was designed to work with 1-ha plots, whereas the windstorm damage model is based on plots with an average area of 0.25 ha. The probability of complete damage is consequently the probability of observing a complete blow-down on 0.25 ha and not 1 ha. Nevertheless, we decided to use 1-ha plots in our simulations. This choice was motivated by the fact that we wanted the simulations to be representative of a forest stand. This being said, we assumed that the damage on 0.25 ha could be extrapolated to the full hectare. The validity of this assumption remains to be evaluated. In addition to this, the rotation lengths we studied here are clearly driven by relative density for a constant target dominant diameter. Scenarios based on different target diameters have not been tested here and should be investigated.

5. Conclusions

In the light of the results of this study, we can conclude that:

- Omitting windstorm damage in growth simulations may result in an overestimation of the carbon balance, given that the stand is vulnerable or will eventually become vulnerable to windstorm damage. For European beech, short and standard rotations keep the stands relatively resistant to this damage and, consequently, the overestimation is negligible.
- Increasing the rotation length leads to a larger overestimation. In our simulations, the carbon balance was overestimated by 8% when windstorm damage was not considered in the scenario with the longest rotation length. As the rotation length and stand height increase, the stand becomes more vulnerable and remains vulnerable for a longer period of time. Consequently, the damage is more frequent and the impacts on the carbon balance are greater.
- The rotation length beyond which the carbon balance would level off could not be identified in this study. According to our simulations, this rotation length is likely to be way off the chart of common sense in silviculture. For the moment, longer rotation lengths in pure even-aged beech are still the most advantageous in terms of carbon balance. However, the marginal gain is lower than that which was expected from deterministic simulations. Considering that forest management is a trade-off between different (and sometime incompatible) goals, this lower marginal gain may reduce the attractiveness of long-rotation management strategies for improving the carbon balance.

Acknowledgments

The authors are grateful to Jean-François Dhôte (ONF), Patrick Vallet (*Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture* - IRSTEA), Frédéric Mothe (INRA), Nicolas Robert (*Institut national de l'information géographique et forestière* - IGN), and all the other people who contributed to the implementation of FAGACEES in the CAPSIS platform. This project was funded by the *Association France-Forêt*, the *Office National des Forêts* (ONF) and the *Institut pour le Développement Forestier* (IDF).

Author Contributions

A. Albrecht and M. Fortin were responsible for implementing the windstorm damage model in CAPSIS, running the simulations and writing the paper. F. Ningre and U. Kohnle participated to the design of the study, provided assistance with the simulations and the writing of the paper.

Conflicts of Interest

The authors declare no conflicts of interest.

References

1. IPCC. *Good Practice Guidance for Land Use, Land-Use Change and Forestry*; The Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan, 2003.
2. Agostini, A.; Giuntoli, J.; Boulamanti, A. *Carbon Accounting of Forest Bioenergy. Conclusions and Recommendations from a Critical Literature Review*; Technical Report; European Commission, Joint Research Center: Ispra, Italy, 2013.
3. Lamers, P.; Junginger, M. The debt is in the detail: A synthesis of recent temporal forest carbon analyses on woody biomass for energy. *Biofuels Bioprod. Biorefin.* **2013**, *7*, 373–385.
4. Shvidenko, A.; Schepaschenko, D.; McCallum, I.; Nilsson, S. Can the Uncertainty of Full Carbon Accounting of Forest Ecosystems be Made Acceptable to Policymakers? In *Greenhouse Gas Inventories*; White, T., Jonas, M., Nahorski, Z., Nilsson, S., Eds.; Springer: New York, USA, 2011; pp. 137–157.
5. Grassi, G.; Elzen, M.G.J.D.; Hof, A.F.; Pilli, R.; Federici, S. The role of the land use, land use change and forestry sector in achieving Annex I reduction pledges. *Clim. Chang.* **2012**, *115*, 873–881.
6. Pingoud, K.; Perälä, A.L.; Pussinen, A. Carbon dynamics in wood products. *Mitig. Adapt. Strat. Glob. Chang.* **2001**, *6*, 91–111.
7. Petersen Raymer, A.K. A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. *Biomass Bioenergy* **2006**, *30*, 605–617.
8. Liski, J.; Pussinen, A.; Pingoud, K.; Mäkipää, R.; Karjalainen, T. Which rotation length is favourable to carbon sequestration? *Can. J. For. Res.* **2001**, *31*, 2004–2013.
9. Zell, J.; Kändler, G.; Hanewinkel, M. Predicting constant decay rates of coarse woody debris–A meta-analysis approach with a mixed model. *Ecol. Modell.* **2009**, *220*, 904–912.
10. Kaipainen, T.; Liski, J.; Pussinen, A.; Karjalainen, T. Managing carbon sinks by changing rotation length in European forests. *Environ. Sci. Policy* **2004**, *7*, 205–219.
11. Perez-Garcia, J.; Lippke, B.; Comnick, J.; Manriquez, C. An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. *Wood Fiber Sci.* **2005**, *37*, 140–148.
12. Vallet, P. Impact de Différentes Stratégies Sylvicoles sur la Fonction 'Puits de Carbone' des Peuplements Forestiers. Modélisation et Simulation à l'Echelle de la Parcelle. Ph.D. Thesis, ENGREF (AgroParisTech), Nancy, France, 2005.
13. Fortin, M.; Ningre, F.; Robert, N.; Mothe, F. Quantifying the impact of forest management on the carbon balance of the forest-wood product chain: A case study applied to even-aged oak stands in France. *For. Ecol. Manag.* **2012**, *279*, 176–188.
14. Zanchi, G.; Pena, N.; Bird, N. Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy* **2012**, *4*, 761772.
15. Kurz, W.A.; Dymond, C.C.; Stinson, G.; Rampley, G.J.; Neilson, E.T.; Carroll, A.L.; Ebata, T.; Safranyik, L. Mountain pine beetle and forest carbon feedback to climate change. *Nature* **2008**, *452*, 987–990.

16. Kurz, W.A.; Stinson, G.; Rampley, G.J.; Dymond, C.C.; Neilson, E.T. Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 1551–1555.
17. Lamers, P.; Junginger, M.; Dymond, C.C.; Faaij, A. Damaged forests provide an opportunity to mitigate climate change. *GCB Bioenergy* **2014**, *6*, 44–60.
18. Mitchell, S.R.; Harmon, M.E.; O'Connell, K.E.B. Carbon debt and carbon sequestration parity in forest bioenergy production. *GCB Bioenergy* **2012**, *4*, 818–827.
19. Schelhaas, M.J.; Nabuurs, G.J.; Schuck, A. Natural disturbances in the European forests in the 19th and 20th centuries. *Glob. Chang. Biol.* **2003**, *9*, 1620–1633.
20. Albrecht, A.; Hanewinkel, M.; Bauhus, J.; Kohnle, U. How does silviculture affect storm damage in forests of south-western Germany? Results from empirical modeling based on long-term observations. *Eur. J. For. Res.* **2012**, *131*, 229–247.
21. Bock, J.; Vinkler, I.; Duplat, P.; Renaud, J.P.; Badeau, V.; Dupouey, J.L. Stabilité au vent des hêtraies: Les enseignements de la tempête de 1999. *Revue Forestière Française* **2005**, *57*, 143–158.
22. BMVEL. *Results for the National Forest Inventory 2001/2*; German Federal Ministry of Food, Agriculture and Consumer Protection: Berlin, Germany, 2006.
23. IFN. *La forêt française. Les résultats issus des campagnes d'inventaire 2005 à 2009*; Inventaire Forestier National: Nogent-sur-Vernisson, France, 2010.
24. Dufour-Kowalski, S.; Courbaud, B.; Dreyfus, P.; Meredieu, C.; de Coligny, F. Capsis: An open software framework and community for forest growth modelling. *Ann. For. Sci.* **2012**, *69*, 221–233.
25. Dhôte, J.-F. Modélisation de la croissance des peuplements réguliers de hêtre: Dynamique des hiérarchies sociales et facteurs de production. *Ann. Sci. For.* **1991**, *48*, 389–416.
26. Dhôte, J.-F. A model of even-aged beech stands productivity with process-based interpretations. *Ann. Sci. For.* **1996**, *53*, 1–20.
27. Le Moguédec, G.; Dhôte, J.-F. Fagacées: A tree-centered growth and yield model for sessile oak (*Quercus petraea* L.) and common beech (*Fagus sylvatica* L.). *Ann. Sci. For.* **2012**, *69*, 257–269.
28. Vallet, P.; Dhôte, J.-F.; Le Moguédec, G.; Ravart, M.; Pignard, G. Development of total aboveground volume equations for seven important forest tree species in France. *For. Ecol. Manag.* **2006**, *229*, 98–110.
29. Drexhage, M.; Colin, F. Estimating root system biomass from breast-height diameters. *Forestry* **2001**, *74*, 491–497.
30. Mothe, F.; Le Moguédec, G.; Nepveu, G.; Bucket, E. A logging module for oak connected to the Fagacées model. Presented at the CAPSIS annual meeting, Montpellier, France, June 2006.
31. Lawless, J.F. *Statistical Models and Methods for Lifetime Data*; Wiley-Interscience: Hoboken, NJ, USA, 2003.
32. UNECE, F.E.; FAO. *State of Europe's Forests 2011, Status & Trends in Sustainable Forest Management in Europe*; Ministerial Conference on the Protection of Forests in Europe: Oslo, Danemark, 2011.

33. ONF. *Gestion des hêtraies dans les forêts publiques françaises*; Rendez-vous techniques; Hors-série no 2; Office National des Forêts: Fontainebleau, France, 2007.
34. Hein, S.; Lenk, E.; Klädtke, J.; Kohnle, U. Z-Baum orientierte Auslesedurchforstung in Buche (*Fagus sylvatica* L.): Auswirkungen auf Qualität, Sortenstruktur und Wertleistung. *Allgemeine Forst-und Jagdzeitung* **2007**, *178*, 1–20.
35. Klädtke, J. Wachstum großkroniger Buchen und waldbauliche Konsequenzen. *Forstarchiv* **2002**, *73*, 211–217.
36. Armand, G. *Le Hêtre Autrement*; Institut pour le Développement Forestier: Paris, France, 2002.
37. ONF. *Guide de sylviculture du Hêtre (La Hêtraie nord-atlantique)*; Office National des Forêts, Direction territoriale Ile de France Nord-Ouest; Paris, France, 2004.
38. Green, C.; Avitabile, V.; Farrell, E.P.; Byrne, K.A. Reporting harvested wood products in national greenhouse gas inventories: Implications for Ireland. *Biomass Bioenergy* **2006**, *30*, 105–114.
39. Harmon, M.E. Carbon sequestration in forests: Addressing the scale question. *J. For.* **2001**, *99*, 24–29.
40. Nykänen, M.L.; Peltola, H.; Quine, C.; Kellomäki, S.; Broadgate, M. Factors affecting snow damage of trees with particular reference to European conditions. **1997**, *Silva Fenn.* 31, 193-213
41. Päätalo, M.L. Risk of snow damage in unmanaged and managed stands of scots pine, norway spruce and birch. *Scand. J. For. Res.* **2000**, *15*, 530–541.
42. Peltola, H.; Nykänen, M.L.; Kellomäki, S. Model computations on the critical combination of snow loading and windspeed for snow damage of scots pine, Norway spruce and Birch sp. at stand edge. *For. Ecol. Manag.* **1997**, *95*, 229–241.
43. Petty, J.A.; Worrell, R. Stability of coniferous tree stems in relation to damage by snow. *Forestry* **1981**, *54*, 115–128.
44. Valinger, E.; Lundqvist, L. The influence of thinning and nitrogen fertilisation on the frequency of snow and wind induced stand damage in forests. *Scot. For.* **1992**, *46*, 311–320.
45. Zubizarreta-Gerendiain, A.; Pellikka, P.; Garcia-Gonzalo, J.; Ikonen, V.P.; Peltola, H. Factors affecting wind and snow damage of individual trees in a small management unit in finland: Assessment based on inventoried damage and mechanistic modelling. *Silva Fenn.* **2012**, *46*, 181–196.
46. Cremer, K.; Borough, C.; McKinnel, F.; Carter, P. Effects of stocking and thinning on wind damage in plantations. *N. Z. J. For. Sci.* **1982**, *12*, 244–268.
47. Scott, R.E.; Mitchell, S.J. Empirical modelling of windthrow risk in partially harvested stands using tree, neighbourhood, and stand attributes. *For. Ecol. Manag.* **2005**, *218*, 193–209.
48. Talkkari, A.; Peltola, H.; Kellomäki, S.; Strandman, H. Integration of component models from the tree, stand and regional levels to assess the risk of wind damage at forest margins. *For. Ecol. Manag.* **2000**, *135*, 303–313.