Coupling a tree growth model with storm damage modeling – Conceptual approach and results of scenario simulations

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Abstract
The purpose of this study was to develop, test and evaluate a software prototype capable of modeling forest growth in consideration of winter storm disturbance and to simulate storm damage in forests under different forest management regimes. The results of a test application showed that simulated storm damage was more strongly influenced by the input data (e.g. tree species and tree height) than by the different forest management regimes. However, early, intense thinnings as well as reducing target diameters by 10% led to reduced storm damage, with decreases as large as 50% of the damage in certain forest stands. The coupled modeling framework was able to simulate interactions between forest growth, storm damage and forest management regimes. Further testing of the prototype appears necessary to investigate a wider range of tree species, soil and site conditions. Also, the use of computational system resources needs improvement.

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Software and/or data availability
Software is available from the authors upon request. Also the data of the model forest stands are available as tree lists for BWinPro from the authors upon request.

1. Introduction

Forest growth is often predicted without considering natural disturbances such as storms, wildfires, or bark beetle infestations. In fact, the inclusion of these disturbances into growth simulations is hindered by the uncertainty associated with the frequency of these phenomena (Schelhaas et al., 2003). Furthermore, the driving factors of forest growth, such as soil fertility, precipitation and competition, differ from the factors causing storm or insect damage (Hanewinkel et al., 2011). Furthermore, predicting the occurrence of storms or favorable habitat conditions for bark beetles requires consideration of spatial scales different from those needed for modeling growth of an individual forest stand. Thus, current software requirements differ between growth models and risk models, leading to independent software architecture and design for these two environmental phenomena. While both risk and growth modeling are still facing challenges each within their disciplines, the difficulty of coupling them has just recently been tackled (Seidl et al., 2014).

Another reason why forest growth and natural risks have not yet been interactively linked in a modeling framework may be that forest scientists and managers have — until now — frequently perceived damage from catastrophic disturbances as non-influenceable. For this reason, forest growth has usually been modeled without any consideration of large-scale disturbances, while the effects of these disturbances have been summarily evaluated ex post, for example, in terms of standing wood volume potentially at risk, potential reduction of harvest revenue under risk, or with survival functions (Dieter et al., 2001; Knoke et al., 2008; Neuner et al., 2014; Staupendahl and Möhring, 2011).
Previous analyses of biotic and abiotic risk in forestry have often led to recommend a reduction of standing wood volume or target diameters (Beinhofer, 2007, 2010; Roessiger et al., 2011). Thus, there are indications that the risk of storm damage in forests is sensitive to forest management actions and influenceable (Achim et al., 2005; Dobbertin, 2002; Jalkanen and Mattila, 2000; Lohmander and Helles, 1987; Mason, 2002; Mason and Quine, 1995; Quine et al., 1995; Slodicáč, 1995). However, many of the recommendations for risk minimization have been elaborated without considering the interaction between forest growth, disturbances and forest management. Forest growth modeling offers the opportunity to implement risk aspects and to serve as an essential tool to better understand and predict these vital interactions.

Forest growth modeling generalizes growth processes of woody plants and quantifies growth on different temporal and spatial scales, usually as some form of biomass increment. A major objective of forest growth modeling is to predict the availability of wood resources for human usage and it helps to understand the underlying drivers of growth (Munro, 1974; Porté and Bartelink, 2002; Vanclay, 1994). Besides other areas of application, different forest management scenarios can be compared based on forest growth simulations (Pretzsch et al., 2002). Such simulations allow, for example, the evaluation of mitigation strategies in changing environmental conditions.

Storm damage modeling in forest sciences specifically analyzes the causes of and the circumstances associated with tree failure in strong winds. A major objective here is to minimize storm damage in forests by understanding the risk factors and the relationships between them, e.g. how the risk of damage can be altered by human action (Gardiner et al., 2008; Gardiner and Quine, 2000). Storm damage modeling serves as a basis for developing risk management strategies (Hanewinkel et al., 2011) and insurance models (Holecy and Hanewinkel, 2006). Other objectives of storm damage modeling are, for example, visualization of landscape dynamics or analyzing the vegetational succession dynamics (Ulanova, 2000).

Landscape-scale interactions on the relation between storm damage and forest management have been illustrated for managed forests only in a few studies. In Finland, Zeng et al. (2007) have focused on the response of newly exposed forest edges after clearcutting to the risk of subsequent storm damage. In the United Kingdom, Gardiner et al. (2003) have designed a framework to calculate windthrow risk for empirical forest stand data. Based on these two approaches damage risk for entire regions was estimated, including some dynamic aspects of growth and the impact of forest management on storm risk. Another regional study analyzed the relationship between ecosystem services as a function of several factors, such as forest management alternatives, climate change impact and disturbances caused by storms (Ray et al., 2014).

Another recent study in this context combined a process-based model of wind-disturbance with a forest growth model (Seidl et al., 2014). Although not explicitly performed in this study, this approach allows to analyze the impact of alternative silvicultural treatment regimes on storm damage by scenario simulations.

Quantifying the effect of disturbances on forest growth and the impact of forest management on the risk of damage is difficult and is associated with high natural variability. While some previous studies have demonstrated the usefulness of combining forest growth models with storm risk models and GIS (e.g. Gardiner et al., 2003), some questions remain unanswered, especially regarding the effect of different thinning regimes and partial harvesting on remaining stands. Therefore, the objective of this study was to propose a modeling framework that combines natural risks, forest growth and forest management. To achieve this, we coupled a storm damage model and a forest growth model. Different management scenarios were then tested to quantify the simulated damage. Our working hypotheses were that (H1) storm damage has significant impact on forest growth (H2) the amount of storm damage is sensitive to forest management regimes.

We used the German federal state Baden-Wuerttemberg in southwest Germany as a case study and focused on the two tree species Norway spruce (Picea abies (L.) Karst.) and Silver fir (Abies alba Mill.).

2. Material and methods

2.1. Growth model

We used the distance-independent individual-tree forest growth simulator BWinPro developed by the Northwest German Forest Research Institute (Hansen and Nagel, 2014; Nagel et al., 2002). The simulator is based on five-year growth intervals. Simulations for longer time intervals are obtained by reinserting the predictions in the model as many times as necessary to reach the desired projection length. For each five-year interval, the simulator performs the following sequence of steps:

1. if required, a user-specified treatment is carried out and the competition indices of remaining trees are updated;
2. competition- and age-induced mortalities are simulated;
3. competition indices of survivor trees are updated;
4. diameter and height increment of survivors is simulated;
5. competition indices are updated (post growth but before next treatment). Loop back to step 1.

The simulator uses a forest stand consisting of individual trees in a tree list as its simulation unit. Competition between individuals in a stand is modeled through a distance-dependent competition index. The competition for a particular tree is expressed as the competition induced by all other trees in that stand, regardless of their distance. Forest management in BW in Pro can be defined in the sub-modules for thinning, harvesting, and planting operations.

The following options are available in the thinning module:

- type of thinning (e.g. thinning from below, thinning from above or thinning with permanent target crop trees)
- minimum stand height for first thinning
- the intensity of thinning, ranging from none to heavy
- minimum and maximum standing wood volume to be removed by thinning operation.

Harvesting operations can be defined by the following parameters:

- type of harvest (individual target diameter, shelterwood harvest, clear cut)
- speed of progress for shelterwood harvest

BW in Pro is adapted for stands with homogeneous structure, which means the tree diameters follow a unimodal distribution, and can be used for single- or mixed-species stands. As a decision support tool it is especially suitable for the comparison of different forest management options. This growth simulator is based on empirical forest growth data measured in long-term monitoring plots and it was originally developed for the growth conditions in northwest Germany (Nagel et al., 2002). As the geographic context in southwest Germany varies from the original parameterization data (northwest Germany), we re-parameterized the simulator’s four basic growth equations using data from southwest Germany (Albrecht et al., 2011, 2012b).

The simulator was implemented in software using the Java language (website in German: http://www.nw-fva.de/?id=194).

2.2. Storm damage model

The storm damage model (SDM) was developed for six major European tree species groups and represents storm damage from three large-scale winter cyclones (1967, 1990, 1999) as well as dispersed damage from minor storms that occurred between 1950 and 2007 in long-term experimental plots located in southwest Germany (Albrecht et al., 2012a). Since it is based on observed storm damage it is considered an empirical SDM, in contrast to mechanistic SDMs which are primarily based on the predicted mechanical behavior of trees under wind loading (Gardiner et al., 2008).
The SDM calculates the storm damage probabilities in four steps and converts the conditional probabilities into a binary prediction (cf. Albrecht et al., 2012a). The first three estimation steps are performed on the level of each forest stand, giving one of the results “stand undamaged”, “stand totally damaged” or “stand partially damaged”. In the first case all trees are marked as undamaged, whereas in the second case all trees are marked as damaged. In the third case a damage proportion is calculated as the percentage of basal area damaged. In Fig. 1 such a damage proportion is indicated by the value 0.32 for example. This stand-level value is then distributed amongst and downscaled to individual trees in step 4 by using tree-level attributes such as relative tree diameter. As a result, each tree is marked as damaged or undamaged.

Albrecht et al.’s SDM (2012a) relies on many predictors such as certain soil and forest site characteristics, topography, modeled wind gust speed, stand and tree dendrometric data, as well as information on forest management. The predictor sets vary across the species. Some of these predictors are site-related and remain constant regardless of forest management. Consequently, the growth simulator has no impact on these predictors. In contrast, other predictors (e.g., stand density, stand height) are influenced by tree growth or management.

For demonstration purposes in our sample simulation we chose two important conifer species in southwest Germany: Norway spruce and Silver fir. The SDM’s predictors for these species are shown in Table 1. These predictors refer mostly to stand-level attributes. Only the relative tree diameter and the relative tree h/d ratio are tree-level predictors. This relative h/d ratio was calculated by dividing the h/d ratio of the individual tree by the mean h/d ratio of the forest stand. Expressing this variable in relative terms allows its use as a predictor for different species and heights. The removal quotient quantifies whether thinned or removed trees are thicker or thinner than the mean stand diameter on average and indicates destabilization by thinning.

Differences between the two species models are that only the model for spruce contains the relative dominant height-diameter ratio and the time since previous thinning as predictors. The dominant height-diameter ratio (H100/D100) is defined as the height of the 100 thickest trees per hectare divided by the mean quadratic diameter. The relative H100/D100 value was obtained by dividing the absolute H100/D100 quotient by a species and height class specific reference value in order to use this predictor for different species and heights. Additionally, the wind gust speed data were not significant for the spruce model. We hypothesize that the spatial resolution of these data (1000 m) was not high enough to capture the topographic effects for this species and that the modeling of wind gust speed data as event-independent annuality did not correlate with the damage patterns observed for this species. For more details on the predictors see Albrecht et al. (2012a).

The uncertainty associated with the prediction of rare storm events in Central Europe (e.g., Knippertz et al., 2000; Pinto et al., 2007) led us to assume for our study that future storminess would remain in the medium term at a level similar to that observed for the period 1950 to 2007. Since the SDM had been parameterized from empirical storm damage data for this period, we consider it representative for this period and, consequently, our approach does not require input assumptions for wind gust speed, frequency or recurrence times of storms.

2.3. Coupling growth and storm damage models

To couple the growth model and the SDM, the growth model was extended by implementing the SDM into a java library (see flowchart Fig. 1). The coupling was eased since both storm-driven mortality and growth data have the same temporal resolution.

To be consistent with the aforementioned growth model, the SDM is activated at the beginning of each five-year simulation step. The wind-damaged trees are removed from the tree list before entering into the growth model. Then, silvicultural treatments are applied, if needed, before predicting the growth of the remaining trees in the stand (Fig. 1).

2.4. Model forest stands and management scenarios

We tested this modeling framework with six generated model forest stands which represent Norway spruce and Silver fir in southwest Germany at three different ages. The tree lists of those stands were generated from mean stand information in German forest yield tables for average site fertility (Landesforstverwaltung Baden-Württemberg 1993). The dendrometric data of the stands at the beginning of the simulation are given in Table 2. We calculated the development of the model stands for 50 years and ran 50-realization Monte Carlo simulations. We ran the simulations with and without the SDM (undisturbed reference) and for three types of forest management, henceforth

![Flowchart of one growth interval for the coupled estimation of forest growth and storm damage. Growth model adapted from Nagel et al. (2002). Storm damage model adapted from Albrecht et al. (2012a).](image)
referred to as the baseline, intensified, and shortened rotation regimes, respectively. Starting from the baseline regime, which represents current forest management in southwest Germany (Tables 3 and 4, scenarios 1, 2 and 3), the settings for alternative forest management regimes were successively intensified. Firstly, target diameters were lowered by 10% and thinning intensity was increased (scenarios 4–7). Secondly, target diameters were lowered by an additional 10% (scenarios 8 and 9). We also varied the thinning type in the scenarios. Thinnings in southwest Germany are commonly performed as thinning from above, which requires removing some dominant competitor trees in a stand in favor of target crop trees. For comparison, however, we defined the thinning type in scenarios 3 and 6 as thinning from below, i.e. to remove only suppressed and intermediate tree individuals within a stand. As an extra variant, we prescribed less frequent thinnings in scenario 7 by raising the minimum thinning volume. Later on in stand development, trees reach their target diameter and may be removed as harvest trees and no longer as thinned trees. Thus, the settings for maximum harvest volume (last column in Table 3) limit the allowable amount of wood which may be removed in one harvest cut per 5 years. In scenarios 4 through 9 we allowed more intense final harvesting by increasing this variable's values from 200 to 300.

The species-specific settings in Table 4 were selected to simulate contrasting stand densities for the respective treatment regimes. The relative density of a stand refers to the maximum density of an unmanaged forest stand at the same H100 value. The different values for different height strata allow the user to vary the target stand density for different stand heights. The thinning intensity is a relative measure indicating how strongly the competitors around the crop trees are removed (the higher its value, the more competitors are removed). The number of crop trees indicates how many trees per hectare are selected as future target trees. Within the simulator, these crop trees are permanently marked and favored by successively removing some competitor trees around the crop trees. For comparison, we defined the thinning type in scenarios 3 and 6 as thinning from below, i.e. to remove only suppressed and intermediate tree individuals within a stand. An extra variant, we prescribed less frequent thinnings in scenario 7 by raising the minimum thinning volume. Later on in stand development, trees reach their target diameter and may be removed as harvest trees and no longer as thinned trees. Thus, the settings for maximum harvest volume (last column in Table 3) limit the allowable amount of wood which may be removed in one harvest cut per 5 years. In scenarios 4 through 9 we allowed more intense final harvesting by increasing this variable's values from 200 to 300.

With the large range of the chosen silvicultural scenarios we intended to quantify the effects of storm damage on forest growth (hypothesis 1) and of the different forest management regimes on the amount of storm damage (hypothesis 2).

The productivity in the different scenarios with storm damage was compared to that of the undisturbed scenario using non-parametric pairwise Kruskal Wallis tests. These comparisons were carried out for three scenario groups: 1) baseline scenarios (undisturbed, reference), 2 and 3;III) intensified scenarios 4 (undisturbed, reference), 5, 6, and 7, and III) shortened rotation scenarios 8 (undisturbed, reference) and 9. The mean annual increment was used as an indicator for quantitative wood productivity. It is calculated as the sum of all removed timber (thinned and wind-thrown trees) during the 50-year simulation period, adding the change in standing wood volume between the beginning and the end of the simulation, and dividing by the number of years, in our case by 50.

Additionally, the amount of storm damage was compared between the scenarios containing storm damage. Again, the comparisons were made using non-parametric pairwise Kruskal Wallis tests for the following pairs: scenarios 5, 7 and 9 were compared to baseline scenario 2, respectively (all thinnings from above); intensified scenario 6 was compared to baseline scenario 3 (all thinnings from below).

In cases where a model stand was entirely damaged by storm during the simulation we replaced it with a young stand of the same species for the remaining simulation time. Growth of each newly replaced young stand was continued until the total simulation period was reached. If, for example, an old Silver fir stand was predicted to be totally damaged by storm after 20 years of simulation, a young stand of age 0 took its place and was grown for the remaining 30 years of the simulation. This assumption was necessary to calculate the dendrometric variables including total volume production, since not assuming any replacement would lead to systematically underestimating productivity.

For the presentation of the results we first show the development of standing wood volume by simulation year and scenario (3.1). Subsequently, to compile the results of all scenarios more concisely, we calculated the mean standing wood volume increment (the so-called mean annual increment, see 3.2), the proportion of storm damage relative to total volume production (3.3), and the proportion of storm damage relative to all removals (3.4).

2.5. Performance evaluation

In a first step BWinPro was evaluated in separate form to test the reliability of the growth component in our framework. We evaluated two key dendrometric variables with quantitative tests based on a previous evaluation study (Albrecht et al., 2011, 2012b) and methodological considerations described by Vanclay and Skovsgaard (1997).

In a second step we evaluated the coupled modeling framework of BWinPro with the SDM following the suggestions by Bennett et al. (2013), complemented by aspects of Robson (2014). We compared the simulation results to observed storm damage data, and the following qualitative and quantitative aspects of evaluation were:

- Reassessing the model's aim, scale and scope
- Comparison of the data for calibration and evaluation
- Visual analysis of modeled and non-modeled behavior
- Basic performance criteria

2.5.1. Evaluation of BWinPro

We evaluated BWinPro based on two key dendrometric variables and calculated the relative decennial bias as a measure of performance. As an indicator for stand density development we selected basal area (G) and as an indicator for height increment we selected dominant stand height (H100) as evaluation variables.

Data from long-term research plots served for the evaluation. Two thirds of these data were used for the re-parameterization of BWinPro for southwest Germany, while the last third was set aside for the evaluation. The evaluation data consisted of 301 Norway spruce and 48 Silver fir stands, representing a total of 375,699 tree observations (Albrecht et al., 2011, 2012b).

### Table 2
Dendrometric stand characteristics of the model forest stands at the beginning of the simulation. Dg: mean quadratic diameter of all trees. D100: mean quadratic diameter of the 100 thickest trees per ha. H100: mean height of the 100 thickest trees per ha. N: number of stems. V: standing wood volume (total stand volume over bark with a 7-cm minimum diameter at smaller end).

<table>
<thead>
<tr>
<th>Stand ID</th>
<th>Short stand ID</th>
<th>Age [years]</th>
<th>Dg [cm]</th>
<th>D100 [cm]</th>
<th>H100 [m]</th>
<th>N [ha⁻¹]</th>
<th>V [m³·ha⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norway spruce young</td>
<td>NSpr_yng</td>
<td>30</td>
<td>11</td>
<td>19</td>
<td>13</td>
<td>3224</td>
<td>139</td>
</tr>
<tr>
<td>Norway spruce medium</td>
<td>NSpr_med</td>
<td>50</td>
<td>17</td>
<td>27</td>
<td>23</td>
<td>1656</td>
<td>351</td>
</tr>
<tr>
<td>Norway spruce older</td>
<td>NSpr_old</td>
<td>80</td>
<td>28</td>
<td>43</td>
<td>31</td>
<td>720</td>
<td>593</td>
</tr>
<tr>
<td>Silver fir young</td>
<td>SFir_yng</td>
<td>30</td>
<td>10</td>
<td>16</td>
<td>12</td>
<td>4556</td>
<td>127</td>
</tr>
<tr>
<td>Silver fir medium</td>
<td>SFir_med</td>
<td>50</td>
<td>18</td>
<td>29</td>
<td>20</td>
<td>1732</td>
<td>360</td>
</tr>
<tr>
<td>Silver fir older</td>
<td>SFir_old</td>
<td>80</td>
<td>33</td>
<td>49</td>
<td>30</td>
<td>572</td>
<td>611</td>
</tr>
</tbody>
</table>

### Table 3
Simulation settings for the forest management scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Regime</th>
<th>Target diameter (height of first thinning)</th>
<th>Type of thinning</th>
<th>Thinning volume (min–max) [m³·ha⁻¹]</th>
<th>Max. harvest volume [m³·ha⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (undisturbed)</td>
<td>Baseline</td>
<td>60 cm (15 m)</td>
<td>From above</td>
<td>10–80</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>Baseline</td>
<td>60 cm (15 m)</td>
<td>From above</td>
<td>10–80</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>Baseline</td>
<td>60 cm (15 m)</td>
<td>From below</td>
<td>10–80</td>
<td>200</td>
</tr>
<tr>
<td>4 (undisturbed)</td>
<td>Intensified</td>
<td>54 cm (14 m)</td>
<td>From above</td>
<td>10–120</td>
<td>300</td>
</tr>
<tr>
<td>5</td>
<td>Intensified</td>
<td>54 cm (14 m)</td>
<td>From above</td>
<td>10–120</td>
<td>300</td>
</tr>
<tr>
<td>6</td>
<td>Intensified</td>
<td>54 cm (14 m)</td>
<td>From below</td>
<td>10–120</td>
<td>300</td>
</tr>
<tr>
<td>7</td>
<td>Intensified</td>
<td>54 cm (14 m)</td>
<td>From above</td>
<td>50–120</td>
<td>300</td>
</tr>
<tr>
<td>8 (undisturbed)</td>
<td>Shortened rotation</td>
<td>49 cm (12 m)</td>
<td>From above</td>
<td>10–120</td>
<td>300</td>
</tr>
<tr>
<td>9</td>
<td>Shortened rotation</td>
<td>49 cm (12 m)</td>
<td>From above</td>
<td>10–120</td>
<td>300</td>
</tr>
</tbody>
</table>
3. Results

3.1. Development of standing wood volume

In the undisturbed scenarios (1, 4 and 8) the mean standing wood volume at an equivalent stand age attained the highest values in the baseline scenario (Fig. 2). The volumes for the intensified and shortened rotation scenarios were well below those values, in some cases 50% lower. The differences between the intensified and the shortened rotation scenarios were smaller than their respective differences to the baseline scenario. In general, Silver fir had a slower volume growth than Norway spruce. Consequently, Norway spruce reached the target diameter earlier and was harvested more quickly than Silver fir, as is apparent by the accelerated decrease of standing wood volume in the older Norway spruce stands and in the young and mid-aged Norway spruce stands of the intensified and shortened rotation scenarios.

The scenarios equivalent to those in Fig. 2, but including storm damage simulations, showed significant drops in standing wood volume, especially in the mid-aged and older stands (Fig. 3). Total storm damage (loss of entire stand) was quite frequent, as indicated by vertical straight lines. In mid-aged and older stands of both species, partial storm damage was apparent by stepwise lowering of standing wood volume.

3.2. Changes in productivity

Norway spruce showed a higher mean annual increment than Silver fir. When comparing the different forest management regimes (baseline, intensified, shortened rotation) productivity was generally lowered by intensifying the interventions. This was especially apparent in Silver fir stands, where productivity drops significantly, whereas it was not very obvious in mid-aged Norway spruce.

For both species, the impact of storm damage on productivity was predominantly negative in all scenarios and age groups. There were only a few cases where productivity did not change as a reaction to storm damage (scenarios without asterisks or circles in Fig. 4). In young stands of both species the productivity actually significantly increased in scenario 7 compared to the undisturbed scenario 4.

The observed differences in productivity were more strongly influenced by the different forest management regimes, tree species and age of the model forest stands than by the presence or absence of storm damage.

3.3. Storm damage relative to total volume production

Storm damage in the young stands was generally low (Fig. 5). Although the damage increased in the mid-aged stands, the median proportion of storm damage remained low and did not exceed 10% of the total volume production in most cases. Actually, only two scenarios of mid-aged Norway spruce stands exhibited median damage larger than 10%. The variability in damage increased in the mid-aged stands, with some Norway spruce stands having more than 50% of damage.

Windstorm damage clearly increased for the older stands and shortened rotation productivity was generally lowered by intensifying the interventions. This was especially apparent in Silver fir stands, where productivity drops significantly, whereas it was not very obvious in mid-aged Norway spruce.

For both species, the impact of storm damage on productivity was predominantly negative in all scenarios and age groups. There were only a few cases where productivity did not change as a reaction to storm damage (scenarios without asterisks or circles in Fig. 4). In young stands of both species the productivity actually significantly increased in scenario 7 compared to the undisturbed scenario 4.

The observed differences in productivity were more strongly influenced by the different forest management regimes, tree species and age of the model forest stands than by the presence or absence of storm damage.

3.4. Storm damage relative to all removals

The amount of storm damaged timber in comparison to all removed timber was an indicator of the degree of disturbance in managed forests. In young stands of both species, the storm damage proportion was below 5%, except in Norway spruce for scenarios 2 and 3 (Fig. 6). In mid-aged and older Norway spruce stands, the highest proportions of storm damage ranged from 30 to slightly more than 40%. Considerably higher proportions were found in older Silver fir stands in scenarios 2 and 3. Comparing the
storm damage proportions between the two species, Norway spruce showed higher damage in young and mid-aged stands, while Silver fir showed heavier damage proportions in older stands.

Comparing differences between the treatment scenarios showed the general trend that intensified treatment and shortened rotation decrease damage proportions. This effect was strong for mid-aged Norway spruce and older Silver fir, but not for mid-aged

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**Fig. 2.** Development of the standing wood volume for the six model forest stands during the 50-year simulation. The different line types depict scenarios without storm damage: 1 (Baseline), 4 (intensified) and 8 (shortened rotation); the multiple lines of each line type show the 50 repeated runs of each scenario. Top row panels: Norway spruce (NSpr), bottom row panels: Silver fir (SFir). The three columns of panels show young (yng), mid-aged (med) and older (old) stands.

**Fig. 3.** Development of the standing wood volume for the six model forest stands for the scenarios with storm damage during the 50-year simulation. The different line types depict the three selected scenarios with storm damage; the multiple lines of each line type show the 50 repeated runs of each scenario. Top row panels: Norway spruce (NSpr), bottom row panels: Silver fir (SFir). The three columns of panels show young (yng), mid-age (med) and older (old) stands.
Silver fir. In older Norway spruce, scenarios 5, 7 and 9 showed less damage than scenarios 2 and 3. However, scenario 6 led to comparable proportions. Scenarios with thinning from below (3 and 6) led to higher damage proportions than the respective scenarios with thinning from above (2 and 5) for Norway spruce and older Silver fir. The less frequent but heavier thinnings in scenario 7 did not show large differences in storm damage proportions compared to scenario 5.

3.5. Performance evaluation

3.5.1. BWinPro

Comparing the development of standing wood volume for the undisturbed scenarios we found noticeable differences between Silver fir and Norway spruce (Fig. 2). The simulations for young and mid-aged Silver fir stands showed slower growth rates than Norway spruce. Additionally, the mean annual increment (Fig. 4) of the Norway spruce model stands of all ages is higher than the increment of Silver fir. As the evaluation data set we used observations from the long-term research plots.

The relative decennial bias for dominant stand height (H100) was positive for both species (Table 5) while overestimation was stronger for Silver fir than for Norway spruce. The density measure basal area (G) was very precisely estimated for Norway spruce but underestimated for Silver fir.

3.5.2. Coupled performance of BWinPro and the SDM

3.5.2.1. Reassessing the model’s aim, scale and scope. The primary aims of our modeling framework were to estimate long-term average storm damage independently of individual storm events and to model storm damage for different management alternatives. Overall, the estimated damage in the simulations was considered to adequately reproduce observed damage patterns, as will be illustrated in more detail below. Besides reproducing this general damage pattern, the different silvicultural scenarios led to different amounts of storm damage (Figs. 5 and 6). Thus, the model’s primary aims are fulfilled, based on visual assessment and qualitative consideration.

The spatial scale of the modeling framework is the forest stand as the prognostic unit. The geographic scale and extent of applicability cover southwest Germany. The model’s scale is thus as desired. However, since the underlying models are empirical models, transferring this system into other geographic areas would require recalibration of the models’ parameters (Porté and Bartelink, 2002). The temporal scale of the underlying data covers the second half of the 20th century and further until 2008 thus providing the reliability of a multi-decade longitudinal dataset for both forest growth and storm damage.

For the purpose of clarity and simplicity we only presented results for two tree species in this study, although the system is available for six species groups and thus has a considerable scope of applicability. The additional four species groups are European beech (Fagus sylvatica L.), Douglas fir (Pseudotsuga menziesii (MIRBEL) FRANCO) each as individual species, pedunculate (Quercus robur (L.)) and sessile oak (Q. petraea (MATTUSCHKA) LIEBL.) grouped together as oaks, and Scots pine (Pinus sylvestris (L.)), European (Larix decidua (MILL.)) and Japanese larch (L. kaempferi (LAMB.) CARRIERE) grouped together as pines and larches. The six
Fig. 5. Comparison of the relative amount of storm damage between the scenarios including windstorms for the six model forest stands. Description of the boxplots see caption of Fig. 4. Triangles: mean values. Asterisks indicate significant differences (α = 0.05) between the scenarios.

Fig. 6. Relative share of removed wood volume (−100%) by cause of removal (‘RemovalCode’). The proportion of ‘storm damage’ characterizes the degree of disturbance. ‘Thinned’ refers to trees removed during the tending and thinning phase of stand development, ‘harvested’ are trees which have reached the target diameter (final crop).
tree species groups for which the system is available represent over 80% of all German and southwest German forests (BMVEL, 2006). However, the scope is limited to uniform age-class and monocultural forest stands. Multi-layered and species-diverse forest stands are unfortunately not represented by the parameterization database.

3.5.2.2. Comparison of calibration and evaluation data.

To check for potential issues of extrapolation of the simulated treatment scenarios we compared the basal area development of the simulated stands to the values in the parameterization data set (Fig. 7). Most values of the simulations are contained in the data area of the parameterization data set of the SDM. The simulated data ranges not covered by the parameterization data are low-density management in Silver fir stands above 30 m in height and stands for both species surpassing 38 m in height.

Additionally, the relative removals were verified and we found the simulated treatments mostly contained within the range of the parameterization data (Fig. 8). For both species, some heavier removals above 0.5 occurred in the simulations but were not observed in the parameterization data. Note that the relative removal is not the same as the variable ‘removal quotient’ which is used in the SDM. However, for the characterization of the management regimes the relative removals are more meaningful.

Based on these comparisons we conclude that the parameterization and the simulation data sets are generally comparable with respect to the key variables describing the forest management regimes. Some minor parts of the simulation data are in the extrapolation zone, especially stands taller than 38 m and low-density Silver fir stands taller than 30 m.

3.5.2.3. Visual analysis of modeled and non-modeled behavior.

The presented framework reproduced partial damage as well as complete loss of stands due to storm. The presence of both these phenomena is illustrated by the U-shaped bimodal distribution of relative storm damage in the simulation data set (Fig. 9). This pattern was also present in the parameterization data set and is characterized by a first peak close to zero and a second peak between 0.75 and 1.0 (total damage). However, for Silver fir, total stand damage (0.6–0.85) was overestimated in frequency in the simulation compared to the observed events in the parameterization data set. Total damage in the simulation data for both species was actually rarely ‘total’, so that in most cases some trees remained in the damaged stands. This becomes apparent by the second peak of the damage distribution which is actually closer to 0.8 than to 1.0 for the simulation data.

3.5.2.4. Basic performance.

Storm damage for the simulated model stands amounts to an average of 3.39 m³ha⁻¹a⁻¹ for Norway spruce and 3.55 m³ha⁻¹a⁻¹ for Silver fir and is thus slightly higher than the mean observation of 2.66 m³ha⁻¹a⁻¹ for both species (Fig. 10; observation data were only available for both species together). This overestimation is on average equivalent to a relative bias of +30%, but differs strongly between the silvicultural scenarios. Especially the baseline scenarios showed high positive bias (Table 6).

4. Discussion

4.1. General reconsideration of the approach

Storm damage in forests is known to depend on site factors, such as geographic position, exposure, soil characteristics etc. (Dobbertin, 2002; Hautala and Vanha-Majamaa, 2006; Nicoll et al., 2006; Zubizarreta-Gerendiain et al., 2012). Our proposed modeling framework is purposely kept insensitive to these site factors due to the following reasons:

- the underlying empirical storm damage model contains some of these site factors as predictor variables, but the factors differ for the different tree species (Albrecht, 2009). Varying the factors for some tree species but not for others would thus impede the comparability between the species analyzed;
- the overall impact of site and soil characteristics on storm damage – although statistically significant – was only moderate compared to the impact of the forest stand attributes;
forest management options within this modeling framework are ideally studied as alternatives for one specific stand at a time. Due to the architecture of the storm damage model, varying the site conditions would only change the general level of damage, but not the relative differences between the treatment options. Consequently, the application of the framework is suited for comparative studies under the assumption of average and constant site conditions under ceteris paribus assumptions.

Damaging large-scale storms in Central Europe are mainly extratropical winter cyclones from the North-Atlantic storm track (Hurrell et al., 2001; Leckebusch et al., 2006). These cyclones are rare events and their occurrence is characterized by enormous long-term variability (Marshall et al., 2001). Much effort has been undertaken to estimate future storm frequencies and intensities and there are some indications that future storms might become more intense or even more frequent (Bengtsson et al., 2006; Beniston et al., 2007; Lambert, 1995; Lambert and Fyfe, 2006; Zhang and Wang, 1997). However, frequency and intensity of storms are not directly linked, and some studies also showed decreasing frequency or intensity of future storms (Finnis et al., 2007; Pinto et al., 2007). Furthermore, it is also possible that long-term meteorological and climatic phenomena (>150 years) may override short and medium term trends, as e.g. observed in shorter time series of wind speed or air pressure data (<150 years).

As a consequence of the inconsistent results in this question we decided to assume average storminess as observed between 1950 and 2007 for our study. Storm damage in our study is thus modeled independently from wind gust speed simulations and from the

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**Fig. 8.** Comparison of the removal intensity for the simulation and the parameterization data sets. Relative removal is calculated as the proportion of wood volume removed divided by standing wood volume before the removal.

**Fig. 9.** Patterns of storm damage occurrence in simulation and parameterization data. Abscissae values are calculated as storm damaged basal area divided by total basal area before storm damage for each stand. Only occurrences with storm damage are displayed.
occurrence frequency of storm events. This approach has the disadvantage of being incapable of considering future changes in storminess. But this disadvantage is at the same time its advantage, since it makes the modeling system independent of any inconsistencies in input data on storminess. Therefore, we judged this approach appropriate for the main objective of our study, which was to develop a software prototype capable of evaluating general and long-term strategies for minimizing the risk of storm damage in forests independently of individual storm events.

### 4.1.1. Simulation data

The choice of the model stands developed for our simulations was driven by the aspects simplicity and neutrality. Since this paper is presenting the functioning of the modeling system we chose a minimal dataset of two species and the dendrometric data listed in the yield tables. All results are thus referring to the context of the minimal dataset of two species and the dendrometric data listed in the yield tables. All results are thus referring to the context of the six model stands. For example, the simulation data do not include stands which are very young at the beginning of the simulation (0 or 5 years). Including those very young stands would most probably reduce the simulated amount of storm damage and thus uncertainty.

Table 6

<table>
<thead>
<tr>
<th>Species</th>
<th>Scenario</th>
<th>Mean annual storm damage $[\text{m}^3\text{ha}^{-1}\text{a}^{-1}]$</th>
<th>Relative bias</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulated</td>
<td>Observed</td>
<td></td>
</tr>
<tr>
<td><strong>NSpr</strong></td>
<td>2</td>
<td>3.96</td>
<td>2.66</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.37</td>
<td>2.66</td>
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<tr>
<td></td>
<td>5</td>
<td>2.60</td>
<td>2.66</td>
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<tr>
<td></td>
<td>6</td>
<td>3.65</td>
<td>2.66</td>
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<td>2.00</td>
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<td>9</td>
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<tr>
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<tr>
<td></td>
<td>3</td>
<td>5.04</td>
<td>2.66</td>
</tr>
<tr>
<td><strong>SFir</strong></td>
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<td>3.17</td>
<td>2.66</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2.79</td>
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<td></td>
<td>Mean</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The observed differences in productivity between Norway spruce and Silver fir were evaluated and do not seem to originate from a malfunctioning of the growth model (Table 5). And while other authors have reported similar and general differences in total volume production between these two species (Schöpfer et al., 1997), the data of the National Forest Inventory do not show such differences for southwest Germany (BMVEL, 2006). This contradiction may be explained by different reference periods of the National Forest Inventory data and the model stand data. Another reason for reduced productivity of Silver fir may be its ecological properties: as it is a shade-tolerant and climax species much more than Norway spruce, it might be physiologically less efficient in expanding into newly created growing space. While heavy thinnings have a strong positive release effect on Norway spruce increment this effect is much less expressed for Silver fir (Spathelf, 1998). Silver fir’s ecological niche as a shade-tolerant species with slower growth reactions may also be explained by its generally higher light use efficiency (Forrester and Albrecht, 2014).

Alternative data sources for the model stands could have been data from the national or local forest inventories. However, after preliminary testing, those data sources had proven unsuitable for our purposes: generating pure stands based on the mentioned inventories yielded stands with unrealistically low density. This problem was especially eminent for Silver fir. We hypothesize that this is due to the sampling scheme of the forest inventories and the algorithms used to extract pure stand data based on empirical data of mixed stands. And since our modeling system requires pure stands we could not use these data.

### 4.1.2. Evaluation results and evaluation data

The occurrence of both partial and total storm damage in the simulation data illustrates the system’s capacity to reproduce realistic damage patterns. This has to be pointed out as well-modeled behavior and as an advance in storm damage modeling, since other modeling approaches either predict the risk of storm damage on the basis of individual trees only (i.e. Schmidt et al., 2010) or on the basis of one average tree per stand or even on the stand-level in general without attributing that risk back to individual trees (i.e. Jalkanen and Mattila, 2000). And although those alternative approaches have other advantages they are less likely to reproduce the characteristic U-shaped distribution patterns.

The overestimation of storm damage in the models by an average of 30% requires further discussion: Firstly, it is not a general characteristic for the entire modeling system but it is restricted to the six model stands. For example, the simulation data do not include stands which are very young at the beginning of the simulation (0 or 5 years). Including those very young stands would most probably reduce the simulated amount of storm damage and thus reduce the overestimation.

Secondly, most forest growth models simply ignore many types of disturbance-based mortality. Although many reasons exist to explain why this is the case, this assumption is actually over-optimistic concerning forest growth as an ecosystem process. And while our approach may have overestimated storm damage for the model stands, it is at least a first step towards more holistic ecosystem modeling. It is certain that including disturbance into forest growth modeling will increase the variability of the results, and thus uncertainty.

For alternative internal evaluation or cross-validation the number of observations for total storm damage in the permanent research plots was too low. Following considerations of Bennett et al. (2013, p. 14) for data-poor situations we chose the above-mentioned alternative evaluation techniques.
A potential future evaluation study based on extensive data representative of empirical southwest German forests could elucidate potential systematic bias for storm damage. Additionally, the effect of different silvicultural regimes on the economic productivity could be investigated in such a study, including the effects of storm damage.

4.1.3. Extrapolation

The performance evaluation additionally revealed an extrapolation problem: low density Silver fir stands (\(\leq 20 \text{ m}^2 \text{ ha}^{-1}\)) above 30 m of dominant height, and all stands of both species taller than 38 m lie in the extrapolation zone which is not covered by the parameterization data. Additionally, some simulated treatments were found to be more intense in terms of relative removed volume than covered in the parameterization data. As extrapolation is a theoretical constraint to any empirical model, we have to specify the short-rotation scenario for older Silver fir stands as well as all scenarios with stands surpassing heights of 38 m as unevaluated and unreliable. One possibility to overcome this issue in future research could be to couple empirical and mechanistic storm damage models and to combine the advantages of both modeling disciplines.

4.2. Hypotheses

4.2.1. H1: storm damage has significant impact on forest growth

The observed changes in mean annual increment as a function of considering storm damage or not, have to be seen as systematic. Productivity is systematically and significantly reduced by storm damage, and consequently we cannot reject hypothesis 1.

The observed effect of treatment on mean annual increment is in many cases stronger than the effect of storm damage. This is an important finding as it shows that in the simulations of our model stands ecosystem productivity seems less influenced by storm damage than by forest management.

An important effect is the impact of strong winds on growth of trees and forest stands that survive storms. If strong winds do not lead to tree failure, the remaining trees react in different ways: height growth in windy sites appears to be reduced compared to sheltered locations (Cremer et al., 1982). However, the overall reduction in height growth due to wind is smaller than the natural variability of height growth due to the fertility of soils, at least for sites with mean annual wind speed below 15 km/h (Watt et al., 2010). Diameter growth, on the other hand, can be either reduced or increased by the impact of wind. If winds are strong and cause uprooting or breakage of trees the remaining trees may suffer, at least temporarily, a reduction of diameter growth. In such cases trees seem to experience either a growth shock due to the sudden release, or may even show structural damage in their tissues due to a storm event. This can lead to reduced photosynthetic activity and diameter growth (Seidl and Blennow, 2012). After this phase remaining trees may experience an increased diameter growth if neighboring trees were windthrown and the growing space was enlarged. Another explanation of increased diameter growth consequential of wind impact is an active physiological process of stabilization which is referred to as acclimation or acclimative growth (Telewski, 1995). Wind also affects the biomass allocation between the root and shoot components of trees (Nicol et al., 2008).

The effects of strong winds on survivor forest stands have not yet been explicitly implemented into forest growth models. The way we implemented the effect of storm damage on the growth of the trees remaining is technically identical to the release effect of regular thinnings. No studies have been carried out to compare the growth reduction and the growth increase as a reaction of the remaining trees to the release caused by storm damage. At this point it is thus not clarified how storm damage affects the remaining forests and forest stands in the mid-term and whether there is a positive or negative net effect on growth. Future studies should investigate these components thoroughly and expand the existing knowledge.

4.2.2. H2: the amount of storm damage is sensitive to forest management regimes

In the simulation scenarios, intensification of forest management significantly reduces storm damage in older stands of Silver fir, but not in Norway spruce. Damage proportions in Silver fir are nearly halved from high values of around 75% to values around 40% by reducing target diameters from 60 to 54 cm, and even reduced more strongly by further reducing target diameters to 49 cm (damage proportions below 20%). However, the intensification of silvicultural management in Silver fir simultaneously leads to significantly reduced productivity. Consequently, when intensifying forest management, losses of total volume production have to be weighed against the aspects of avoiding storm damage.

For the older stands of Norway spruce, such a reduction of damage was not observed for the analyzed sample stands in our study. However, in mid-aged Norway spruce, intensified management lead to a reduction in storm damage.

Our findings underline the potential to minimize risk of storm damage by adapting silvicultural treatment. However, they also show that the appropriate treatment strategy has to be elaborated carefully and individually for every forest situation. We can confirm reducing target diameters as a measure to reduce storm damage for some situations. Bock et al. (2005) recommended shortening the rotation length for European beech stands as a silvicultural means for reducing vulnerability to wind storm damage. Although we reach similar conclusions, our findings are naturally limited to the model stands used in our simulations.

Comparing the thinning types we found that ‘thinning from below’ showed a light tendency to increase storm damage when related to the total volume production (mid-aged Norway spruce in scenario 3, older Silver fir and Norway spruce in scenario 6, Fig. 5). The same tendency appeared more pronounced in the proportion of storm damage to all removed wood volume (Fig. 6). We do not have knowledge of other studies analyzing storm damage as a function of the type of thinning. However, the intensity of thinning has previously been found to be positively correlated with storm damage (Cremer et al., 1982; Lohmander and Helles, 1987; Schmid-Haas and Bachofen, 1991; Wallentin and Nilsson, 2014).

The same finding additionally indicates that the meaning of the removal quotient as an indicator for destabilization is somewhat limited. Although removing dominant trees in tall stands produced a high risk of subsequent storm damage in the study of Albrecht et al. (2012a), the results of our study rather associate higher risk with thinning from below, at least for mid-aged and older Norway spruce. In summary, the removal quotient has significant impact on storm risk, but not of the same direction for all cases. And compared to other risk factors such as stand height and tree species, the overall magnitude of its effect as a risk indicator is subordinate. Unfortunately, no other studies in this context are known to the authors.

By comparing scenarios 5 and 7 we analyzed the detailed forest management question of how many thinning interventions one should remove a given amount of wood volume per decade. We found that the intensified scenario, where thinnings were conducted less frequently but more heavily (scenario 7), performed very similarly to scenario 5. Differences between these two scenarios would have revealed whether the temporary destabilization
of forest stands by thinnings is mostly proportional to the frequency of interventions or more linked to the intensity of thinnings. However, we could not detect differences between these two thinning types and have to reject hypothesis 2 in this partial question. For the minimization of storm damage in applied forestry this means that one strong thinning per decade is equivalent to many thinnings as long as the same volume is harvested. However, we recommend caution in generalizing this finding since it is limited to the analyzed model stands and contrary to common notion among forest practitioners. Although much practical knowledge exists among forest managers, no comparable scientific publications concerning this aspect are known to the authors.

Nevertheless, in the context of the objectives of our study the important finding is that the tested modeling framework reacts sensibly and sensitively to different forest management settings. Thus, the results support hypothesis 2.

5. Conclusions

The proposed framework for combining forest growth simulations with storm damage modeling produces results for different scenario calculations. As intended, it is sensitive to different input forest stand data and to forest management settings and information about the effects of storm damage on the development of forest stands and forest growth. As a decision support tool it is suited to compare the risk of storm damage for different tree species, stand ages and alternative treatment options. For the presented sample data it showed clear differences when varying these factors. However, small changes in the settings as well as in the input data led to considerable changes in the simulation results. Due to the basic characteristics of the modeling system we suggest its use only for long-term simulation and silvicultural optimization (30–50 years) but not for short and mid-term prognosis (10–20 years).

This prototype system can thus be employed to develop new strategies for risk reduction and to evaluate existing strategies. It helps synthesize knowledge previously gained for clear-cut forestry systems (Zeng et al., 2004, 2007) and extends the considerations of risk minimization to non-clear-cut forestry. However, for reliable forest management recommendations we suggest conducting further simulation studies with more sample stands, additional species and variation in soil and site settings.

Our sample application of the proposed coupled modeling framework suggests that certain measures of forest management may significantly influence the amount of storm damage in forests. For example, reducing target diameters by 10% reduced the amount of storm damage by 50% in some cases for Silver fir. Thus, this measure seems over-proportionally effective when mitigating the impact of storm damage in forest ecosystems.

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References


