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독일 아이펠의 지역적 관리에 따른 유럽너도밤나무 숲의 생장변화 추정을 위한 시뮬레이션 개발

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Development of Simulation for Estimating Growth Changes of Locally Managed European Beech Forests in the Eifel Region of Germany

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ABSTRACT

Forest management is known to beneficially influence stand structure and wood production, yet quantitative understanding as well as an illustrative depiction of the effects of different management approaches on tree growth and stand dynamics are still scarce. Long-term management of beech forests must balance public interests with ecological aspects. Efficient forest management requires the reliable prediction of tree growth change. We aimed to develop a novel hybrid simulation approach, which realistically simulates short- as well as long-term effects of different forest management regimes commonly applied, but not limited, to German low mountain ranges, including near-natural forest management based on single-tree selection harvesting.

The model basically consists of three modules for (a) natural seedling regeneration, (b) mortality adjustment, and (c) tree growth simulation. In our approach, an existing validated growth model was used to calculate single year tree growth, and expanded on by including in a newly developed simulation process using calibrated modules based on practical experience in forest management and advice from the local forest. We included the following different beech forest-management scenarios that are representative for German low mountain ranges to our simulation tool: (1) plantation, (2) continuous cover forestry, and (3) reserved forest. The simulation results show a robust consistency with expert knowledge as well as a great comparability with mid-term monitoring data, indicating a strong model performance.

We successfully developed a hybrid simulation that realistically reflects different management strategies and tree growth in low mountain range. This study represents a basis for a new model calibration method, which has translational potential for further studies to develop reliable tailor-made models adjusted to local situations in beech forest management.

Key words : European beech, Hybrid simulation, Long-term stand dynamics, Local forest management

요 약

숲을 체계적으로 관리하고 경영하기 위해서는 나무생장 변화에 대한 신뢰성 있는 예측이 필요하다. 독일의 아이펠 지역에서는 주요 목재종인 유럽너도밤나무가 식재되어 관리되어 지고 있다. 본 지역의 산림관리자의 실제 산림경영의 경험과 조언을 토대로, 다양한 산림 관리에 따른 단기 및 장기 효과를 예측하고자 지역 특수성을 지니는 시뮬레이션 모델의 접근방법을 개발하고자 하였다. 시뮬레이션 모델은 (1) 묘목 생성, (2) 나무 사멸 조절 (3) 나무 생장의 세 가지 모듈로 구성된다. 산림관리자에 의해 제공된 너도밤나무 숲의 실제 부피 변화를 근사화하기 위해 다양한 변수(나무수, 나무간 거리, 씨앗의 분포, 경쟁)를 반복적으로 수정하여 세 가지 모듈을 결합한 하이브리드 시뮬레이션 모델을 개발할 수 있었다. 본 연구를 통해 유럽너도밤나무 숲의 350년을 모의하여 생장 변화를 예측하였으며, 아이펠 지역의 세 가지 다른 관리 방법 (숲을 보호한 상태에서 목재벌채, 선택적 벌목, 보호림) 시나리오를 적용하였을 때 모의된 결과를 비교하였다. 시뮬레이션 결과를 통해 나무 생장의 변화가 현실적으로 잘 반영되었다는 것을 확인할 수 있었으며, 미래에 장기간 실제 축적된 산림 데이터를 획득하여, 검증과 보정의 과정을 반복한다면 더 높은 정확도의 지역 맞춤형 모델이 개발될 수 있을 것으로 사료된다.

주요어 : 유럽너도밤나무, 하이브리드 시뮬레이션, 지역 숲 관리, 장기적인 숲 구조 변화

1. Introduction

Currently, the European beech (*Fagus sylvatica*) is the most common tree species in Germany. Beech forests cover an area of 1.68 million hectares, which represents approximately 15 % of Germany’s total forest

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* A part of model validation was based on data that are part of the ICP Forests Database (see www.icp-forests.org)

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area (BMEL, 2015). Due to past land-use conflicts between forestry and agriculture (Leys and Vanclay, 2010; Gillet et al., 2014), many forested sites are currently located within the low mountain ranges. Apart from timber production, these forests represent a fundamental ecosystem and host a high diversity of plant and animal species. Because German forests are predominantly cultivated, a near-natural stands management is pursued in order to conserve biodiversity and to sustain forest productivity and the provision of ecosystem services (Brunet et al. 2010). Since European beeches have a long lifespan of about 300 years (San-Miguel-Ayanz 2016), an adequate long-term management strategy plays an important role during forest growth in beech stands.

Tree growth models are fundamental to forest management, especially with regard to a sustainable forest utilization. Simulation models can provide objective forecasts and decision support, offering forest managers the information needed to set harvest quantity and timeframe while maintaining a sustainable capacity of forest trees (Vanclay 1994). As forest management not only alters wood production but also transforms stand structure and dynamics, the effects of various forest management strategies have to be quantified and implemented in simulation tools in order to allow for reliable predictions of short- and long-term impacts of different forest management approaches.

Models often used for the prediction of forest growth are FORMIND (Fischer et al. 2015), TREEMIG (Lischke et al. 2006) and SILVA (Pretzsch et al. 2002). FORMIND is an individual-species-based forest model on a hectare scale. It consists of four main processes, including growth of individual single trees, establishment of new trees, tree mortality, and competition among trees for light and space (Fischer et al. 2018). This model has recently been applied in various European regions and has been used in a variety of applications such as coupling remote sensing simulations (Knapp et al. 2018a), biomass change estimation (Knapp et al. 2018b), carbon stocks estimation (Rödig et al. 2018) and forest dynamics simulation (Armstrong et al. 2018). Despite this great versatility, the simulation of smaller special scales, especially when depicting spatial positions of individual trees within the stand, as well as the simulation of detailed and customized forest management methods is severely limited in FORMIND.

TREEMIG is a spatially explicit forest gap model which simulates the changes on forests of different scale (Thuiller et al. 2008). It is a grid-based forest-landscape model and this can be applied to a broad range of spatial scales with a resolution of 100 to 1000 m (Lischke et al. 2006). The TREEMIG model simulates seed reproduction, growth dynamics and light intensity change based on multi-species population dynamics, and it is commonly executed to model changes in the abundance of tree species (Lischke et al. 2006). In terms of applicability, the model has been developed to identify climatic influences on tree species' migration (Nabel et al. 2013), to increase the scale, and to minimize computational resource expenses by coupling several modules (Nabel 2015)

SILVA is a single tree-based spatially explicit stand growth simulator (Pretzsch et al. 2002). Due to its profound set of parameterization data from which the user can select suitable site conditions for customization, SILVA produces reliable simulation results for most parts of Germany (Hausler and Scherer-Lorenzen 2001). Schmid et al (2006) and Mette et al. (2009) evaluated the model in Switzerland and in South-West Germany. SILVA simulates forest dynamics at the individual tree level in five-year time steps considering the four main processes tree growth, competition, mortality, and forest management activities. Growth of an individual tree depends on its position within the forest stand, and the model accounts for the trees' competition for space. SILVA has been remarkably successful in many respects. It was primarily designed to assist decision making in forest management (Schmid et al. 2006), nevertheless SILVA is widely used for general predictions of tree growth (Pretzsch and Schütze 2009) and for comparing stand growth performance under different management regimes (Hanewinkel and Pretzsch 2000). However, opportunities for realistically simulating long-term stand dynamics with SILVA are rather limited, especially with regard to near-natural forest management. Among the three models, the SILVA model was selected, which considers the location of the individual tree and can easily apply the management strategy applied to the actual German forest. As a limitation, SILVA does not take into account how parent trees influence distribution of the offspring seedlings, and neither does SILVA account for irregular tree mortality that is caused by harvesting activities.

The aim of this study is to develop a regional forest stand dynamics model that realistically simulates the short- as well as the long-term effects of different forest management approaches including near-natural forest management based on single-tree selection harvesting. Intensive regeneration cutting or clear-cutting which has been widely applied for many decades in Europe is nowadays known to have many negative effects on beech forests (Brunet et al. 2010). Plantation and continuous cover forestry (CCF) have been the dominant forest management strategies worldwide (Pommerening and Grabarnik 2019). These two management approaches are also pervasive in the German Eifel region where regional forest policies have the declared goal to increase both quantity and quality of forests (Vandekerkhove et al. 2009). In addition, a small number of unmanaged forest reserves have been established in order to conserve biodiversity and natural processes (Brunet et al. 2010).

In general, any model development needs to comprise several interrelated steps depending on the purpose and regional application of the model (Vanclay and Skovsgaard 1997). In order to simulate natural forest development for the German low mountain region, we had to add natural forest regeneration into the model, adjust the parameters of tree mortality to age- and competition-based processes, and calibrate the model for specific site factors. In order to calibrate a forest growth model for a specific regional context, it is crucial to implement accurate information about the specific regional tree growth and the local management history. Such information can be gathered for instance from the literature, from forest managers, or from forest inventory data. The growth of beech trees varies with climate (Trasobares et al. 2016) and site conditions (González de Andrés et al. 2018). Furthermore, forest management strategies may differ regionally (Schall et al. 2018a; Schall et al. 2018b; Barna and Bosela 2015).

Hybrid models that integrate above-mentioned information are being used to build a local-comprehensive model. Cuddington et al. (2013) introduced different modeling approaches through the linkage between ecological theory, models and management. In various ecological fields, the hybrid modeling has been used for highly accurate estimation (Cabral and Schurr 2010; Liu et al. 2018; Peng et al. 2002; Rinke et al. 2010; Scholz-Starke et al. 2013; Von Stosch et al. 2014).

The current paper describes the process of developing a tailor-made model for short- and long-term stand dynamics of differently managed beech stands. To reflect realistic long-term stand dynamics under a specifically customized local management strategy with a simulation model, we developed (1) a seedling regeneration module and (2) a mortality adjustment module, and we (3) combined these modules with the tree growth simulator. We (4) parameterized our combined model with spatially explicit empirical field data and (5) calibrated it by taking expert knowledge from forest managers into account. Finally (6), we validated the calibrated model by comparing simulation results with expert knowledge from the local forest managers and with mid-term monitoring data (15 years), confirming that our model effectively explained actual tree growth with high coefficients of determination.

2. Methods

2.1 Model construction

2.1.1 Model structure

Our model consists of three modules: (1) seedling regeneration, (2) mortality adjustment and (3) tree growth simulation, which are further described in the following.

Empirical field data such as size and spatial information of each tree served as initial input for the simulation. In the first module, the seedlings are distributed in a circular area of canopy width around their parent tree by the regeneration module based on coupled gamma and binominal function. In the second module, tree mortality is adjusted to a natural level. Data constructed by these modules are used as input data for the SILVA tree growth simulator in the third module. These three different modules are combined and iteratively run in a user-defined wrapper function (Fig. 1) to simulate long-term tree growth. The wrapper function opens data files, reads input data, executes calculations, links the modules, saves results and closes data files as a single model.

The calibration process involved iterative adjustments of parameters within each module until feasible values, guided by expert knowledge, were achieved. The interaction of the three modules is depicted in Fig. 1. Each parameter was manipulated until the feasible value under expert information was reached. For instance, when adjusting the number of seedlings of a single tree, other parameters were fixed to produce the simulation result. Using wrapper function, many iterations were performed during calibration over a long period (over 100 years). The stepwise determination of optimal parameter values, guided by the expected forest structure derived from expert knowledge. The iterative calculations until the stem volume met the anticipated forest structure performed to achieving realistic simulation outcomes.

(1) Seedlings regeneration module

In order to realistically reflect short- and long-term forest development, we had to implement natural forest regeneration based on seedling recruitment. The number of established seedlings as well as their spatial distribution were implemented within our model.

Generally, the number of beech seedlings in beech forest depends on canopy openness and is thus reduced by increased canopy density (Madsen and Larsen 1997). Commarmot (2013) investigated primeval beech forest of about 10,000 ha in the Ukraine, containing between 400 and 600 trees per ha. The number of seedlings produced by our model was adjusted to lie within that range. Beech can produce seeds at an age of about 40~60 years (Diaci and Rozenbergar 2001), thus, trees over 40 years are considered potential parent trees by the model. Our model calculates tree age by using morphometric factors based on the DBH according to Rozas (2003) in Eq. (1).

$$Age(years) = 4.143 \times stem\ diameter(cm) \quad (1)$$

The number of seedlings is an important parameter

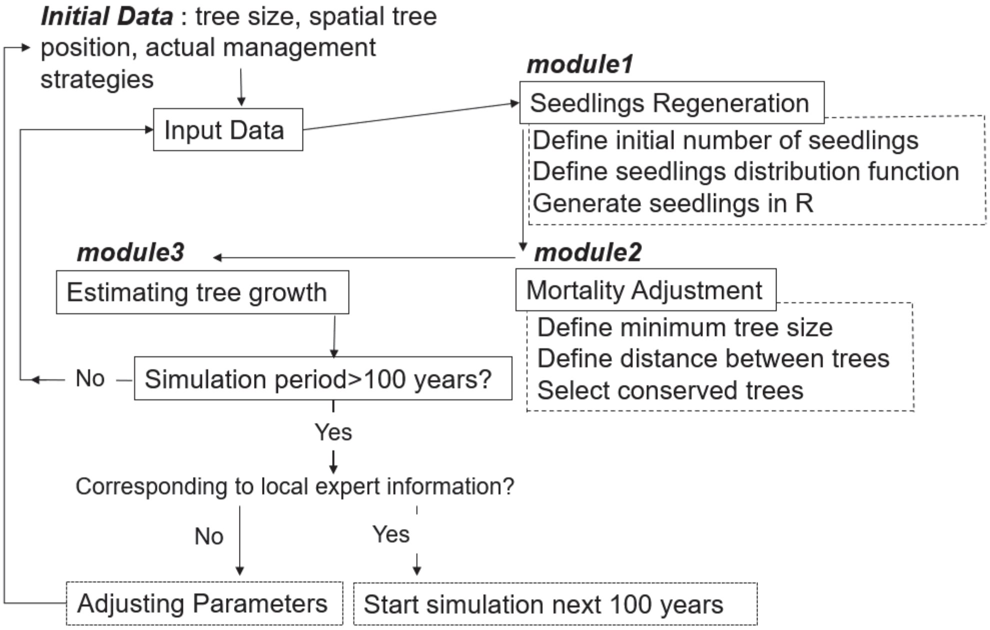

Fig. 1. Simulation and calibration process using wrapper-based approach

for stand regeneration, calling for particular thoroughness in parametrizing it. During the model development, the number of seedlings was repeatedly adjusted to calculate realistic number of viable seedlings depending on a specific stand density.

Dispersal of beech seeds is generally poor because the average beechnut weights about 350-400 mg and it has no specific adaptations for long-distance transport by animals or wind. Because of that, most beechnuts end up directly beneath the parent tree. Only few, mainly lighter seeds, might be blown away 20 to 35 m from their parent trees into canopy gaps (Diaci and Rozenbergar 2001).

We chose the gamma distribution (Burgin 1975; Wilk et al. 1962) for modelling seedling distribution here as well, as it assumes that seed distribution depends on the crown width of the respective parent tree based on the empirical observation of the forest manager. The general formula for the probability density function of the gamma distribution (Dennis and Patil 1984; Nelson 1964) is shown in Eq. (2) where γ is the shape parameter, μ is the location parameter, β is the scale parameter, with Γ is the gamma function depending on time t in Eq. (3). The special case where $\mu = 0$ and $\beta = 1$ is called standard gamma distribution. The equation for the standard gamma distribution reduces to Eq. (4). This module simulates the distribution of seedlings at specific points in time, utilizing distribution functions to create independent distributions at each time point instead of relying on various simulation paradigms. By directly incorporating distribution, the module efficiently generates distributions for seedlings at each time point, reducing the need for complex computations or iterations. Moreover, employing distribution functions allows for the inclusion of probabilistic elements, enhancing the realism of the model.

$$f(x) = \frac{(\frac{x-\mu}{\beta})^{\gamma-1} exp\,(\frac{-x-\mu}{\beta})}{\beta\Gamma(\gamma)} x \geq \mu; \gamma, \beta > 0 \qquad (2)$$

$$\Gamma(a) = \int_0^\infty t^{a-1} e^{-t} dt \qquad (3)$$

$$f(x) = \frac{x^{\gamma-1} e^{-x}}{\Gamma(\gamma)} x \geq 0; \gamma > 0 \qquad (4)$$

The binomial distribution can be used when there are exactly two mutually exclusive outcomes of a trial. These outcomes are appropriately labeled 0 and 1. The probability of x seeds being taken when each has a probability p is px, and the formula is given in Eq. (5) where n is number of trials, and p is the probability of success on each trial. To prevent a skewed gamma distribution of dispersed seedlings, the position of a selected number of seedlings was randomly converted to the opposite side of the parent tree, using the binominal function (Bliss and Fisher 1953; Bolker 2008; Guisan and Zimmermann 2000; Lindén and Mäntyniemi 2011). In our study, we converted seedling position as described above when the outcome of Eq. (5) was 0.

$$P(x; p, n) = \frac{n!}{x!(n-x)!} (p)^x (1-p)^{(n-x)} \qquad (5)$$

(2) Mortality adjustment module

Although *Fagus sylvatica* has a lifespan of about 300 years (Giesecke et al. 2007), the simulation with SILVA assumes some large trees to unexpectedly die even if they did not reach maximum tree age yet. Natural tree mortality *P* is estimated in SILVA using the probability Eq. (6) (Pretzsch et al. 2002), where *ig* represents the estimated tree basal area growth (cm^2 / 5 years); *SI* is the site index, expressed as maximum stand height at age 50 years; *a*0,⋯,*a*4 are the estimated coefficients. All trees with *P* greater than a threshold of 0.5 are defined as dying trees.

To avoid such unexpected death of mature trees, we implemented a mortality adjustment module, in which tree mortality is made dependent on tree-tree competition. Pommerening and Grabarnik (2019) introduced a similar concept of a frame-tree method to describe a tree competition based on the nearest-neighbor principle. The trees that are superior to the competition were defined as frame trees. Using an R-script in Version 4.0.2 (R core team, 2015), these frame trees were selected to be excluded from dying, taking into account the distance between adjacent trees and the size of the competing trees. Suppressed trees that are outcompeted by others were determined to die.

Since trees are not homogeneously distributed in our model, the residuals of the *P*-function had been used to calibrate *Pm* function in Eq. (7) (with the probability value of single tree mortality Pm, $b0,\cdots,b2$ the tree species-specific estimated parameters).

$$P = \frac{1}{1+e^{-(a_0+a_1 d+a_2(\frac{ig}{dbh})+a_3(\frac{h}{dbh})+a_4 SI)}} \tag{6}$$

$$P_m = \frac{b_0}{e^{b_1 P_2^b}} \tag{7}$$

(3) Tree growth module

The growth simulator SILVA was used to estimate tree growth during a single growth period 5 years. This model has been applied in the past for various forest management purposes by several German forestry authorities and private forest owners and has been validated with a huge database (Pretzsch et al. 2002). Mainly, DBH increment in Eq. (8), tree height growth in Eq. (9) and competition index in Eq. (10) are calculated by SILVA, where zd_{pot} is the potential diameter increment (cm / 5 years); $j1,j2,j3$ the species-specific parameters, h_{pot} is the potential tree height at age *t*, and *A*, *k*, *p* are the species-specific parameters.

$$zd_{pot} = j_1(1-e^{-j_2 \cdot dbh})_3^j \cdot j_2 \cdot j_3 \cdot e^{-j_2 \cdot dbh} \tag{8}$$

$$h_{pot} = A(1-e^{-kt})^p \tag{9}$$

$$CI_i = \sum_{j=1}^{n} \beta_j \cdot \frac{CCA_j}{CCA_i} \cdot TM(j) \tag{10}$$

The competition index (*CI*) is defined as the sum of all competitor contributions, with CI_i = competition index for tree *i*; β_j = angle between cone vertex and top of competitor *j*; *CCAj*, *CCAi* = crown cross-sectional area of trees *j* and *i*, respectively; *TMj* = species specific transmission coefficient for tree *j* (*TM* = 0.8 for European beech); *n* = number of competitors of tree *i*. The competition index reflects to which extend an individual tree occupies the limited growing space within a stand (ranging from 0 = dominant open grown trees to 30 = suppressed trees). In the study of Pretzsch and Schütze (2009), a long-term growth comparison was excluded due to varying and inconsistent results. The dominant beech trees survive up to 200-300 years (Diaci and Rozenbergar 2001) and it needs long-term simulations to observe at least one cycle of beech forest development due to this long lifespan. As introduced by Poschenrieder et al (2013), SILVA can be combined with other modules in order to improve the accuracy of model predictions.

2.1.2 Model parameterization

(1) Integrating site-specific management methods into SILVA

SILVA has various options to set different management scenarios. It includes thinning specifications, which allows to adjust the thinning actions during the simulation run. Three different harvesting specifications (final crop-tree concept, selective cutting, or no thinning) were used to reflect the three different management practices which will be used in model validation (plantation, continuous cover, and reserved forestry, respectively).

The final crop-tree concept particularly reflects managed stands in planation. Periodic thinning removes a sub-set of small trees, which stand in greater competition with each other. Plantation is generally considered regeneration of even-aged trees retaining widely spaced residual trees in order to achieve a uniform seed dispersal across the harvested area. During the final harvest, 8-12 shelterwood trees per 0.15 hectare (30x50m) are left in order to shelter forest regeneration. They are usually retained until the regeneration has been established. Thinning and shelter tree cut were controlled in our model by setting a maximum stand volume limit during the simulation runs.

Continuous cover forestry (CCF) was chosen to simulate near-naturally managed stands in SILVA. Some saplings were cut to release the future target trees from competition. To encourage fast growth in reduced under-story light, *A*-values (intensity of competition) by Johann (1982) were used. The option defines number of future trees and competitor trees and thinning intensity derived from Eq. (11) (with *A*: intensity of competition; *e*: elite tree (future target tree); *c*: competitor tree; *Dce*: distance between future target tree and competitor).

$$D_{ce} \leq \frac{H_e}{DBH_e} \cdot \frac{DBH_c}{A} \qquad (11)$$

For the beech reserves, no thinning option was selected in SILVA. To keep dominant trees alive in spite of the random mortality, some trees with large stem volume and small competition values were excluded from dying.

2.1.3 Simulation process

The simulation process (see Fig. 1) was initialized with empirical data on tree size and spatial reference (tree diameter, tree height and coordinates of individual trees) as well as specific stand management information. Based on the characteristics of the mature trees, new seedlings were generated by the regeneration module. Tree mortality in SILVA was adjusted by the mortality adjustment tool depending on tree‑tree competition. The surviving trees and seedlings data were used in the tree growth module as input. New tree growth data were iteratively generated in five-year time steps. Based on the desired simulation time frame of 300 years, this iterative simulation cycle was performed 100 times.

2.1.4 Validation

The results of the simulations were validated using expert knowledge for long-term and empirical mid-term monitoring data for a simulation period of 15 years.

First, the simulated long-term forest development under different management regimes was validated by a local forest manager on the basis of his experience on stem volume and management concepts. Empirical stem volume and predicted stem volume were visually compared over time.

Second, the mid-term simulation results were validated using actual monitoring data for a period of 15 years, which were provided by the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests, 2018; Lorenz 1995). Available ICP Validation Data were constrained to single-condition pure beech plots in the database. Plots that had been thinned during the monitoring period (i.e., 2000-2010) were excluded from the analysis. From the monitoring data of three stands meeting the specified criteria, tree growth was simulated for a 15-year period using the initial data from year 1. Simulated results were compared with actual monitoring data from year 15, focusing on stem volume, basal area, and tree count.

According to the forest manager, the approximate stem volume ranges for each management method are as follows: 1) Under the plantation management method, harvesting is planned at intervals of 140 years. At the final harvest, the stem volume is expected to reach 500 m^3. 2) In continuous cover forestry management, where various tree ages coexist, the stem volume in a stand is typically maintained within the range of 250 to 350 m^3. 3) Under reserved forest management, the stem volume tends to gradually increase over time. However, it rarely surpasses 900 m^3, with the management aiming to sustain a generally high stem volume despite fluctuations. It is crucial for these estimations to closely align with the final simulation results to ensure the accuracy and consistency of the simulation outcomes.

3. Results

3.1 Model calibration

3.1.1 Distribution of seedlings

We took into account that the weight of a beech seed is quite large. The seeds are scattered randomly by wind and weight itself and the probability is high that they are placed directly beneath the crown of the parent tree. We used a gamma function and a binominal function to distribute seedlings around the parent tree. At first, we applied a gamma function (Fig. 2 left). As it is skewed to the right side, we added a binominal function of discrete type (Fig. 2 right). The Combination of gamma function and binominal function resulted in distributing seedlings fairly around the parent tree, which fit better to empirical knowledge of the local forester.

3.1.2 Number of seedlings

The number of seedlings that can be produced per

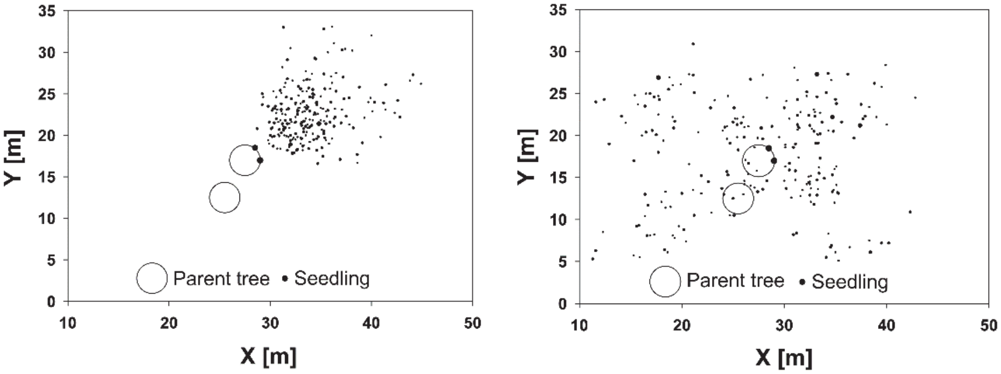

Fig. 2. Differently distributed seedlings by gamma function (left) and by a combination of gamma and binomial function (right)

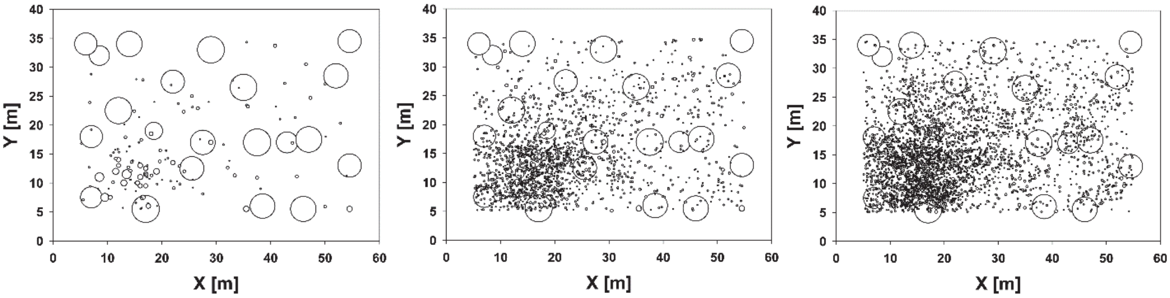

Fig. 3. Seedlings Distribution with different initial number of seedlings in 0.15 ha. Marks used were stem diameter; sparse seedling density when each parent tree produces 3 seedlings (left), moderately dense with number of seedlings is 10 (centre) and highly dense with number of seedlings is 15 (right).

tree was set as a function of the total stand stem volume. Figure 3 shows the spatial seedling distribution based on different initial number of seedlings. When the stand stem volume is low, a relatively large number of seedlings are distributed around the parent trees whereas in very dense stands, the number of seedlings produced near the tree is limited. The numbers of seedlings have a tree density-dependent relationship. For instance, number of seedlings decrease when stand volume is very dense, and number relatively increases under opened forest stand (Webb, 1999).

3.1.3 Mortality adjustment

During the simulation in SILVA, some large trees unexpectedly die due to the mortality probability calculated in this simulator. This mortality was estimated using a probability equation (Eq. 6). To avoid such unexpected death, the trees that are superior to the competition were defined as dominant trees. Using an R-script, these trees were selected to be excluded from death considering the size and the distance between adjacent trees. Figure 4 shows two comparable results when using SILVA (Fig. 4c) and combining the mortality adjustment module in which large and competitive trees are excluded from the death (Fig. 4b). Without the mortality adjustment module, some large trees randomly died during simulation and the resulting stand was very sparse. However, in practice, un-thinned forest should become a closed structure as time passes. The mortality-adjusted stands showed a much more realistic density compared to the simulation without mortality adjustment.

3.2 Model validation

3.2.1 Simulation and comparisons with ICP plots

Three ICP experimental plots were used to validate

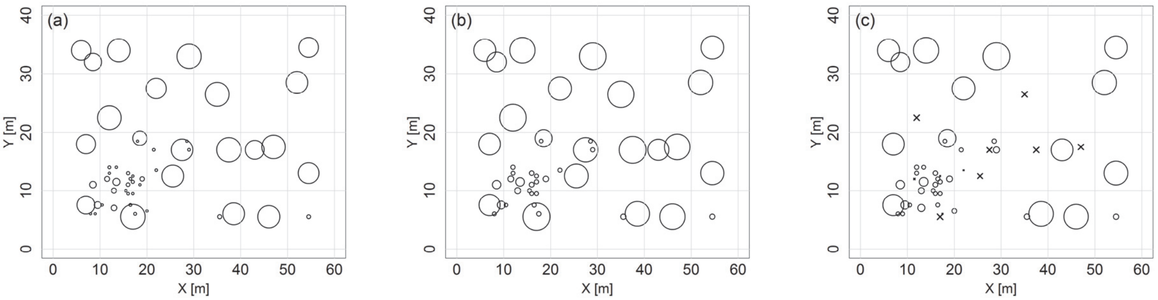

Fig. 4. Spatial stem distribution by tree growth simulation. The size of the circle represents the relative size of the DBH and x symbol meanss dead stem; (a): Initial field data, (b): simulation result in 20 years by adding mortality adjustment, (c): simulation result after 20 years without mortality adjustment

the simulation of 15 years tree growth (ICP forests, 2018). The ICP dataset provides field monitoring data about individual tree characteristics such as number of trees per plot, diameter at breast height (1.3m) and tree height from 2000 to 2015, however, it does not include spatial information of each tree. Thus, the trees were randomly distributed for initial input to the model. The empirical stand density after 15 years of the three selected ICP plots are compared to simulation results in Figure 5. The trends of both show high similarities. Two trends were examined for statistical validity through cross- validation of simulation results. The coefficient of determination (R^2) was computed from cross-validation between observed and predicted values. Basal area and stem volume were found to be well explained by the predicted values across regions a, b, and c. In contrast, the number of trees was not statistically significantly explained. The number of trees tends to fluctuate frequently due to small trees, leading to frequent variations in the number of trees depending on the locations of individual trees. The variability in tree numbers arises from substantial fluctuations in inter-tree competition, which are driven by the frequent changes in the number of small trees.

3.2.2 Simulations on study sites compared to expert knowledge

The simulations conducted on the study sites, spanning 350 years, were compared visually with expert knowledge. As illustrated in Figure 6, the results closely align with the desired stem volume targets and the management strategies provided by local foresters (see 2.1.4).

Plantations managed forests exhibited regular fluctuations in stand growth with a 140-year cycle, where growth experiences periodic decreases and increases. Continuous cover forestry regions maintained the quantitative structure of forests without significant alterations, effectively preserving the existing forest form. In reserved forest areas, the volume of timber steadily increased up to 900 m^3 and subsequently stabilizes at relatively stable levels with fluctuations thereafter. As mentioned in Section 2.1.4, these findings are consistent with the experiences of forest managers and the objectives of forest management.

4. Discussion

In this study, we developed a model based on expert knowledge, which is both as simple as possible and easy to parameterize. Two modules, seedling regeneration and mortality adjustment as sub-models, were developed and combined with the commonly used tree growth simulator SILVA. The combined model aims to generate realistic long-term simulations for beech tree growth and stand dynamics through customized management strategies. We focused on balancing simplicity and practicality. Simulation models need to have a good linkage between modeling and management considering regional growth characteristics. Vanclay and Skovsgaard (1997) advised modelers to be more proactive in discussing

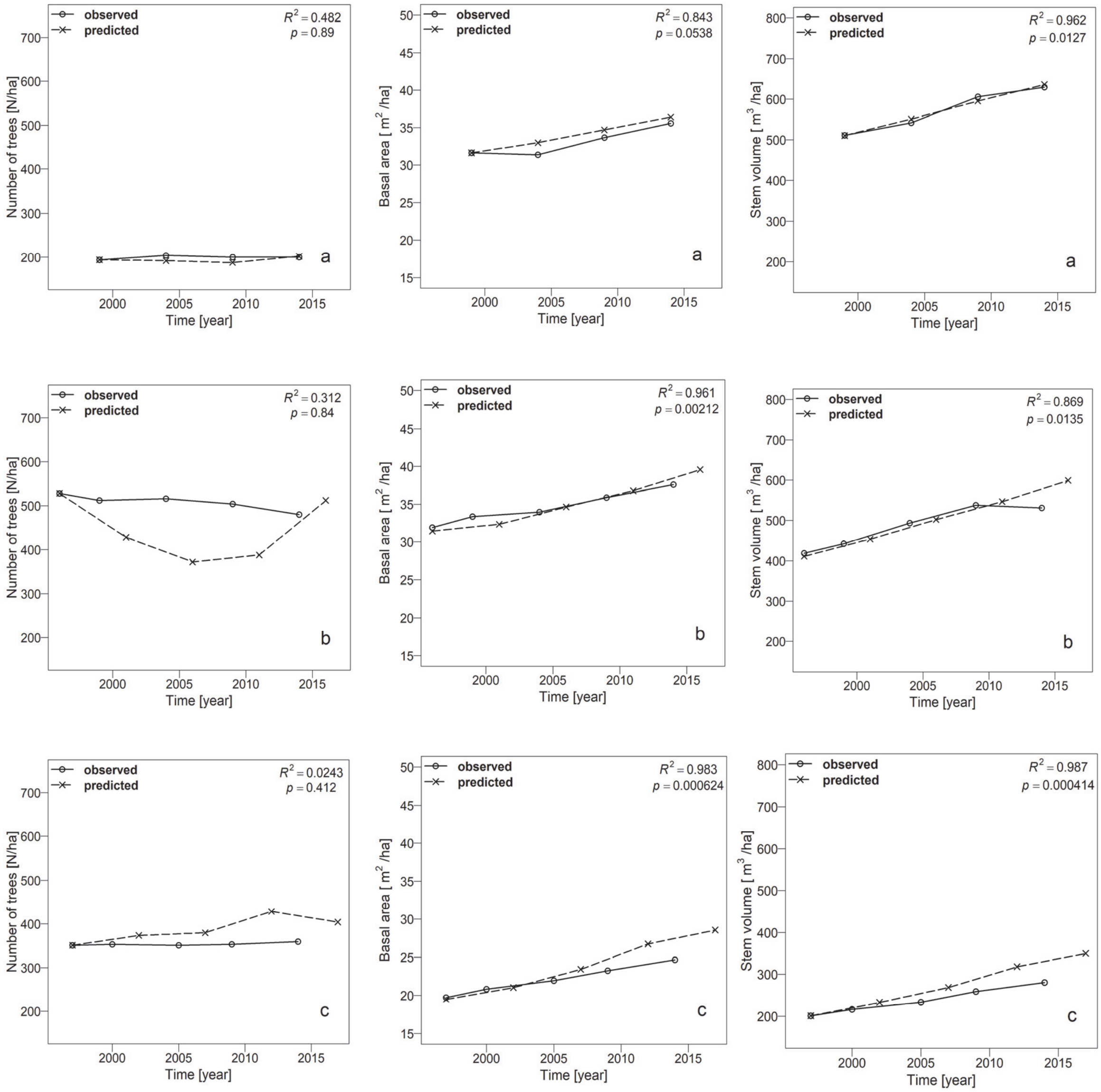

Fig. 5. Comparison between observed and predicted stand density. (left: Number of trees; mid: Basal area; right: Stem volume; a: Kadenbach in Western Germany; b: Unterlüß in Northern Germany; c: Aquila in Central Italy)

model evaluation with forest managers. Therefore, we intensively discussed model performance with the local forest manager within the iterative calibration process. To reflect the actual growth and management of regional forests, a method of customized calibration was developed and parameter estimation and modeling was processed.

4.1 Model parameter calibration

Natural regeneration is difficult to predict since seed dispersal of beech is irregular and widely varied. Dominant trees typically produce 1850-3400 seeds per m^2 in good mast years (Diaci and Rozenbergar 2001), so we used a large number of initial seeds at the beginning of the model calibration process. However, the calculation of the exact competition between seeds

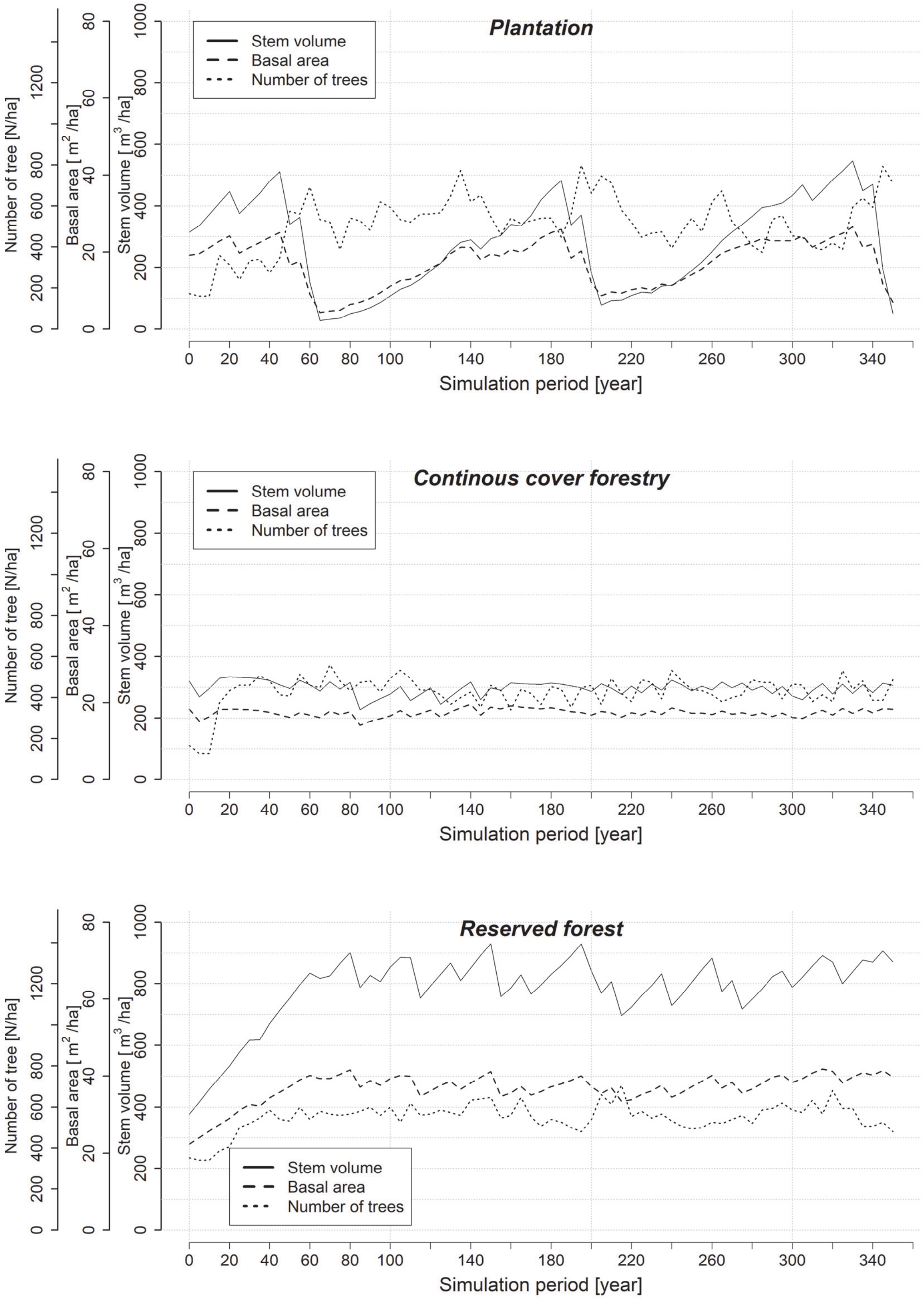

Fig. 6. Growth dynamics for validating trend in stand volume, basal area and number of trees over time by simulating tree growth from the validation.

and the existing trees appeared to be rather time-consuming. Moreover, simulation results showed the survival of only few seedlings. Therefore, we avoided time-consuming calculations by determining the number of seedlings a priori.

In addition, the model generates interconnected results regarding the number of established seedlings, tree mortality, and forest management activities and the relationship affects simulation results during calibration. Thus, the parameters were adjusted between the simulation cycles. Through many iterative adjustments, the realistic number of seedlings was determined based on the expected stand growth provided by expert knowledge.

4.2 Simulations

Stand growth (as shown in Fig. 6) showed realistic dynamics for beech stands under different management regimes. The number of trees (dotted line in Fig. 6) showed significant differences depending on management types. Tree numbers in stand of plantation showed the highest variation over time between the maximum a number of trees (820 n/ha) and the minimum number of trees (433 n/ha); thus, stand structure differs markedly, indicating a high disturbance level as well as a high regeneration potential. The number of trees in near-naturally managed (CCF) and unmanaged forest constantly showed relatively low fluctuation. Applying management kept stand structure and regeneration homogenous over time. Also, in terms of stem volume (solid line Figure 6), the simulations showed characteristic dynamics depending on management strategies. Planation forests reflected the rotation period of the shelterwood cutting system remarkably well, showing very regular patterns recurring every 140 years. However, the stem volumes at the final thinning stage are slightly different from each other. Different initial distributions of trees contribute to different growth patterns and resulting stem volume. Stem volumes in near-naturally managed and unmanaged stands were relatively constant over time due to the balancing of regeneration patterns and the cutting of older trees. The unmanaged forest was dense due to no human disturbance. It had the highest stem-volume ratio and its stand grew up to 1000 m^3/ha.

4.3 Model validation and assessment

Growth models may have deficiencies involving growth patterns, calibration procedures and performance in empirical tests. We confirmed that our developed model accurately simulated mid-term stand growth by comparing the simulation results to ICP field data for 15 years. Figure 5b shows quite different number of trees between field data and the simulation result for Northern Germany. Because spatial information of individual tree is missing in ICP data, spatial information was randomly generated in the simulations. This may result in different interrelations between small and large trees compared to the ICP data. Since small trees under 10 cm DBH (diameter at breast height) are vulnerable to strong competition, fluctuating dynamics in the number of trees are the consequence. Also converting tree densities per plot of the output data to numbers of trees per hectare causes an amplification of these differences between observed and predicted tree numbers. In the study of Pommerning and Grabarnik (2019, p. 58), the authors depicted general biomass development in different management approaches. It showed a trend similar to our simulation results and we accordingly confirmed that our model reflects general silvicultural regimes.

Recent research predominantly relies on data-driven or statistically based simulations of long-term tree growth (Tatarinov et al. 2009; Matsushita et al. 2015; Halpin et al. 2016). While this approach facilitates simulations of typical tree growth patterns, accurately estimating and depicting the region of interest presents challenges. This is because each region’s forests are actively managed by local forest managers, and forest growth is influenced by various factors. Considering diverse factors like climate and soil could provide insights into more precise tree growth. However, simulating climate and soil changes also increases the complexity, introducing numerous variables that may reduce the accuracy of the intended tree growth calculations.

Given the diverse management practices specific to local forest regions, accurately estimating and characterizing the area presents a significant challenge. While incorporating these factors may provide more detailed insights into tree growth, it also increases model complexity and introduces numerous variables. Therefore, by basing the simulation on the expertise of local experts in the desired region, iteratively refining the simulation, and achieving results that align with the predictions of actual experts, natural elements such as forests that require long-term predictions may actually benefit from estimating more accurate quantitative changes.

5. Conclusions

This study demonstrates a comprehensive approach to developing and validating a simulation for beech tree growth and stand dynamics. Our simulation development approach emphasized on creating a model that’s simple, easy to parameterize, and relevant for practical forest management scenarios. The simulation focused on integrating expert knowledge into the model’s development and calibration processes. The three modules such as seedling regeneration, mortality adjustment and Tree growth simulation played complementary roles in applying tree growth and forest management methods to the Eifel region. Each parameter within these modules underwent iterative adjustments until feasible values are achieved, leveraging expert input. Iterative adjustments occurred over a prolonged period (over 100 years) using a wrapper function to calibrate the model. During this process, parameters were manipulated while maintaining others fixed to achieve desired simulation outcomes.

Long-term tree growth estimated under various management strategies undergo a plausibility check led by a local forest manager. This validation ensured that simulated outcomes closely align with real-local observations and management practices. Optimal parameter values were determined sequentially, guided by expected forest structures derived from expert knowledge. Finally, by integrating the interconnected modules into a single simulation, it became possible to effectively simulate the specific dynamics of forest growth anticipated in the distant future.

There are still areas that need enhancement, notably in the complexity of seedling regeneration and the necessity for sufficient long-term validation data. Predicting natural regeneration requires additional verification and exploration due to the irregular distribution and quantity of seeds. While this study simulated tree growth over 350 years and was validated by expert information, the availability of long-term monitored forest data could enable more robust calibration and validation through specific statistical validation.

Nevertheless, considering the forest management practices and growth characteristics unique to the Eifel region, this simulation approach continue to facilitate the application of tree growth and forest management practices tailored to the region. Also, the calibration process enhances the understanding of how the model was fine-tuned to simulate realistic forest dynamics under different management scenarios. It also underscores the importance of integrating expert knowledge and empirical validation into simulation modeling efforts for natural systems like forests.

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