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Forests in transition: a harvesting model for uneven-aged mixed species forests in Austria

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Summary

Harvesting models are needed within simulation studies to assess 'business as usual' scenarios in future stand development. Such models require data from repeated observations addressing the removals as they are based on specific silvicultural management regimes. The purpose of this paper was to develop and apply a harvesting model for uneven-aged single-tree forest management based on data from the forest company 'Forstbetrieb Ligist, Souveräner Malteser Ritterorden' in Austria. This company has been known for its transition from even-aged to uneven-aged forest management since the 1930s. Our harvesting model comprises two logistic functions to simulate a single-tree selection process: (1) predicting the probability of harvesting and (2) removal. The set of equations are tested and implemented in the tree growth model MOSES (MOdelling Stand rESponse). MOSES is used as a diagnostic tool to assess different forest management regimes. In this study, we are specifically interested in (1) evaluating the model by comparing predicted and observed removals and (2) predicting future stand development considering the current management practices—the business as usual as it can be derived from the harvesting model. The results suggest that in combination with MOSES, our model correctly mimics the growth development over time since no systematic trends between predicted and observed diameter growth at breast height classes are apparent. Furthermore, it is evident that by applying the current plenter harvesting strategy, a constant stand basal area of ~35 m^2 ha^{-1} will be achieved.

Introduction

The increasing gap between economic demands and ecological considerations influences silvicultural concepts and trends (Schütz, 2001). While in the past the traditional clear-cut system was considered to be a simple and easy solution to ensure sustainable forest management, uneven-aged forest management regimes are experiencing a renaissance. As a result of this development, companies have established permanent inventory systems (Kangas and Maltamo, 2006) and tree growth modelling theories have been developed (Hasenauer, 2006) to address the increasing demand for monitoring and predicting volume growth in uneven-aged mixed species forest stands.

One alternative to traditional even-aged forest management regimes is the plenter or tree selection system. Due to the difficulties in efficiently assessing the sustainability of such prescriptions, this system was disparaged and partly forbidden in Europe in the early nineteenth century (Hockenjos, 2008). It was reintroduced (for forest companies) based on Biolley's control method (Biolley, 1980). Sample inventory combined with modern single-tree growth models like MOSES (MOdelling Stand rESponse) (Hasenauer, 1994) offer a new generation of forest management planning and controlling tools for uneven-aged mixed species forests.

The harvesting strategy in plenter and/or selection forests comprises nearly all working steps that are separately run in even-aged forests (Schütz, 2001). It may also depend on specific needs or strategies such as a certain target diameter, etc. As a consequence, the interventions cannot easily be determined. A possible solution for this problem is the development or definition of a harvesting model (Ledermann, 2002) based on repeated measurements within such forests.

Harvesting models provide a mathematical solution to mimic the selection procedure for trees which are selected for cutting according to a given management regime. This selection process is commonly done by the local foresters and may be seen as the result of the management philosophy based on the existing experience and know-how of a given company. Once these rules are mathematically defined (e.g. in a harvesting model), we can represent the typical management regime of the company which allows us to apply the current regime in the future assuming that the general management routine remains unchanged. With such a model, it is possible to simulate the so called 'business as usual' case and predict stand development for future years with the same harvesting strategy as was applied in the past. Knowledge of these business as usual strategies is needed to assess future stand development under current harvesting conditions and also for comparing alternative and/or new silvicultural management strategies with the existing management.

In this study, a logistic harvesting model is introduced that mimics the plenter management regime of a forest company that is currently in the transition phase from an even to uneven-aged mixed species forest or plenter system. Silvicultural knowledge of such a transition is given by Reininger (2000), Duchiron (2000) and Schütz (2001). The logistic model approach is chosen because the harvesting strategy in mixed species forests during the transition phase is difficult to describe with harvesting rules. The available dataset comprises a large variety of stands at different transition phases and the logistic model provides the theoretical framework for harvesting criteria derived from the available dataset. According to Söderbergh and Ledermann (2003), this harvesting algorithm can be classified as empirical. Other rule-based systems, such as fuzzy–logic, are not applicable because precisely formulated harvesting rules for forests in transition do not exist (Duda, 2006).

For this study, we propose two logistic functions, similar to the harvesting models described in Ledermann (2002). Logistic functions are also capable of modelling the tree selection depending on human preferences in harvesting (Füldner, 1996). Logistic harvesting models have been developed for Austria (Sterba *et al.*, 2000) and the theory of LOGIT functions has been applied on modelling tree mortality (Monserud and Sterba, 1999) and regeneration (Schweiger and Sterba, 1997; Hasenauer and Kindermann, 2006).

The aim of this paper was to develop a harvesting routine for forests in transition (from even to uneven-aged mixed species forests) and implement the algorithm in the tree growth model MOSES to mimic the long-term forest management implications. The specific tasks can be summarized as follows:

1. Develop a plenter harvesting model with data from the forest company 'Ligist'.
2. Evaluate the model by comparing predicted *vs* observed removals.
3. Implement the harvesting model in the tree growth model MOSES to project the current harvesting strategy and predict future stand development.

Methods

The tree growth model MOSES

The distance dependent, potential based single-tree growth model MOSES (Hasenauer, 1994) is used for this study. MOSES consists of increment models for diameter growth at breast height (d.b.h.) and height, a dynamic crown model, a LOGIT function for mortality and a set of LOGIT functions for estimating the regeneration (Kindermann and Hasenauer, 2007). The interaction among trees is described by a distance-dependent competition index (Ek and Monserud, 1974). One simulation period is 5 years and the number of simulated periods is set by the user.

The increment calculation in MOSES is based on the idea that the increment is limited by a predefined potential. This potential is calculated and then reduced to a value according to the competition situation of the tree within the stand. The potential d.b.h. increment is derived from solitary tree d.b.h.–height relations (Hasenauer, 1997). For the potential height increment, the behaviour of top–height curves is defined (Monserud, 1975; Kindermann and Hasenauer, 2005).

Competition is described both for the past and for the present. The past influence of neighbouring trees is given by the crown ratio, whereas the actual situation is estimated with a distance-dependent competition index for each tree. Potential crown projection areas are calculated using the d.b.h. to crown radius or height to crown radius relations (Hasenauer, 1997). Based on the tree positions, overlapping zones of the crown projection areas are calculated and weighted by the height of the trees. By including the change of competition index due to mortality and management, the (non-linear) reaction of a tree due to management can be considered.

Data for calibration and validation of the increment and mortality functions of MOSES came from permanent investigative plots across Austria, Switzerland and parts of Germany. The 57 000 calibration and 225 000 validation increment pairs (repeated observations) cover a wide range of tree species mixtures, age structures, management regimes, etc., and all common silvicultural treatment scenarios are covered. The model has been widely used for typical tree growth model applications and has been proven to provide unbiased and consistent results (Hasenauer, 1994; Hallenbarter and Hasenauer, 2003; Steinmetz, 2004; Hallenbarter *et al.*, 2005; Klopf, 2007)

The harvesting model

We developed a harvesting model based on two separate logistic equations. The general form of a LOGIT function is:

$$P = \frac{1}{1+e^{b \circ X}}, \tag{1}$$

where P is the probability that is calculated by a linear combination $b \circ X$ with a set of independent variables X and their associated coefficients b. The model estimates the probability of a dichotomous-dependent variable.

In the first equation of the harvesting model (described later as equation (7)), the dependent variable is the occurrence of harvesting. This equation operates on the whole plot. It depends on the quadratic mean diameter and the crown competition factor (CCF; Krajicek *et al.*, 1961) of the plot and on the length of the measurement period. The calculated probability is then compared to a uniformly distributed random number between 0 and 1. If the random number is smaller than the calculated probability, harvesting occurs. The CCF is calculated as follows:

$$\mathrm{CCF} = \frac{\sum_{i=1}^{n} r^2 \cdot \pi}{A} \cdot 100. \qquad (2)$$

The CCF describes the proportion of the crown coverage based on open grown trees over the plot area A. The crown radius r for each tree is calculated using the d.b.h.—crown radius equations with species-specific parameters according to Hasenauer (1997). With data derived from angle count sampling, the crown area of the sample trees has to be multiplied with the representative stem number of the sample tree and the plot area A set as 1 ha.

If harvesting occurs, the second equation (described later as equation (8)) is executed which is again a LOGIT function. It operates on a tree level, which means that it is executed to every single tree on a harvested plot. It calculates the probability of a tree being removed. The dependent variables comprise the d.b.h., CCF of larger trees and the tree species. As in the first equation, the period length is also part of the second. Again, the probability is compared to a random number, removing the tree only if the random number is smaller than the estimation results. Both equations were calibrated using the open source statistical software R (R Development Core Team, 2010).

Data

The forest enterprise

About 40–80 years ago, the forest enterprise 'Forstbetrieb Ligist, Souveräner Malteser Ritterorden' began changing its forest management regime from a typical clear cut to a single-tree selection or plenter system. The forests of the company are located in Styria and Carinthia in southern Austria. The dominant tree species with respect to the number of stems per hectare is Norway spruce (*Picea abies*, 78 per cent), followed by European larch (*Larix decidua*, 6 per cent), Scots pine (*Pinus sylvestris*, 5 per cent), silver fir (*Abies alba*, 4 per cent), common beech (*Fagus sylvatica*, 3 per cent) and other tree species (4 per cent). The exact species composition is given in Table 1.

In 1980, a permanent inventory design consisting of 1150 angle count sampling points (Bitterlich, 1948) was established to monitor the forest development over time. The plots were remeasured every 5 or 10 years. The total forest area is 3140 ha and divided into five management regions, three of them were considered in this study. Region Sommereben comprises 900 ha, sits at 270–1700 m a.s.l. and contains 225 angle count sampling points. It is located in the districts Voitsberg and Deutschlandsberg in Styria. The management regime was changed to the plenter system between 1960 and 1970. The second region, Hebalm (1490 ha), is located in Voitsberg with some parts in Wolfsberg in Carinthia. It sits at 390–1280 m a.s.l. and contains 366 sampling points. The plenter management regime was established in the early 1970s. Region Fürstenfeld is in the eastern part of Styria in the districts Fürstenfeld and Hartberg. The size of this region is 450 ha comprising 229 angle count sampling points. The altitude is 270–360 m. This was the first region that changed the management regime, sometime before the 1930s. The time of the measurements and/or the period length is different in each region. The length of a measurement period is either five or 10 years. Region Sommereben was measured in 1980, 1985, 1990 and 2000, Hebalm in 1985, 1995 and 2000 and Fürstenfeld in 1980, 1990 and 2000. Only sample points that have a full data record are considered in the study. This reduces the number of points to 209 for Sommereben, 277 for Hebalm and 132 for Fürstenfeld. Stand characteristics for the three regions can be found in Table 2.

Data preparation

MOSES needs the tree position, d.b.h., height and height to the live crown (HLC) of each tree in a plot. In the dataset,

Table 1: Species composition with respect to the number of stems per hectare in the regions Sommereben, Hebalm and Fürstenfeld for each measurement year used for model calibration

Year	Spruce (%)	Fir (%)	Larch (%)	Pine (%)	Beech (%)	Other (%)
Sommereben						
1980	72.96	11.54	6.33	5.55	2.56	1.04
1985	73.53	10.61	5.57	5.23	3.9	1.15
1990	75.54	9.74	4.88	4.29	4.55	0.99
Hebalm						
1985	97.12	0.22	2.06	0.1	0.13	0.38
1995	95.46	0.16	1.99	0.09	0.14	2.17
Fürstenfeld						
1980	70.83	2.82	1.39	15.15	1.88	7.93
1990	68.47	3.55	0.98	12.54	3.3	11.16

Table 2: Stand characteristics for the regions Sommereben, Hebalm and Fürstenfeld for each measurement year that is used for the model calibration

Year	N_{rep}	N_{rep} rem	BA (m² ha⁻¹)	BA rem (m² ha⁻¹)	Equation 7			Equation 8	
					dg (cm)	$CCF_{conifer}$	$CCF_{broadleaf}$	d.b.h. (cm)	CCFL
Sommereben									
1980	807 (31–4920)	160 (0–4006)	32.84 (4–68)	4.48 (0–36)	28.38 (8.04–53.27)	166.48 (11.26–409.62)	18.25 (0–274.86)	19.84 (5.1–89.1)	132.35 (0–489.7)
1985	695 (26–4595)	80 (0–3458)	32.83 (4–76)	3.4 (0–32)	29.97 (9.13–56.33)	155.59 (12.8–563.74)	20.81 (0–310.97)	21.34 (5.5–85.3)	125.94 (0–504.5)
1990	668 (31–3878)	148 (0–1857)	31.87 (4–68)	6.37 (0–48)	30.43 (9.51–56.74)	147.42 (12.85–400.21)	21.79 (0–296.58)	21.13 (5.2–79.3)	114.76 (0–465.71)
Hebalm									
1985	839 (5–3907)	145 (0–3225)	28.48 (4–84)	4.88 (0–36)	27.63 (5.3–98)	146.1 (0–347.9)	3.28 (0–150.69)	17.31 (5.1–98)	98.4 (0–308.81)
1995	827 (6–4310)	127 (0–2187)	30.32 (4–76)	4.4 (0–24)	28.94 (9.02–92)	153.3 (7.37–396.37)	6.55 (0–699.63)	18.43 (5.2–100)	120.27 (0–681.74)
Fürstenfeld									
1980	931 (55–5296)	327 (0–2335)	35.88 (4–64)	11.42 (0–48)	24.93 (8.2–53.27)	182.33 (10.86–407.24)	37.56 (0–317.13)	20.24 (5.6–66.5)	137.52 (0–361.94)
1990	736 (58–3962)	223 (0–1455)	33.36 (4–60)	10.51 (0–52)	27.16 (12.42–50.57)	150.25 (0–359.21)	47.02 (0–451.44)	21.55 (6.8–70)	130.84 (0–389.69)

N_{rep} denotes the number of trees per hectare, N_{rep} rem the number of removed trees, BA the basal area, BA rem the basal area of the removed trees, *dg* the quadratic mean diameter, $CCF_{conifer}$ the crown competition factor of conifer trees, $CCF_{broadleaf}$ the crown competition factor of broadleaf trees, d.b.h. the diameter at breast height and CCFL the crown competition factor of larger trees. The numbers in the cells show the mean values with minimum and maximum in parenthesis. The indices are grouped by their inclusion in equations (7) and (8).

only the d.b.h. of the sample trees is provided. Trees with a d.b.h. smaller than 5 cm are not measured. Since with a basal area factor of 4, each tree in an angle count sample represents 4 m², a representative number of trees (N_{rep}) can be calculated according to the d.b.h.. Thus, for each sample tree, N_{rep} trees with the same d.b.h. are generated. The position of the trees is determined using the program STANDGEN (Kittenberger, 2003). Structural information about the aggregation of the plot is incorporated by the Clark–Evans index (Clark and Evans, 1954). Properties of species mixtures are integrated using the Füldner index (Füldner, 1996). Both indices are needed for the stand generation routine in STANDGEN. For each angle count sampling point, a representative 1 ha plot was generated and used for model simulation.

Measurements for the height of the trees are only available in the year 2000 for the trees with the median of the basal area distribution on each point and for each tree species. Based on these trees, height curves according to Pollanschütz (Pollanschütz, 1973), Petterson (Schmidt, 1956) and Kern (Prodan, 1965) are parameterized to calculate the missing heights.

Pollanschütz:

$$h = e^{a + \frac{b}{\mathrm{DBH}}} + 1.3. \tag{3}$$

Petterson:

$$h = \frac{1}{\left(a + \frac{b}{\mathrm{DBH}}\right)^2} + 1.3. \tag{4}$$

Kern:

$$h = e^{a + b \cdot \ln\left(\frac{\mathrm{DBH}}{\mathrm{DBH}+1}\right)} + 1.3, \tag{5}$$

whereas *a*, *b* and *c* are species-specific coefficients. The HLC is calculated according to Kahn and Pretzsch (1997) with parameters defined in Wurzer (2009):

$$\mathrm{HLC} = h \cdot \left(1 - e^{a + b \cdot \frac{h}{\mathrm{DBH}} + c * \mathrm{DBH}}\right). \tag{6}$$

Analysis and results

Model calibration

Modelling a single-tree selection process for the simulation of a harvesting regime has already been applied by Sterba *et al*. (2000) and Ledermann (2002). The concept of using two logistic functions – one to determine the harvesting probability of a plot and another to calculate the removal probability of a single tree – is similar to the approach described in Ledermann (2002). However, in our application, the resulting probabilities are compared with random numbers to define if a plot is harvested and which tree is removed, while in Ledermann (2002), two thresholds are defined to determine whether the tree removals take place.

Next, we need to define the set of independent variables for our harvesting equations. Since the d.b.h. was the only repeated measurement for every tree of the available dataset, we decided to integrate the d.b.h. in both equations.

The first equation predicts the probability of harvesting which may take place at a given plot. The quadratic mean diameter (*dg*) was calculated and used as an independent predictor. For the second equation of our harvesting tool, the d.b.h. for each tree is used to predict the removal probability. The squared d.b.h. term in equation (8) was introduced because the available removal data suggest a parabolic shape of the removal probability of the trees with a minimum in the middle d.b.h. classes.

Our tree data come from permanent angle count sampling plots. Thus, we decided to choose the distance-independent CCF according to Krajicek *et al.* (1961) as an additional driver for tree harvesting. Since the length of a remeasurement period was either 5 or 10 years, a dummy variable addressing the length of the period (*pl*) was introduced. If the remeasurement period was 5 years, the dummy variable is set to 1, otherwise to 0. With this dummy setting, the differences in the harvesting probabilities according to the differences in the length of the remeasurement period are addressed.

Species mixture influences tree mortality and the harvesting strategy of uneven-aged mixed plenter forests. Thus, we calculated a species-specific CCF for conifer and broadleaf trees and integrated them separately in the first equation that calculates the harvesting probability. In the second equation that operates on a tree level and calculates the removal probability, there are five dummy variables for the different tree species (spruce, fir, larch, pine and beech).

Other variables such as the proportion of conifer and broadleaf trees at a given plot were also tested but only those that were significant at a α = 0.05 level were selected. Only the d.b.h. was repeatedly measured. Thus, we decided not to include tree height or height – diameter ratios (H/D – ratio) since they would have been derived from d.b.h. and such smoothed height information reduces the variation *vs* observed height data and may effect the error structure of model results (Hasenauer and Monserud, 1997).

The harvesting model was calibrated using the full company dataset covering the three regions Sommereben, Hebalm and Fürstenfeld. The first equation that calculates the harvesting probability of a plot has the following form:

$$P_{\text{Harvest}} = \frac{1}{1 + e^{a_0 + a_1 \cdot dg + a_2 \cdot \text{CCF}_{\text{conifer}} + a_3 \cdot \text{CCF}^2_{\text{conifer}} + a_4 \cdot \text{CCF}_{\text{broadleaf}} + a_5 \cdot pl}}, \quad (7)$$

where P_{Harvest} is the resulting probability of harvesting a plot. Variable *dg* denotes the quadratic mean diameter; CCF is the crown competition factor (Krajicek *et al.*, 1961). As mentioned before, the CCF is calculated independently for conifer ($\text{CCF}_{\text{conifer}}$) and broadleaf ($\text{CCF}_{\text{broadleaf}}$) trees to be able to take care of mixture effects. *pl* denotes the dummy variable for the period length. Wald chi-square test statistics (Wald, 1943) were used for independent variable selection at a significance level of α = 0.05. The results are given in Table 3.

The second equation of our harvesting model calculates the removal probability of every tree on a plot where harvesting occurred. It has the following form:

$$P_{\text{Remove}} = \frac{1}{1 + e^{b_0 + b_1 \cdot \text{DBH} + b_2 \cdot \text{DBH}^2 + b_3 \cdot \text{CCFL} + b_4 \cdot pl + b_5 \cdot \text{spruce} + b_6 \cdot \text{fir} + b_7 \cdot \text{larch} + b_8 \cdot \text{pine} + b_9 \cdot \text{beech}}}, \quad (8)$$

where P_{Remove} denotes the probability of a tree to be removed; d.b.h. is the diameter at breast height and is included in the equation in two ways, the actual d.b.h. and the squared d.b.h. So it is possible to calculate a minimum or maximum probability for a particular d.b.h. Similar to the first equation, the period length (*pl*) is included because different probabilities are expected within a different period length. The mixture effect is maintained by five

Table 3: Estimated coefficients of equations (7) and (8), the standard error, the Wald chi-square statistics and the *P*-values

Variable	Coefficient	SE	Wald chi-square	*P* > chi-square
Equation 7				
a_0	3.257	0.394	8	<0.0001
a_1	−0.05095	0.006446	62	<0.0001
a_2	−0.02058	0.002829	53	<0.0001
a_3	0.00002048	0.000007667	7	0.007563
a_4	−0.01016	0.001747	34	<0.0001
a_5	0.9899	0.1223	66	<0.0001
Equation 8				
b_0	0.8808	0.02036	1871	<0.0001
b_1	0.05136	0.0008188	3935	<0.0001
b_2	−0.0007128	0.00001476	2331	<0.0001
b_3	−0.001567	0.00003523	1979	<0.0001
b_4	0.3003	0.005354	3145	<0.0001
b_5	−0.6965	0.01558	1998	<0.0001
b_6	−0.3547	0.01937	335	<0.0001
b_7	−0.7561	0.02096	1301	<0.0001
b_8	−1.082	0.01859	3388	<0.0001
b_9	1.278	0.03529	1312	<0.0001

For the calibration process, N_{rep} trees were generated for each sample tree of the angle count sampling in order to take care of the weighting effect in the sampling method. This resulted in the total number of 1 131 820 trees used for the calibration.

dummy variables for the different tree species (spruce, fir, larch, pine and beech). All selected independent coefficient variables had to be significant ($\alpha = 0.05$) according to the Wald chi-square test statistic. The results are given in Table 3.

Model evaluation

Long-term permanent inventory data from uneven-aged mixed species forests across larger forest areas are very difficult to obtain. Thus, in our calibration process, we used all the available information to mimic the typical silvicultural forest management system of the company. The disadvantage of this approach is that no independent data for a classical model validation were available. Therefore, we decided to evaluate our harvesting model as follows:

1 We implement the harvesting model in the tree growth model MOSES.
2 We initialize the forest stands using the permanent plot data information at plot establishment: 1980 for Sommereben and Fürstenfeld and 1985 for Hebalm.
3 We run MOSES for 50 years and apply the developed harvesting model in each period. Thus, each forest stand covers ten 5-year period since the prediction period in MOSES comprises 5 years.
4 Compare predicted results *vs* observed harvesting data supplied by the company districts.

After running the model on the available dataset, 69 per cent of all trees were classified correctly. Among the removed trees, the proportion of correct classified trees was 24 per cent, whereas 80 per cent of the remaining trees were classified correctly. The model also predicted 60 per cent of all plots correctly as being harvested or not: 68 per cent of the harvested and 48 per cent of the non-harvested plots. The small percentage of correct classified removed trees is an effect of overall model interpretation. If harvesting a plot is not classified correctly in the first step, then all trees that are removed on that plot are not taken into consideration for step 2. If however we applied the second equation only on the plots where harvesting was observed according to the dataset, the proportion of correctly classified removed trees increased to 34 and to 83 per cent for the remaining trees (73 per cent for all trees).

Figure 1 shows the probability of a tree being removed in relation to d.b.h. on all plots where harvesting was applied. Only the probabilities for spruce, fir and beech are depicted; other tree species behave similarly. The probability exhibits a parabolic shape with the highest values for trees with low and high d.b.h. This is a result of the squared d.b.h. term in equation (8). It is also evident that trees are more likely to be removed in a 10-year period than in a 5-year period. The tree species with the highest removal probability is spruce, followed by fir. Beeches are very unlikely to be taken out since the current management regime tries to increase the species diversity by supporting other species than spruce.

Next, we were interested in a comparison of observed *vs* predicted proportions of removed trees evident from the dataset and the MOSES simulations (Figure 2). The proportions are grouped into 5 cm d.b.h. classes. The figure depicts the mean values per 5-year period and plot. The parabolic shape is most evident in the region

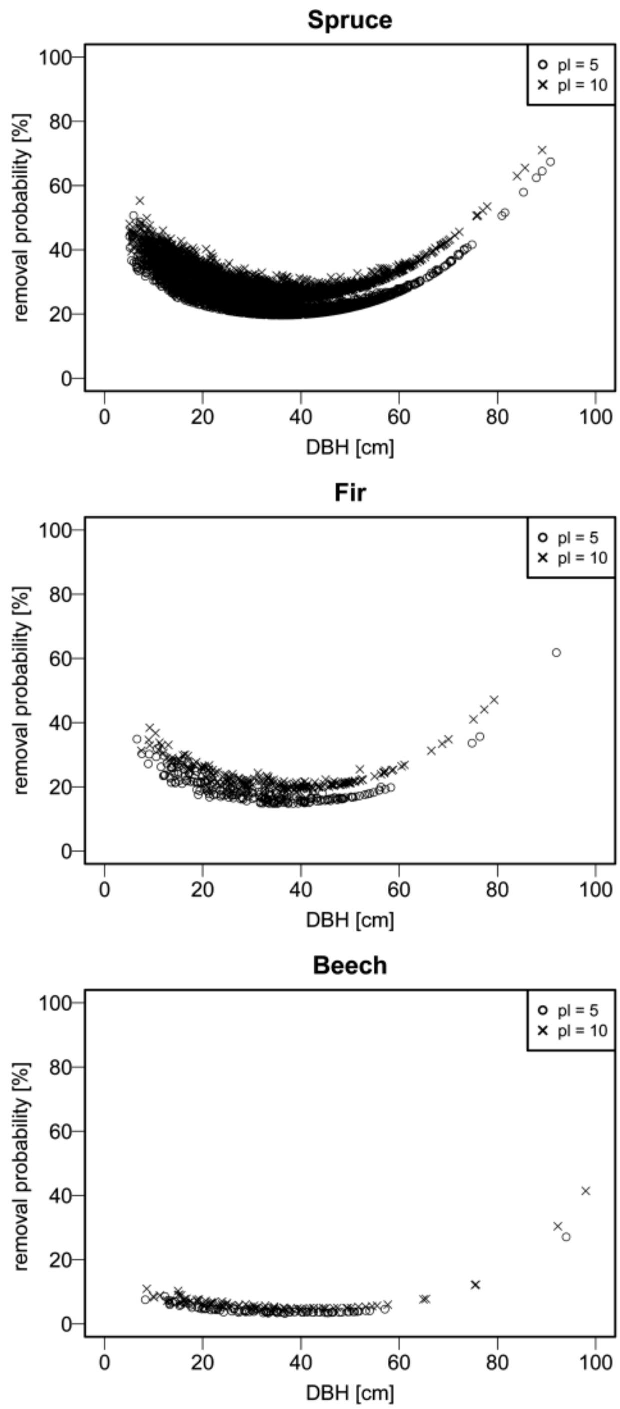

Figure 1. The probability of a tree being removed according to its d.b.h. (centimetre), calculated by the harvesting model. Only trees on plots on which harvesting is predicted are shown. The cycles show the probability of trees in a 5-year period; the probabilities denoted by an 'x' show trees of a 10-year period. The first graphic shows the probability of spruce, the second of fir and the last of beech.

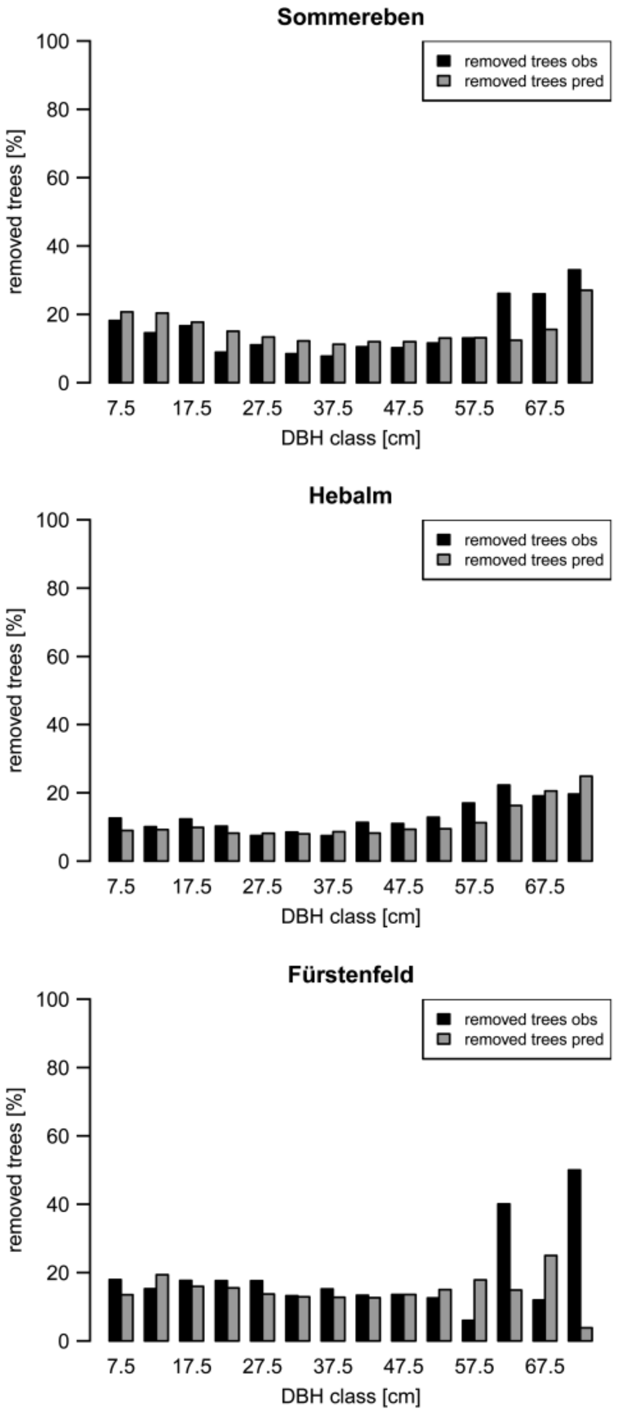

Figure 2. The predicted (pred) and observed (obs) proportion of removed trees (stem number) per 5-year period. The figure shows the mean value per plot. The first graphic shows the proportion in region Sommereben, the second in Hebalm and the third in Fürstenfeld.

Sommereben. This suggests that the MOSES simulation slightly overestimates tree harvesting in the low and medium d.b.h. classes and underestimates in the high ones. There are not many trees in the high d.b.h. classes (>60 cm), so the variance is high. In region Hebalm, the parabolic shape is not so evident as in Sommereben, but the relationship between predicted and observed probabilities is consistent. There is a minor underestimation in the low d.b.h. classes and in the classes between 40 and 60 cm. The results for region Fürstenfeld do not depict the expected shape of the removal probability, but the comparison of predicted and observed removals also suggests that the harvesting model in combination with MOSES creates a valid result. It is important to note that with each new remeasurement, more data for model calibration are available and this enhances the reliability of the calibrated models and the resulting predictions.

One important issue within uneven-aged forest management is the existence of a continuous harvesting regime so that a plenter harvesting balance may be created. A simple measure for such a balance is basal area and its change over time (O'Hara *et al.*, 2007). In Figure 3, the predicted *vs* observed basal area development is shown. Only trees with a d.b.h. >5 cm are used for calculation. Observed values are only available until the year 2000. The predicted development is calculated for 10 periods (50 years) starting at the first measurement and ending in 2030 in Sommereben and Fürstenfeld and 2035 in Hebalm. The basal area development is shown for both the remaining and the removed trees. In Sommereben, the predicted and observed development of the remaining stand is almost identical, the removals are slightly overestimated between 1985 and 2000. The simulated remaining stand basal area is almost constant at the beginning and increases to ~35 $m^2\ ha^{-1}$. In Hebalm, the harvesting model underestimates the predicted basal area development; the removed basal area is overestimated from 1985 to 1995. The predicted and observed basal area development shows an increasing trend with a smaller magnitude in the predictions. At the end of the simulation, the basal area levels-out at ~32 $m^2\ ha^{-1}$. In the last region, Fürstenfeld, the decreasing trend in the remaining basal area development is evident in the observation as well as in the prediction, although the prediction clearly overestimates from 1990 to 2000. This is also shown in the underestimation of the removals between 1990 and 2000. In the long term, the prediction shows a constant development suggesting a basal area of ~35 $m^2\ ha^{-1}$ across all sites.

Discussion

Uneven-aged forests or plenter forests require a sophisticated management regime with selective, individual and regular harvesting (Reininger, 2000). The selection of the trees to be removed cannot be easily translated into defined harvesting rules since each company may have different silvicultural strategies according to their history as well as existing stand and site constraints. Thus, a probabilistic plenter harvesting model with two logistic functions, similar to Ledermann (2002), was fit to a dataset of three forest regions where plenter harvesting is applied. The potential of logistic functions to model tree selection

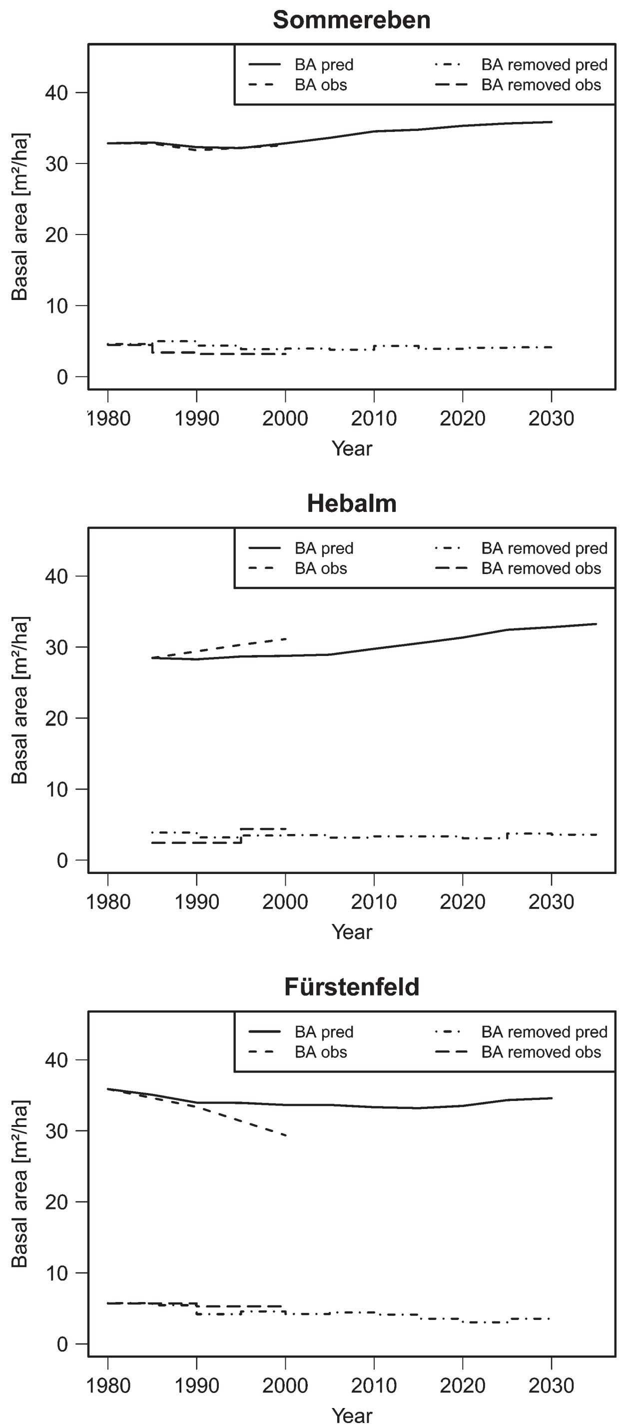

Figure 3. The predicted (pred) and observed (obs) basal area development (square metres per hectare) for the remaining stand (BA) and the removed trees (BA removed), respectively. The figure shows the mean values per plot. The first graphic shows the proportion in region Sommereben, the second in Hebalm and the third in Fürstenfeld.

preferences was shown by Füldner (1996). All regions are still in the transition phase from even to uneven-aged treatment, the beginning of the management change varied from 40 to 80 years. Not every plot in the plenter forest of the available dataset is harvested in a constant 5-year time period. The prediction of the probability of a plot to be harvested makes the model robust to inconsistent harvesting periods because the harvesting of a plot depends on site characteristics and not on a constant time period. For the model calibration, only 5- and 10-year measurement periods are available. The LOGIT functions of the two equations contain the period as a dummy variable that is set to one if the length of the period is 5 years. That results in a lower probability of trees being removed in a 5-year period (Figure 1). Possible species mixture effects are integrated in equation (7) by calculating the CCF (Krajicek *et al.*, 1961) for conifer and broadleaf trees, respectively. In equation (8), there are dummy variables for spruce, fir, larch, pine and beech that take care of existing species-driven selection criteria for harvesting.

The parabolic shape of the removal probabilities of the trees according to the d.b.h. (Figure 1) is a result of the squared d.b.h. term in equation (8). A higher probability of small trees being removed is plausible in the plenter management regime due to the stem reduction or pre-commercial thinning on young plots. Since in uneven-aged mixed species forests, a high natural regeneration is expected, a lot of small trees have to be removed. The model predicts the lowest removal probability at a d.b.h. between 30 and 50 cm. Trees with a larger d.b.h. are again more likely to be removed as they reach their harvesting volume or target diameter.

According to Figure 1, the management regime supports other trees than spruce, especially beech, in order to increase the species diversity. This is a desired characteristic in uneven-aged managed forests in this area. Only pine has a higher removal probability than spruce (result not depicted). Pine trees are mainly located in region Fürstenfeld followed by Sommereben (Table 1). The current management regime does not support pine in this area because the conditions there are not suitable for a light-demanding tree species such as Scots pine. All other tree species show a lower removal probability than spruce.

Figure 2 shows the predicted and observed mean proportion of removed trees per period in the observation time span until the year 2000. Compared with the parabolic shape of the removal probabilities of the model in Figure 1, the expected shape is mainly evident in region Sommereben followed by Hebalm. Fürstenfeld shows a more or less constant removal proportion over all d.b.h. classes. Especially in region Sommereben, it is obvious that the model smoothes the removal proportion to the expected parabolic shape over the d.b.h. classes.

The predicted stand suggests that the basal area of all regions will level-out at ~32 to 36 m^2ha^{-1} with a more or less constant removal over time (Figure 3). This leads to a sustainable forest assuming that the current management regime is applied continuously. One problem of our current results may be an underestimation of the basal area in Hebalm and an overestimation in Fürstenfeld (see Figure 3). However, the harvesting regime is not constant during the transition phase from even to uneven-aged forest management and the timing of the silvicultural management change is an important factor. Hebalm changed the harvesting regime at the beginning of the 1970s and thus was the last region that entered the transition phase from an even-aged mainly spruce-dominated forest to an uneven-aged mixed species plenter forest. Fürstenfeld had already changed in the 1930s. In this region, the model overestimates the basal area of the remaining stand (underestimates the removals), whereas in the region with the most recent change, the basal area is underestimated. For Sommereben, where the timing of the management change was between that of Fürstenfeld and Hebalm, the model predictions show the best result. This suggests that the timing of the management change is important for the modelled harvesting results. The company established a permanent forest inventory in the early 1980s with remeasurement intervals of 5–10 years. With each remeasurement, the database will be improved and any recalibration of our model approach by adding new data will enhance the reliability of the resulting predictions.

One problem of the dataset and the calibration process is the lack of regeneration information because only trees with a d.b.h. greater than 5 cm were measured. Therefore, the harvesting model could not be calibrated for smaller trees which might have a much higher removal probability than shown in Figure 1. In the simulation, a lot of small trees are generated within the regeneration model provided in MOSES (Hasenauer and Kindermann, 2006). Again, we can assume that with an increasing number of repeated measurements and recalibration of our approach, the quality of the resulting harvesting model for the three different districts will be systematically improved.

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Conflict of interest statement

None declared.

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