EVALUATION OF BIODIVERSITY FOR MULTI-PURPOSE FOREST MANAGEMENT USING A NON-LINEAR OPTIMIZATION APPROACH

YOUSEFPOUR, R.[1]* – HANEWINKEL, M.[2] – LE MOGUÉDEC, G.[3]

[1]*Institute of Forestry Economics and Management*
Tennenbacherstr. 4, D-79085 Freiburg, Germany
(phone: +49-761-203-3780; fax: +49-761-203-3690)

[2]*Forest Reasearch Institute of Baden Württemberg*
Wonnhaldestr. 4, D-79100 Freiburg, Germany

[3]*LERFoB – UMR INRA-ENGREF 1092*
Centre INRA de Nancy, 54280 Champenoux, France

**Corresponding author*
e-mail: r.yousefpour@ife.uni-freiburg.de

(Received 28th January 2010 ; accepted 28th May 2010)

Abstract. The paper applies a non-linear optimization approach to evaluate biodiversity in the multi-purpose modelling of forest management. An even-aged forest of pure Norway spruce was generated from large-scale inventory data of the Black Forest of southwest Germany. The effects of different management alternatives including five conversion schemes, two traditional age-class and single-tree-selection systems and a “Do-nothing” strategy were simulated using the forest growth model “BWINPro-S”. Optimal allocation of management strategies to the forest area was found subject to the hard constraints of “area” and “protection” and the chance constraint “wood even flow”. A utility function representing the value of biodiversity was estimated based on the opportunity costs of different biodiversity levels. The upper and lower boundaries of the function were determined by successive optimization runs. Subsequently, the obtained monetary value of biodiversity was directly integrated into the optimization of a particular forest to identify the optimal allocation of management schemes to entire forest enterprise. Conservation or “Do-Nothing” was the most desirable scenario combined with the partial establishment of beech regeneration. Economic and silvicultural consequences of the optimal multi-purpose forest management plan were discussed and compared to the alternative business-as-usual strategies.
Keywords: *Non-linear Optimization; Biodiversity; Multi-purpose Forest Management; Black Forest; Climate Change*

Introduction

Multi-purpose forest management and biodiversity

Sustainable management of forest ecosystems has to provide forest goods and services without jeopardizing the ecological and environmental quality. Therefore, in many countries, forest management practices have been changed and there is a trend to move away from homogeneous and non-site adapted even-aged plantation forestry to more close-to-nature ecosystems (Hanewinkel and Pretzsch, 2000; Schröder et al., 2007; Knoke et al., 2008). The conversion of pure coniferous stands into mixed-species forests, as an adaptation strategy to climate change (Böttcher, 2007) is a focus of contemporary forest management and policy in Europe (Bladt et al. 2009; Kint et al. 2009), especially in Germany (Hanewinkel and Pretzsch, 2000; Spiecker, 2003;

Schröder et al., 2007; Pretzsch et al., 2007). The scope of forest conversion is to enhance the level of biodiversity considerations in a cost-effective way based on the idea of multi-purpose forest management (Steuer and Schuler, 1978; Kangas and Kuusipalo, 1993; Briceno-Elizondo et al., 2008; Bladt et al., 2009). Nonetheless, a comprehensive analysis of forest conversion within multi-purpose forest management particularly including the valuation of biodiversity is still lacking.

One concern is that biodiversity and its related indices are very difficult to integrate into optimization models of forest management planning (Steuer and Schuler, 1978; Schulte et al., 1998; Hanewinkel and Pretzsch, 2000; Koskela et al., 2007). The reason for this is not only the lack of a unified theory of biodiversity (Schulte et al., 1998; Buongiorno and Gilles, 2003) and, consequently, of a universal indicator for biodiversity (Kangas and Kuusipalo, 1993; Zhou and Buongiorno, 2006; Yousefpour and Hanewinkel, 2009) but also the mathematical complexity (i. e. the non-linear nature) of most of the popular indices such as the Shannon index (Koskela et al., 2007).

Integration of biodiversity into forest optimization

In the present study, the management problem to be analyzed was the conversion of pure Norway spruce stands (*Picea abies* L. Karst) into mixed stands of Norway spruce and European beech (*Fagus sylvatica* L.) including economic and ecological aspects. To model forest conversion, a forest growth simulator is necessary in order to predict the effects of different silvicultural treatments on the development of the main forest characteristics (Hanewinkel, 2001; Hasenauer, 2006; Kint et al., 2009). Despite their limitations, these simulators are also practical in comparing consequences of such strategies considering a wide variety of forest characteristics such as biodiversity (Schröder, 2005). For this study, a single-tree growth simulator “BWINPro-S” was selected which included the necessary juvenile module to model the establishment of beech regeneration under the canopy of Norway spruce trees (Schröder et al., 2007; Röhle, 2009).

The integration of biodiversity in forest optimization is not new (Steuer and Schuler, 1978; Kangas and Kuusipalo, 1993; Buongiorno and Gilless, 2003; Kurttila et al., 2006; Briceno-Elizondo et al., 2008; Koskela et al., 2007). However, the studies have rarely identified the most desirable forest management plan based on a recommendable level of biodiversity, meaning a level that can be achieved under given framework conditions (e.g. constraints) and that – at same time – reaches an optimum (Kurttila et al., 2006).

In order to incorporate biodiversity into the process of forest management modeling, there is a need to monetize its value (Kangas and Kuusipalo, 1993; Kurttila et al., 2006; Koskela et al., 2007; Yousefpour and Hanewinkel, 2009). The standard approach therefore is an indirect one: biodiversity is formulated as a constraint within an optimization procedure to calculate its opportunity costs (Buongiorno and Gilless, 2003; Kurttila et al., 2006; Koskela et al., 2007). In this study, a more direct way is proposed to integrate biodiversity into a multi-objective optimization problem. A great advantage of this approach is identifying the upper and lower boundaries of the regional utility-loss function for biodiversity (regarded as a public good) and, consequently, evaluation of biodiversity for the multi-purpose modeling of a particular forest which is so far not available in the literature.

Goal of the study

The goal of the present study was to develop a new method to valuate biodiversity based on a non-linear optimization procedure. Therefore, in a first optimization step, a global utility function for a forest management problem subject to a biodiversity constraint was defined and the boundaries from which biodiversity influenced the global utility function were derived. A non-linear function related to the opportunity cost (utility-loss) of biodiversity within the derived boundaries of the feasible solution space was parameterized. The effectiveness of the developed procedure was demonstrated by applying it to the problem of finding the optimal forest management pathway for a forest conversion problem based on a recommendable level of biodiversity within a second optimization step. Furthermore, a related sensitivity analysis of the best management solution was examined in a post-optimality analysis (Buongiorno and Gilless, 2003; Kurttila et al., 2006).

The paper is organized as follows. The section the materials and methods introduces an adopted methodology to evaluate and integrate biodiversity in the modeling of forest management. This is proposed to integrate biodiversity into a multi-objective optimization problem by identifying the upper and lower boundaries of the regional utility-loss function for biodiversity and evaluation of biodiversity for the multi-purpose modeling of a particular forest. Section of results outlines the most desirable solution and analyses the trade-offs between goals. Variety of forest strategies have been compared at the end of this section too. The last section is first and foremost devoted to the discussion of the modeling approach, its limitations and advantageous. Afterwards, the main findings of provided numerical applications have been interpreted for the case of Black Forest to achieve the multiple goals of regional forest management.

Materials and methods

Forest management scenarios

Eight different forest management scenarios representing forest conversion (five scenarios), a traditional age-class management, a single-tree-selection system for the transformation of even-aged into uneven-aged stands and a nature conservation strategy were defined (*Table 1*). Five different forest conversion scenarios, from pure- to mixed-stands, were developed by applying different silvicultural systems, namely: “**G**roup **F**elling” (GF), “**Sh**elterwood” (Sh), “**S**trip **C**utting” (SC), “**A**ge-**C**lass” (AC) and “**Tr**ansformation” (Tr, by means of a “Single-tree-selection” system) all of which include regeneration (planting of 1,500 beech seedlings per ha). These scenarios were formulated in detail (*Table 1*) according to the approach of (Hanewinkel and Pretzsch, 2000). The conversion scenarios were compared to the traditional age-class system of managing pure Norway spruce in the Black Forest area of Southwest Germany to the transformation of the even-aged Norway spruce forest into an uneven-aged one and to a “Do-nothing” alternative corresponding to a nature conservation scenario. The intensity of the thinning activities of the different scenarios was expressed by the A-value according to (Johann, 1982). The baseline conversion-, age-class- and transformation-scenarios were formulated according to (Hanewinkel and Pretzsch**,** 2000) and (Hanewinkel, 2001) where details of the management prescriptions for the different alternatives can be found.

Table 1. *Management prescriptions for the different silvicultural scenarios*

Scenario	Period 1	Period 2	Period 3	Period 4
Conversion (I-V)	A-Value = 4 (= 150 Crop tree/ha)	A- Value = 6 (= 200 Crop tree/ha)	Group Felling (I) (3 * 25dm); Shelterwood (II) (25 %); Strip Cutting (III) (50 %); Age-Class (IV) (even-aged); Transformation (V) Single-tree-selection } + Plantation (1500/ha)	+ Target -diameter -harvest (50 %) D.B.H.= 45cm (scenarios I-VII)
Age-Class (VI)	A-Value = 7 (= 300 Crop tree/ha)	Age-Class even-aged	Cutting Break	
Transformation (VII)	A-Value = 6 (= 200 Crop tree/ha)	Single-tree-selection uneven-aged	Single-tree-selection uneven-aged	
Conservation (VIII)		Do-nothing		

Period I-IV: Planning periods of 10 years each
*(I) Group Felling (3*25m) = felling of three gaps with a diameter of 25 m each by "Group Felling"*
(II) Shelterwood (25 %) = removal of 25 % of the growing stock by "Shelterwood" cutting
(III) Strip Cutting (50 %) = removal of 50 % of the growing stock by "Strip Cutting"
(IV) Age-Class = a traditional even-aged management system (also in scenario VI)
(V) Transformation = Transformation of the even-aged stand into an uneven-aged one following an inverse j-shaped curve for the diameter distribution by "Single-tree-selection" system (also in scenario VII)
(VIII) Conservation = to do no interventions in the forest
Target diameter harvest (50 %)- d.b.h = 45cm = removal of 50 % of the trees having reached a target diameter of 45cm d.b.h

Simulation of decision alternatives

Simulation of forest stands and the prediction of the effects of different silvicultural treatments on these stands as management decision alternatives is a primary modeling step towards forest enterprise optimization (Hasenauer, 2006; Pretzsch et al., 2007). To accomplish this, a model of an even-age forest enterprise was generated according to the technique of strata planning (Hanewinkel and Pretzsch, 2000) deduced from large-scale inventory data (permanent plots of the national forest inventory of Germany) of the northern Black Forest. Site productivity was assumed to be constant over space and time. To test the decision alternatives for different stands, an age-class forest enterprise consisting of five model stands in five age-classes of 30, 50, 70, 90 and 110 years with 200 ha of area each was simulated over a planning period of 40 years, divided into four steps of ten years each. *Table 2* shows the main inventory data of the generated stands.

Table 2. *Description of the stands (age-classes) deduced from large-scale inventory data (permanent plots of the national forest inventory of Germany) of the northern Black Forest*

Age (years)	D100 (cm)	H100 (m)	N/ha	Dg (cm)	Hg (m)	B/ha (m2/ha)	V/ha (m3/ha)
30-50	25.6	14.4	1648	15.7	12.5	31,9	207
50-70	36.2	21.4	728	24.0	19.5	32.9	318.6
70-90	46.2	27.8	277	35.3	27.5	27	329.8
90-110	55.5	33.5	180	46.8	32.7	30.9	435.7
110-130	62.7	38.1	150	56.6	37.6	37.7	587

D100 = average diameter of 100 highest trees
H100 = average height of 100 highest trees
N/ha = number of trees (with the diameter of above 7 centimeters)
Dg = average diameter of all trees
Hg = average height of all trees
B/ha = average Basal area of all trees
V/ha = average Volume of all trees

The growth and yield simulator “BWINPro-S” which was used in this study is, aside from the model SILVA (Pretzsch, 2001), one of the two computer-based simulators currently used in Germany for a multitude of applications. Its regional relevance ranges from the Pleistocene lowland conditions to sites on Palaeozoic rocks in a chilly and humid highland climate (Schröder et al., 2007, according to Fürst et al., 2004) and can therefore be applied to site conditions of the Black Forest. In the present study, the distance-dependent version of the growth and yield simulator “BWINPro-S” was used for the simulations (Röhle, 2009). One of the unique features of “BWINPro-S” is a module to simulate juvenile growth of beech under the canopy of Norway spruce (Schröder et al., 2007), and thereby enabling the simulator to model the establishment of regeneration. *Fig. 1* illustrates how growth and yield predictions in “BWINPro-S” may be combined with thinning and harvesting operations in order to simulate different management options that can be compared by means of their financial outcomes (Röhle, 2009).

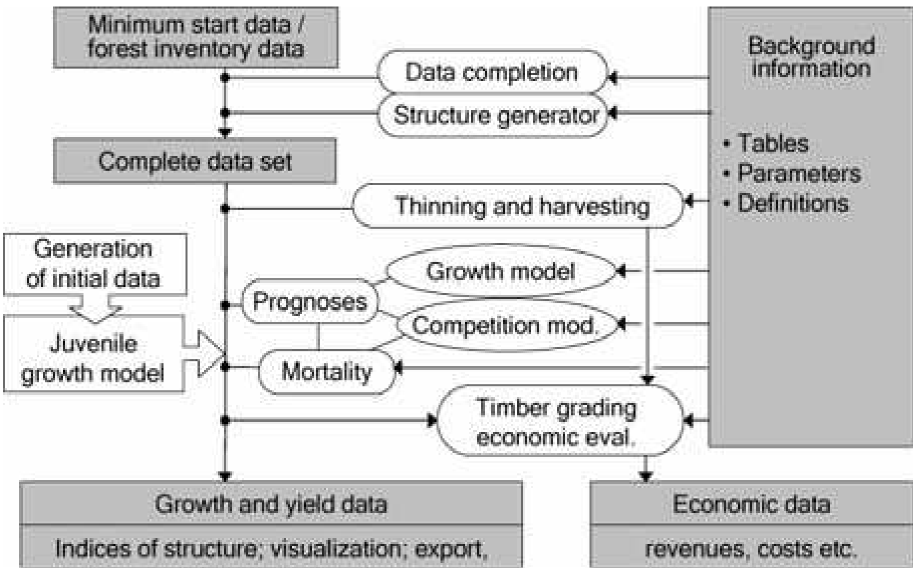

Figure 1. *Main modules of the simulator “BWINPro-S” in Röhle, 2009*

Wood prices and the costs of silvicultural and forest improvements were based on the deflated average realized prices and costs during the five-year period from 2000-2005 to calculate the net revenues of timber production. The establishment cost of beech regeneration was integrated into the harvesting cost to make the calculations straightforward. A mean price of 3 € per seedling was used to calculate regeneration costs.

The simulation and optimization procedures were run separately in different software environments. The output of the simulations runs were stored in a database and then used as an input for the following optimization procedures using the Solver Premium Platform (Buongiorno and Gilless, 2003; Dirsch and Knoke, 2007; Yousefpour and Hanewinkel, 2009).

Quantifying biodiversity

The scope of forest conversion in the present study is to enhance the level of biodiversity (structural diversity) of the managed forests. Therefore, to express this in a quantitative way, an adapted Shannon index was used. The index calculates the evenness (uniformity) of the distribution of species (i.e. Norway spruce and European beech) in the entire forest area and is therefore a good measure of conversion (*Equation 1*). A major goal of forest conversion in the Black Forest area is to improve the structural diversity in pure monocultures of Norway spruce by establishing beech (Hanewinkel and Pretzsch, 2000; Hanewinkel, 2001; Kint et al., 2009). The index reaches its maximum value when all species are represented equally.

$$Sh = -\sum_{n=1}^{N} Gn * \ln(G_n), Gn = g_n / g_N \qquad \text{(Eq. 1)}$$

Where **G**n is the proportion of the basal area in a particular species (gn), of which there are n, to the total basal area of all species in the stand (g_N , N is the number of species in a stand).

General formulation of the optimization problem

Global utility function

Multi-objective optimization procedures are often used to support the process of decision- making in forest management planning (Steuer and Schuler, 1978; Buongiorno and Gilless, 2003; Baskent and Sedat, 2005; Dirsch and Knoke, 2007; Yoshimoto and Marusak, 2007; Briceno-Elizondo et al., 2008; Yousefpour and Hanewinkel, 2009; Tahvonen, 2009). In this study, an additive utility function was defined to simultaneously consider the values of harvesting activities and standing volume. The forest optimization problem was formulated for a model age-class forest. The stand types (**s**) of this model forest standing for different age-classes were treated with different silvicultural scenarios (treatments - **t**) over several planning periods (**p**). To represent a model age-class forest optimization problem, the additive utility function **AUF** (global utility/objective function) to be maximized can be written as (*Equation 2*):

$$AUF(X) = (U_H + [U_L - U_I]) * X \qquad \text{(Eq. 2)}$$

With:

U_H = net present value (**U**tility) of all **H**arvest activities

$$U_H = \sum_{s=0}^{S} \sum_{t=0}^{T} \sum_{p=0}^{P} d_{i,p} u_H(s,t,p) \qquad \text{(Eq. 3)}$$

s = stand (age-class 1-5)
t = silvicultural treatment (1-8) (see *Table 1*)
p = planning period of 10 years (1-4)
$d_{i,p} = \frac{1}{(1+i)^{p*10}}$ is the discount factor, which depends on the period **p** and;
i = discount rate

U_L is the net present value (**U**tility) of the standing volume at the **L**ast period ***P*** which was also subject to wood stumpage prices.

$$U_L = \sum_{s=0}^{S} \sum_{t=0}^{T} d_{i,p} u_L(s,t,P) \qquad \text{(Eq. 4)}$$

U_I is the net present value (**U**tility) of the standing volume at the **I**nitial period p_0 (period zero).

$$U_I = \sum_{s=0}^{S} \sum_{t=0}^{T} d_{i,p} u_I(s,t,p_0) \qquad \text{(Eq. 5)}$$

Consequently $[U_L - U_I]$ is the change of the net present value of the standing volume during the conversion period of forty years (***P**- **P**0*).

X is the area of the stand (s) to be optimally allocated to the treatment (t).

$$X = x(s,t) \qquad \text{(Eq. 6)}$$

The considered revenues in **AUF** (Equation 2) are U_H (*Equation 3*) and $[U_L - U_I]$ (*Equation 4 and 5*), which correspond respectively to the direct financial revenue due to harvest (as calculated by the simulator) and the value of standing volume (calculated with the subtraction of the value of the standing volume at the initial step and last step, derived from the simulator). An actual discount rate of 2% (**i** = 0.02) and stumpage prices of different stand ages were applied to obtain the present value of both coefficients. The decision variable, **X** (Equation 6), represents the total area of a stand type s devoted to treatment t. The optimization problem consists of finding the space optimal; $\{\mathbf{x}(s,t)\}_{s=1..S,t=1..T}$ set of values.

Global constraints

Along with the **AUF**, the most important forest enterprise constraints were formulated. The constraints under examination were the asset management (reality hard constraint); wood even flow (which was considered as soft/chance constraints) and the conservation of a proportion of the oldest stand area (hard constraint). The punishment function for the soft constraint (wood even flow) included the standard deviation (expression 7) which represents the absolute amount by which the constraint has gone beyond its limit and was not met. The optimization procedure was subject to these constraints which signify supplementary objectives of a forest owner.

$$100 * (\exp(deviation \ / 100) - 1) \quad \text{(Eq. 7)}$$

The first constraint is an area (asset management) constraint ($Ca._{(max)}$) allocated to different decision alternatives. *Equation 8* expresses that for each stand type **s** symbolizing one age-class, the total area must be allocated among the entire set of available treatments.

$$\forall s, \ (s = 1,..., S); \sum_{t=1}^{T} x_{(s,t)} = A_{(s)} = Ca._{(max)} \quad \text{(Eq. 8)}$$

In each planning period, the area of each stand type (age-class) must therefore be equal to 200 ha.

The forest enterprise should ensure that it will be able to produce a minimum volume **C**wef. of wood to be sold in each period. Equation 9 demonstrates such a volume constraint that is applied in each period, where **wef**.(s,t) represents the volume of wood to be harvested in period **p** per hectare of stand **s** where the treatment t is applied.

$$\forall p, (p = 1,..., P); \sum_{s=1}^{S} \sum_{t=1}^{T} \text{wef.(s, t, p)} * \text{x(s, t)} \geq \text{Cwef.}_{(min)} \quad \text{(Eq. 9)}$$

The lower bound of the wood even flow constraint ($Cwef._{(min)}$) was fixed at 4.0 m^3 per year and ha (40 m^3 per 10-year-period), which on the one hand is well below the site productivity to guarantee a minimum harvest and allow for the necessary harvesting activities to install the regeneration in the conversion strategies and, on the other, prevent excessive volume accumulation in the even-aged schemes. The volume constraints of this optimization correspond to the silvicultural prescriptions that have been developed by the State Forest Service Baden-Württemberg in Southwest Germany for the management of pure spruce forests in Southwest Germany (MLR, 1999). In order for the forest types “stable mixed spruce forests” and “spruce forests to be converted into mixed beech forests” (MLR, 1999), a thinning interval of three to ten years and a maximum of 80 m^3/ha per thinning intervention was foreseen. The volume constraints of those applied to this optimization were a compromise in part between silvicultural needs, which should guarantee a successful conversion for the forest enterprise, and the other hand prescriptions to safeguard sustainability.

Finally, to represent a "protected area" policy, a conservation constraint (**C**p) was applied (*Equation 10)* to guarantee that at least a given proportion (**Pr**) of the area of the oldest stand a(**S**) is devoted to a "Do-nothing" treatment (**T**).

$$Cp\ .\ \geq\ \Pr * a(S),\ a(S) = x(S,T) \qquad \text{(Eq. 10)}$$

The proportion of the oldest stand (**S**) to be reserved for nature conservation purposes (treatment **T** which is Do-nothing scenario) was fixed at 10 % of its area (**Pr*a(S)** = 0.1*200=20 ha).

The adapted objective function and the set of constraints defined above was applied to analyze the optimization problem from the forest enterprise point of view by dedicating an optimal area of each stand to each scenario taking into account sustainable forest management goals of a virtual forest owner.

Integration of biodiversity into the optimization

A fictional additional global utility due to biodiversity (expressed as the Shannon index) was derived and integrated into the modeling of multi-purpose forest management. To develop a global utility function for biodiversity, the Shannon Index had to be computed for the entire forest enterprise due to its non-linear nature. The main reason for this choice was that it is a well-known index which is computable from the model outputs of most of the forest simulators. A two-step optimization procedure was designed (*Fig. 2*) that first defines a utility function for the Shannon index (optimization-**α**) and then – as a demonstrator of the effectiveness of the procedure – integrates the values into the optimization of a particular forest management plan (optimization- **β)**.

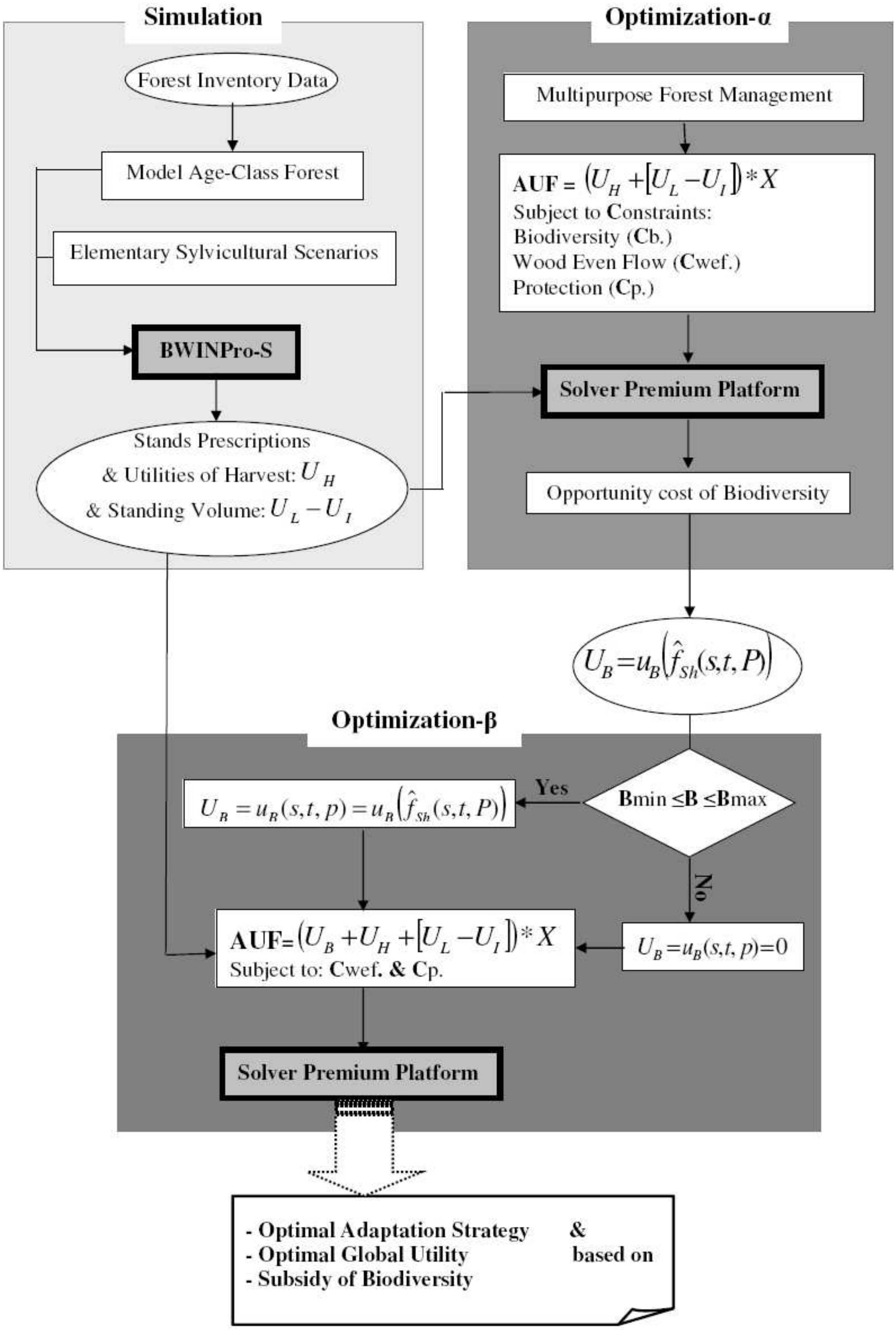

Figure 2. *Flowchart showing how biodiversity was conducted and integrated as a non-smooth objective (IF-THEN function) in the two-steps simulation-optimization procedure Parameters as described in section 2.2*

Optimization-**α** successively uses the output of the simulation runs and optimizes the global utility (*Equation 1*) subject to global constraints by iterating the variable level of the Shannon index as a global constraint (**C**b.). From a certain level on ($\mathbf{B}_{min}$ – *Fig. 3*), **C**b. becomes an active constraint and consequently decreases the global utility to a level where the optimization no longer has a feasible solution ($\mathbf{B}_{max}$, as described in *Fig. 3*). Afterwards, the opportunity cost of the different levels of the constraint "Biodiversity" (Shannon Index) in its active area between $\mathbf{B}_{min}$ and $\mathbf{B}_{max}$ was calculated based on the loss in global utility due to the constraint. The opportunity cost of different levels of Shannon index allows for the adjustment of a parametric (θ) function $\hat{f}_{Sh}\theta$ (*Fig. 3*), which can serve as a utility function of the Shannon index, $u_B\left(\hat{f}_{Sh}(s,t,P)\right)$. The obtained utility function can now be reused in any optimization of a particular forest enterprise with similar management objectives and constraints simultaneously considering the values of biodiversity and timber production.

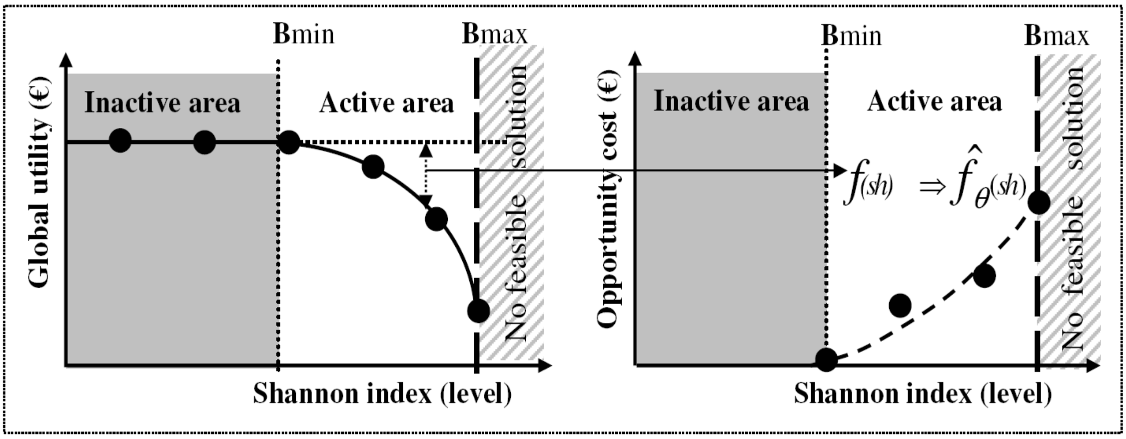

Figure 3. *Schematic depiction of how to adjust the utility function of the Shannon index by iteratively estimating the opportunity costs in the optimization runs*

The adjustment of the utility function of the Shannon index is a complex procedure. In the present study, an IF-THEN function was used to serve as the utility of biodiversity in the AUF. This type of objective function for the evaluation of the global utility leads to a non-smooth optimization procedure. This is an important issue in the integration of the utility of biodiversity in order to prevent overestimation or underestimation of its value compared to other objectives.

For demonstration purposes, the adjusted function was then integrated into the formulation of the global utility of the optimization-**β** including biodiversity as an objective (*Fig. 2*). Optimization-**β** provided the opportunity for biodiversity to compete with other objectives (e. g. timber production) and identified the optimal forest management plan with the allocation of different alternatives to the entire forest enterprise area with the most recommendable level of biodiversity as expressed by the Shannon index. Optimization-**β** therefore maximizes the optimal global utility with multiple values of biodiversity and timber production (*Equation 11*).

$$AUF(X) = \left(U_B + U_H + \left[U_L - U_I\right]\right) * X \qquad \text{(Eq. 11)}$$

In this study, an identical dataset was used for optimization-**α** – and **β** to demonstrate the procedure of valuating biodiversity. Mathematically, this is a repetition of the optimization-**α** with **B**max as the highest, most recommendable level of biodiversity. In a practical application , the results of optimization-**α** and the developed utility function should be applied to particular forest enterprises with similar framework conditions in order to determine the financial effects of a recommendable level of biodiversity for management strategies such as forest conversion. Nevertheless, this example was demonstrated in this study to show trade-offs between timber and non-timber objectives in the process of multi-purpose forest modeling.

Results

Estimation of the utility function for the shannon index

The extracted forest characteristics from the simulator for the optimization were biomass, harvest revenues, operation costs and managed area whereas a non-linear optimization procedure was formulated based on these results and on the Premium Solver Platform of Frontline Systems© (Frontline 2009). The first step was to calculate the opportunity cost of biodiversity (optimization-**α**) by using **t**he observations of the Shannon index. A parametric function was adjusted to the calculated values for the Shannon index, $u_B\left(\hat{f}_{Sh}(s,t,P)\right)$. Subsequently, two different exponential utility functions for the Shannon index were derived and integrated into the optimization-**β** procedure with the following IF-THEN function (*Equation 12*):

$$\begin{cases} \text{If:} \quad 0.25 < Sh \leq 0.5, U_B = u_B\left(\hat{f}_{Sh}(s,t,P)\right) = 4919.1 * Sh^{3.4434} (R^2 = 0.99) \\ \text{If:} \quad 0.5 < Sh \leq 0.625, U_B = u_B\left(\hat{f}_{Sh}(s,t,P)\right) = 5729.1 * Sh^{3.8924} (R^2 = 0.95) \\ \text{Otherwise:} \quad U_B = u_B\left(\hat{f}_{Sh}(s,t,P)\right) = 0 \end{cases} \qquad \text{(Eq. 12)}$$

Optimizing forest management incorporating biodiversity

Assuming of stability in the current discount rate of 2% and using the global additive utility function which include revenues from harvest as well as biodiversity (optimization-**β**) led to an overall optimum (or near optimum) utility for the entire enterprise of 7,958 €/ha. The optimal global utility consists of the utility of the harvest (1,016 €/ha), standing volume (6,134 €/ha) and biodiversity (807 €/ha) with 13, 67 and 10 percent of the total utility respectively. This optimal solution resulted in a recommendable level for the Shannon index of 0.625 (when planting beech on an area of 21 ha in stand-2 and 180 ha in stand-5) with related opportunity costs of 807 €/ha.

This optimum led to the distribution of the different silvicultural treatments to the different age-classes (“stands”). *Fig. 4* shows that the optimal solution does not consist of a unique treatment for the entire forest enterprises and all age-classes, but of a combination of different treatments in different stands (age-classes).

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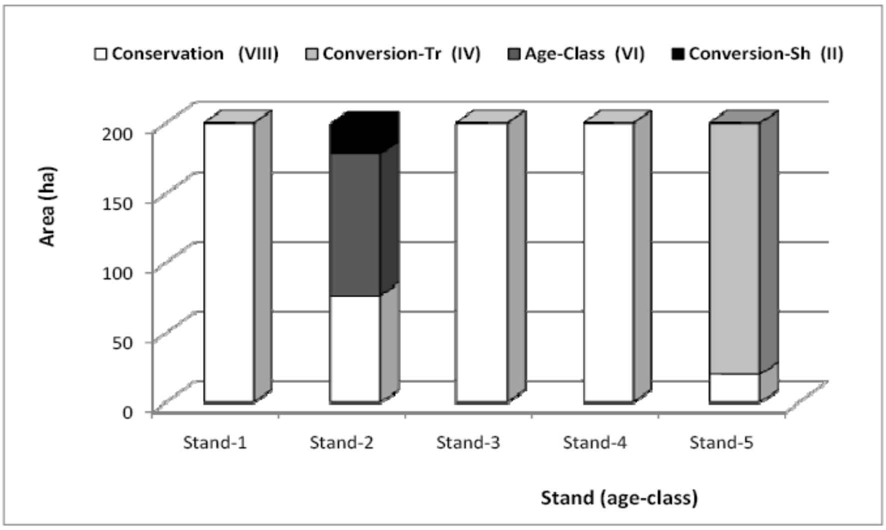

Figure 4. *Results of the optimization for the entire forest enterprise – distribution of the different silvicultural treatments to different age-classes (stands) including biodiversity Silvicultural strategies as described in Table 1:*
*(II) Conversion-Sh: "**S**helterwood" used for the gap installation in the 3rd period of Conversion*
*(IV) Conversion-Tr: **Tr**ansformation by the means of "Single-tree-selection" system used for the gap installation in the 3rd period of Conversion to transform the even-aged forest to uneven-aged one*
(VII) Age-Class: a traditional even-aged management system
(VIII) Conservation: „Do-nothing"strategy

Although the optimal pathway for stands 2 and 5 is a combination of different treatments, the conservation strategy (Do-nothing) is the dominant scenario in stands 1, 3 and 5. Despite the integration of biodiversity into the optimization, conversion which also include the introduction of beech seedlings appears as optimal only in stand-2 by shelterwood cutting and stand-5 by transformation into an uneven-aged forest). This is mainly due to the rather high costs of harvesting and planting beech and high accumulation of standing volume in the "Do-nothing" scenario that makes harvesting less attractive. Other alternative scenarios such as traditional age-class forestry are an option for more than 50 % (101 ha) of stand-2.

Comparing the results of the forest optimization with and without integration of biodiversity proved the necessity of directly integrating biodiversity as an objective into the planning process. *Fig. 5* shows the results of the optimization without taking biodiversity into account. The optimal solution is similar to that in *Fig.4* except for a replacement of the conversion scenario to non-conversion in stand-5. The absence of the notion of biodiversity in the body of the optimization causes a shift towards traditional silvicultural systems such as age-class (even-aged) forestry in the oldest stand. Conversion (with group felling) appears only in a part of stand-2 (59 ha or 27 %). Moreover, the level of Shannon index for the entire forest enterprise decreases from 0.625 to 0.183.

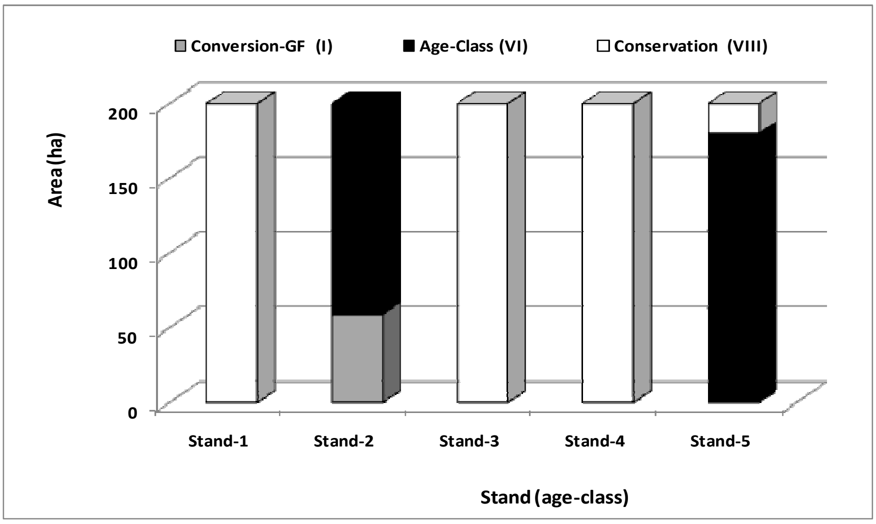

Figure 5. *Results of the optimization for the forest enterprise – distribution of the different silvicultural treatments to different age-classes (stands) without biodiversity*
Silvicultural strategies as described in Table 1:
*(I) Conversion-GF: "**G**roup **F**elling" used for the gap installation in the 3rd period of Conversion*
(VI) Age-Class: a traditional even-aged management system
(VIII) Conservation: „Do-nothing" strategy

Comparison of forest management strategies – forest enterprise level

To compare potential alternative strategies for the entire forest enterprise and their effects on the global utility, the optimization procedure was run separately for each of the main silvicultural strategies: i) "Do nothing" (Conservation), ii) Traditional "Age-Class" Forestry, iii) Transformation (even-aged to uneven-aged) and iv) Conversion (pure to mixed stands). The global utility of these main strategies was differentiated among the utility of harvest U_H, standing volume $[U_L - U_I]$ and the utility of biodiversity U_B and compared to that of the optimal forest plan (see last section) as a baseline. This allowed for the calculation of the cost of different forest strategies when applied to the entire forest enterprise and for the analysis of the effect of the different utilities (*Table 3*). In the present study, the post-optimality analysis is of specific discount in that it shows the effect of the opportunity cost of biodiversity on the whole forest enterprise level.

Table 3. *Global Utility and Utilities of different forest strategies when applied to the entire forest enterprise*

Forest Strategies	**Global Utility***	**Utility of Harvest ***	**Utility of Biodiversity***	**Utility of Standing Volume***
Conservation	8344	0	0	8344
Age-Class	7220	3738 (52%)	0	3482 (48%)
Transformation	5904	4447 (75%)	0	1457 (25%)
Conversion	5769	2817 (48%)	1356 (24%)	1597 (27%)
Optimal Forest Plan	7958	1016 (13%)	807 (10%)	6134 (77%)

** = figures are all in €/ha*

Table 3 shows the utilities of different strategies when applied to the entire forest enterprise. Compared to the optimal forest plan, the cost of converting the entire forest enterprise from pure stands of Norway spruce into mixed stands of Norway spruce and European beech would amount to 7,958 – 5,769 = 2,189 € /ha (2,189,000 € overall) in 40 years. The utility of biodiversity for this scenario was 1,356 €/ha, which was noticeably (nearly two times) higher than that of the optimal forest plan. This is due to intensive forest management aiming at establishing mixed stands on the entire forest area and consequently imposes a higher opportunity cost. Transforming the entire forest enterprise from even-aged into uneven-aged stands of Norway spruce led in costs of more than 1,316 €/ha and by applying a traditional age-class system, reduced the global utility by more than 738 €/ha. This was an effect of the earlier revenues from harvesting when reducing the standing volume to install regeneration or the approach to the uneven-aged structure in the transformation and conversion strategies in the 40-year planning period. The conservation (Do-nothing) strategy comprised the maximum global utility, which is due to the fact that there is no possibility to implement the global constraint of wood even flow for this strategy.

Discussion

Limitations of the models

As in many other studies (Buongiorono and Gilles, 2003; Hasenauer, 2006; Dirsch and Knoke, 2007), the present investigation used a modern growth simulator to depict growth and yield of a model forest enterprise. Therefore, all the results that are presented here are subject to the limitations of these growth models. One of the important limitations is the lack of a natural regeneration module that applies to most of the simulators (except “BWINPro-S” with the beech regeneration module). Another limitation of the simulators is the increase of uncertainty with increasing duration of the simulation. Thus, the optimization took place in finite time and was restricted to a time span of 40 years (4 periods of 10 years each). Longer simulations lead to a distinct increase of the uncertainty linked to the prognosis of growth and yield (Pretzsch et al., 2007) and to a high risk of producing artefacts within the present goal-seeking investment problem.

In this study a procedure was developed to integrate biodiversity via an estimated utility function in the post-simulation planning of a forest enterprise in the Black Forest area of Southwest Germany. The presented utility function of biodiversity is, of course, dependent on the index for biodiversity that was used (in this case the Shannon index), the parameters of the growth model (“BWINPro-S”) and the underlying silvicultural scenarios. Therefore, the value function as well as the results should be primarily regarded as an application of the introduced methodology in the sense of a demonstration. A generalization of the findings in the model forest used in this study is therefore not possible and was not intended. However, the methodology introduced in the present investigation can be adopted to optimize forest management planning taking into account other non-monetary criteria and preferences of decision-makers.

Integration of biodiversity

Multi-criteria decision-making techniques are common tools for treating biodiversity in forest planning (Kangas and Kuusipalo, 1993; Wikström and Eriksson, 2000; Buongiorno and Gilles, 2003; Kurttila et al., 2006; Briceno-Elizondo et al., 2008). Biodiversity has been considered as an attribute for alternative management scenarios in forest planning (Wikström and Eriksson, 2000), as an objective in the analytic hierarchy process (Kangas and Kuusipalo, 1993; Briceno-Elizondo et al., 2008), as a constraint in optimization processes (Buongiorno and Gilless, 2003; Kurttila et al., 2006). Biodiversity has thus far not been directly integrated into the optimization process as an objective due to valuation problems. The present paper suggests a way of evaluating biodiversity based on the Shannon index, a commonly used and available measure of biodiversity (Önal, 1997; Buongiorno and Gilless, 2003), in forest enterprise level.

Kurttila et al. (2006) and Koskela et al. (2007) examined the first-best instrument for biodiversity maintenance on the stand level. Kurttila et al. (2006) defined the bidding price demand for the biodiversity objective and calculated the subsidy of holding the same total utility as clear cutting on a stand level. They came up with a value between 290 and 403 €/ha for a protection period of twenty year at a discount rate of 4%. Koskela et al. (2007) found that a fully synchronized combination of retention tree subsidy and harvest tax is needed to achieve the goal of biodiversity management in Boreal forests. Furthermore, it has been demonstrated that when combined with a harvest tax, the retention tree subsidy was 1,000 €/ha and 750 €/ha using a Faustmann and a Hartman model, respectively. When used with a timber subsidy or a site value tax, the retention tree subsidy was 1,700 €/ha in both models.

The results of the present study in *Table 3* show that for the optimal model, a subsidy of 807 €/ha would be needed to compensate for the opportunity costs of biodiversity. This would increase to 1,356 €/ha if a conversion scenario were applied to the total forest area (discount rate = 4%). Yoshimoto and Marusak (2007) used a similar approach for determining the price of carbon as subsidy, which can be regarded as compensation or cost for carbon loss. They found that at an discount rate of 2%, the annual cost for the amount of carbon sequestered in the remaining trees ranged between 763 and 106 Yen/Ct/year (equal to 28-206 €/ha).

Multi-purpose forest management

The results indicate that the optimal management plan may vary with and without pricing and integration of biodiversity as an objective into the optimization procedure (Kangas and Kuusipalo, 1993; Wikström and Eriksson, 2000; Briceno-Elizondo et al., 2008). The optimal solution also identifies the optimal level of all integrated objectives such as biodiversity. This is one of the main findings of this study that maybe used by forest policy-makers in order to decide which level of biodiversity is achievable and at the same time, cost-efficient when designing forest conversion strategies for different forest enterprises on a larger area. Once, the utility function is available, different forest enterprises can use it to identify optimum solutions for conversion strategies under similar conditions. The obtained optimal solution is not only efficient because of simultaneous approvals for the recommendable level of biodiversity, but also controllable due to the identified optimal management pathways. Koskela et al. (2007) came to a similar conclusion that a combination of subsidy and a corrective tax/subsidy is necessary to induce the landowner to follow the target of biodiversity maintenance in

Boreal forests, which in this case means to lengthen optimal rotation periods and to provide an incentive to leave retention trees.

In this study, including biodiversity in the optimization of the forest management plan leads to the conversion of the oldest stands of Norway spruce into mixed stands of spruce and beech. Optimal silvicultural pathways may differ not only among different stands, but also at times within a given stand when multiple values beyond timber production such as carbon sequestration or biodiversity are taken into account (Zhou and Buongiorno, 2006). Backéus et al. (2005) revealed that by assigning a monetary value to carbon storage as an objective of optimization with linear programming, the harvest levels will be influenced. Koskela et al. (2007) also found that the harvest tax rate varies within the range of 40–65% in the Faustmann model and 20–40% in the Hartman model, while timber subsidy is between 0.5–1.0% and site value tax is approximately 1.75%. The integration of criteria other than the net present values of harvesting and standing volume such as biodiversity (in the sense of the Shannon index) and the respective constraints into the forest management decision-making process usually leads to a diversification of silvicultural strategies (Schulte et al., 1998). However, the “Do-nothing scenario was the most allocated scheme in the entire forest area in this study.

Conversion as adaptation strategy to climate change

Knoke et al. (2008) compared pure and mixed forests with mixed-species stands and concluded that mixed forests are better able to compensate for disturbances than monocultures, more resistant against biotic and abiotic disturbances and by applying an extended forest economic model, mixing large blocks of native broadleaf species into pure conifer forests may lead to a significant reduction of financial risk. This is of crucial importance when taking into account an expected climate change with increasing temperatures that will deteriorate growth conditions especially for non-site-adapted secondary coniferous forests such as Norway spruce (Spiecker, 2003). One of the major adaptation strategies is the conversion of these forests into more site-adapted species such as European beech. A general problem when implementing this type of strategy is the lack of a quantitative basis to control the success of the measures that are foreseen.

The methodology presented in this study is not only able to calculate the cost of different forest management strategies such as adaptation with forest conversion, but also to propose an optimal management plan for the silvicultural interventions necessary to achieve the desired status. The results (*Fig. 3 and 4*) showed that the optimal management plan may vary with and without pricing and integration of biodiversity. Consequently, the variation imposed a shift from conservation to active, silvicultural interventions with partial introduction of beech especially in the oldest stand and this increases the share of the biodiversity in the global utility from 10 to 24 percent (*Tabl 3*). These results confirm the importance of taking the value of various ecological considerations into account in order to achieve the optimal level of ecological considerations with consequential pathways for the sustainable forest management.

Considering different adaptation strategies in the same optimization procedure can assist forest decision-makers to compare management alternatives such as adaptation with forest conservation, “Do-nothing”, traditional age-class forestry or conversion from pure to mixed stands in a quantitative way (*Table 3*). In this study, the optimization leads to a mixture of different silvicultural strategies for the entire forest enterprise with at least partial introduction of beech regeneration (*Fig. 4*). Hanewinkel (2001) and Knoke and Plusczyk (2001) evaluated different conversion strategies from pure to mixed stands. Depending on the discount rate, the conversion systems applied in these studies, proved to be financially advantageous due to the earlier revenues issued from the more intensive thinning and openings of the canopy to allow regeneration. Tahvonen (2009) also mentioned that although even- and uneven-aged systems may represent locally optimal solutions with equal economic outcomes, changes in decision parameters such as the rate of discount, timber price, or planting cost may imply that the optimal solution shifts from even- to uneven-aged management. Moreover, the optimal solution for Norway spruce represents an intermediate case between the two management systems, even – and uneven-aged forestry, and yields about 30% higher economic output compared to a solution where the even-aged forestry is predetermined. This is all an effect that is also visible in the present study, namely in the conversion strategies foreseen in the optimal solutions for stand-2 (*Fig. 4 and 5*).

Acknowledgements. This study was a part of first author’s PhD thesis at the Institute of Forestry Economics of the University of Freiburg and the German-French project “Forix” within the program of the German–French University (DFH).

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http://www.ecology.uni-corvinus.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)