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# Integrating selected ecological effects of mixed European beech–Norway spruce stands in bioeconomic modelling

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ABSTRACT

The simplicity of many bioeconomic models has been criticised several times, due to their lack of realism resulting from a deterministic nature and a single-species focus. In this context it was interesting to test the financial sensitivity of bioeconomic modelling against fairly well documented ecological effects in mixed forests. For this purpose our study linked existing results of ecological research with bioeconomic modelling. The presented methodological approach could not only show the importance of considering ecological effects in bioeconomic models; it in fact enabled prioritising ecological research from a financial point of view.

In a first step, the possible influence of the tree species mixture on forest stand resistance, productivity and timber quality was derived from existing studies. In a second step, the available Monte Carlo simulations for Norway spruce (*Picea abies* [L.] Karst.) and European beech (*Fagus sylvatica* L.), simulated under site conditions and risks typical of southern Germany, were extended by the mentioned ecological effects and then evaluated from a financial perspective.

The results showed a clear influence of all tested ecological effects on the financial indicators, financial risk and return. While testing each ecological effect separately, an increased resistance against wind, snow and insect attacks had the greatest influence on financial risk and return. It over-proportionally enhanced the financial return while simultaneously the financial risk was reduced. In contrast, a degraded timber quality could eliminate the positive effect of risk compensation in mixed forests almost completely. The least influence on the financial indicators finally showed a changed volume growth in mixed forests.

A combination of the separately tested ecological effects (increased resistance, changed volume growth and decreased timber quality), between both tree species, underlined the dominating importance of the stand resistance. The integration of ecological effects, induced by interdependent tree species, in our bioeconomic model resulted in significantly lower financial risk than ignoring these effects. Moreover, the financial return of mixed stand variants with a proportion of Norway spruce greater than 60% even exceeded that of the most profitable pure stand.

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In conclusion this paper clearly confirmed that ignoring ecological effects in bioeconomic models could lead to seriously biased financial results. While a changed volume growth proved rather to be of minor importance for European beech/Norway spruce stands, tree resistance and timber quality may change the financial results significantly.


## 1. Introduction

Economists often use simplifying or even simplistic bioeconomic models to evaluate alternatives in ecosystem management (Armstrong, 2007). Bulte and van Kooten (1999) already pointed out that many of these models suffer from lack of (biological) realism. Often cited shortcomings include the deterministic nature of bioeconomic models, and their focus on single-species. As a consequence of these shortcomings, Fleming and Alexander (2003) emphasised severe bias when transferring single-species models to multi-species problems.

Economists, however, may defend their simplifying assumptions with the argument that complex ecological models create "black box" systems, which result in minor analytical progress. Moreover, they can argue that even simple models sufficiently consider the major forces, which control the financial return. Yet, little is known on the effects of the more realistic biological assumptions in bioeconomic models on the financially relevant parameters, like financial risk and return.

The above situation is, for instance, very clearly visible in forest economics. In this case the models often do not only ignore relevant factors like a possible compensation between financial risks of tree species (Knoke and Wurm, 2006). They also disregard ecological effects of mixing tree species and the resulting biophysical consequences (Knoke et al., 2007). Mostly, only mono-species models are calculated, excluding possible ecological interdependence between different tree species.

The example of mixed forests seems particularly valuable for investigating the impact of ecological effects on financial parameters. Mixed forests have already been controversially discussed for at least 200 years in Central Europe (Hartig, 1800; Cotta, 1828). Also the international scientific interest in mixing tree species has risen significantly (e.g., Gamborg and Larsen, 2003; Scherer-Lorenzen et al., 2005; Nichols et al., 2006; Knoke et al., 2007). The ignorance of ecological effects could lead to severely biased financial decisions on whether or not to mix tree species.

Some well-documented ecological effects of mixing tree species certainly have a direct impact on the financial results of forest management. For instance, changing resistance against biophysical risks (Jactel et al., 2005; Schütz et al., 2006) and altering tree productivity in mixed stands (e.g., Pretzsch, 2005) or decreasing timber quality (Röhrig et al., 2006) will probably affect the financial consequences of mixed forests.

Even though financial consequences of ecological effects of interdependent tree species seem intuitively evident, studies which quantify possible effects are hard to find. It is still an unanswered question whether or not the integration of ecological effects in bioeconomic models for mixed forests would change the financial results substantially. Moreover, quantifying these effects from a financial point of view would allow ranking their financial importance.[1] This could help linking ecological and economic research in order to prioritise ecological investigations from a management perspective. To contribute to the above research field this paper sets out to test the following hypotheses:

- The financial results derived from two bioeconomic models, one which considers while the other ignores possible ecological effects of tree mixing, will differ significantly.
- Possible ecological effects of tree mixing, such as increased resistance, changed productivity and decreased timber quality are of the similar financial importance.

## 2. Materials and methods

### 2.1. *Forestry background and chosen tree species*

Throughout the Northern hemisphere and in Australia a recent intellectual shift towards forestry approaches and management practices which may be identified as "close-to-nature", "nature-based", "near-natural" or "ecosystem management", is evident (Gamborg and Larsen, 2003; Bristow et al., 2006). Mixed species approaches can be considered as a sub-trend of this overall shift to ecologically oriented forest management. Yet, mixed forests have no practical relevance in forest plantations, when considered by their area coverage worldwide (e.g., Nichols et al., 2006).

As already mentioned, the intellectual and practical interest in tree mixing is comparatively old in Central Europe. In contrast to the situation worldwide, the shift towards mixed forests has already taken place, for example, in German forest practice (Knoke et al., 2007), where the historical development of forestry in the 19th and 20th centuries led to more or less mono-species conifer forest types (Spiecker, 2003). The debate on forest decline in the 1980s and severe damage of mono-species forests through storms and insects provoked criticism on pure conifer forests from an ecological point of view (Weber and Jenssen, 2006). Nowadays the conversion of mono-species into mixed-species forests causes a major forest management and policy concern (e.g., Baumgarten and von Teuffel, 2005; Fritz, 2006). Yet, the trend towards mixed forests is based on the idea that ecological benefits are inherent in mixed forests rather than on sound biophysical and financial analysis.

The long tradition in mixing tree species and the practical relevance of mixed forests in Central Europe justified using a German example to investigate the research hypothe-

[1] Knoke (2002) and Knoke et al. (2006), for instance, tested this approach for the example of timber quality of European beech.

ses, although the analysed problem is certainly of broader and international interest. Consequently, we based our model on forests consisting of Norway spruce (*Picea abies* [L.] Karst.) and European beech (*Fagus sylvatica* L.). While European beech is the native tree species at most of the sites in Germany, the natural range of Norway spruce is restricted to the mountainous areas, but the range of the last species has been extended far beyond its natural limits.

### 2.2. *Investigated ecological effects of mixing tree species*

We will analyse the financial consequences of the documented effects of mixed stands resistance against wind, snow and insects, volume growth and timber quality in European beech and Norway spruce stands (Section 2.4). Already existing results on financial implications of mixing both species in large blocks (Knoke et al., 2005, 2007; Knoke and Wurm, 2006) serve as a reference to evaluate the financial effects of interdependent tree species (Section 2.3).

Before starting the analysis we have to decide how tree species are to be mixed, since a mixed forest may comprise of mixtures with different intensities. For instance, in our reference situation the mixture consists of large blocks of different tree species, showing more or less the ecological characteristics of pure forest stands. Ecological interdependence of the tree species is negligible in this case, as it occurs only within a zone where different tree species have contact. Even though almost no ecological effects will result from this type of mixture, we can say that mixing tree species in large blocks will form a mixed forest, although not at the stand level but at the level of the forest enterprise. Mixing tree species in large blocks may lead to financial risk compensation due to an asynchronous fluctuation of financial returns even if both tree species grow independently (Knoke et al., 2005). Section 2.3 as well as Tables 2 and 3 present basic biophysical and financial data on our reference situation.

Yet, the narrow scope of the study is not the large block mixture; we rather focus on a more intimate mixture. Between the mixing of large blocks and a very intimate tree-by-tree mixture, we find several variants. European forest practice, for example, usually introduces mixtures of groups of different tree species. Such groups normally cover an area of 0.1 ha. An alternative is to mix different tree species in rows, as common in international plantation forestry (Nichols et al., 2006). In contrast to the single-tree and row mixtures, mixing in groups has the advantage that tree species with different growth dynamics may be mixed without the risk of loosing those, which initially have slower growth rates.

Despite the variety of possible types of mixtures, this study will compare only the tree mixtures in groups with the reference of mixing tree species in large blocks. Mixing tree species in groups is a frequent forest practice used and many of the ecological and forest yield science studies analysed for our work are built on this kind of mixture (e.g., Kennel, 1965; Pretzsch, 2003, 2005). Moreover, we focus solely on the effect of mixing European beech and Norway spruce and not on effects of the silvicultural treatment, e.g., thinning, although we are aware that also these effects may have an influence on stand resistance (Mason, 2002), volume growth (Pretzsch, 2005) and timber quality (Seeling, 2001).

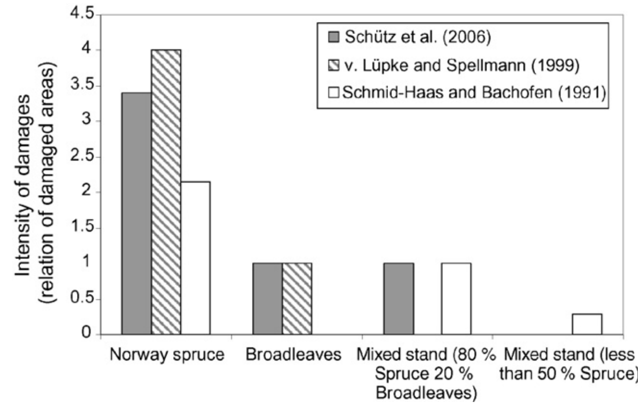


**Fig. 1 – Damage intensities reported in the literature (for Central Europe). The volume or area of the species damaged by the storms 1990 and 1999 as a percentage to their total standing volume or area were evaluated and compared (Schmid-Haas and Bachofen, 1991; Lüpke and Spellman, 1999) or the area of gaps after storm damages 1999 in different stands (Schütz et al., 2006).**

We defined a group of trees to form a rectangular area of 25 by 40 m (1000 m$^2$). A width of 25 m allows establishing a group between two logging trails (lanes where skidders manipulate the harvested trees), which typically have a distance of 30 m.

#### 2.2.1. *The effect of mixing tree species on resistance*

A review on the effects of tree species mixtures on resistance against wind damage and insect attacks in Central Europe (Knoke et al., 2007) provided evidence that Norway spruce gains physical stability in a mixed stand (Schmid-Haas and Bachofen, 1991; König, 1995; Mayer et al., 2005; Schütz et al., 2006; Fig. 1).

Schütz et al. (2006) pointed out an overall accepted positive effect on resistance for Norway spruce/European beech mixtures and proved this effect by means of a statistical model. The authors argue that Norway spruce develop longer crowns in mixtures because assimilation lingers during late autumn and sometimes winter, when neighbouring broadleaved trees loose their leaves. Moreover, the probability of insect attacks is reduced in mixed stands (Jactel et al., 2005). Consequently,

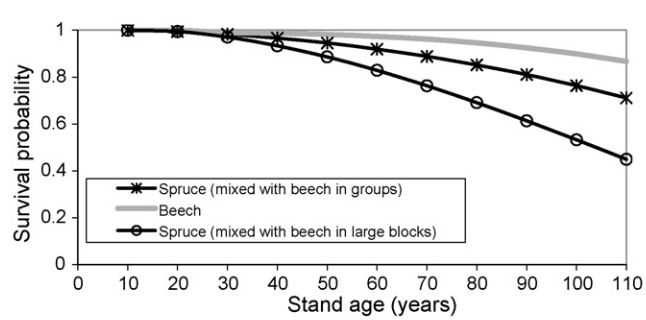


**Fig. 2 – Survival probabilities in mixed and pure stands.**

our investigation tested the influence of an increased survival probability for Norway spruce (Fig. 2).

The following polynomial equations form the survival probabilities in Fig. 1:

$$\begin{aligned} SP_b &= 0.990 + 9.000 \times 10^{-5} \times Age_b - 1.000 \times 10^{-7} \times Age_b^3, \\ SP_s &= 1.000 + 1.320 \times 10^{-3} \times Age_s - 8.404 \times 10^{-5} \times Age_s^2 \\ &\quad + 2.410 \times 10^{-7} \times Age_s^3, \\ SP_{s\_mixed} &= 1.000 + 3.950 \times 10^{-4} \times Age_s - 2.373 \times 10^{-5} \times Age_s^2 \\ &\quad + 1.177 \times 10^{-8} \times Age_s^3 \end{aligned} \qquad (1)$$

where $SP_b$ is the survival probability of European beech, $SP_s$ the survival probability of Norway spruce (pure stand), $SP_{s\_mixed}$ the survival probability of Norway spruce when mixed with European beech, $Age_b$ the age of European beech and $Age_s$ is the age of Norway spruce.

Based on the analysis of studies in Central Europe (Fig. 1) we deduced an average relation of damage to Norway spruce of about 2.5:1 when pure and mixed stands of Norway spruce and broadleaves were compared. With survival probabilities of 0.53 for pure Norway spruce (reference case) and 0.81 for Norway spruce mixed with broadleaves, the damage of 47% reduced to 19% over a 100-year time period. Given the validity of the results of Schütz et al. (2006), who found a relation of damages between pure conifer and mixed stands of 3.4:1, this assumption is rather conservative.

However, Schütz et al. (2006) identified the same reduction of storm damage for mixed stands with admixtures of only 20% broadleaves compared to almost pure broadleaved stands (proportion of broadleaves above 80%). Because no data on the potential effect of different proportions of broadleaves on the stand resistance was available, we assumed a constant curve for the survival probability in mixed stands up to a proportion of Norway spruce of 80%.

Note that not all studies agree with the frequently proven finding that mixing tree species will increase stand resistance. Koricheva et al. (2006), for instance, questioned the diversification of tree stands as a means to control pests and diseases. However, even this rather sceptical paper found evidence of beneficial effects of tree species diversity on stand vulnerability. But the authors mention that these effects were not consistent over time and space and thus conclude that the effects of forest diversification are unpredictable.

When compared to the effect evaluated in our study, it is obvious that different kinds of resistance were considered by Koricheva et al. (2006). While our study rather focussed on resistance of Central European forests against wind, the Koricheva study investigated the effects of tree species mixing on pests and diseases in boreal forests. Further, the mentioned authors provided conclusions which are not shared by other authors. For example, Jactel et al. (2005) obtained similar results but interpreted them as a beneficial effect of tree mixing on the resistance of stands against pests and diseases. The obviously different opinions of scientists stress the need to clarify the reasons for possibly non-consistent effects of forest stand diversification on pests and diseases. However, we will concentrate on the results of Central European studies, since here wind damage is the most important source of risk.

### 2.2.2. *Changed volume growth*

So far studies in forest science concentrated primarily on the productivity of mixed (diverse) forest stands. For example Kennel (1965) investigated mixed forest stands of European beech and Norway spruce, Frivold and Frank (2002) concentrated on mixed birch-coniferous forests, Pretzsch (2003, 2005) focussed on mixtures of European beech and Norway spruce, Vilà et al. (2003) analysed tree diversity in pine forests, Chen and Klinka (2003) explored mixed stands of western hemlock and western red cedar and Légaré et al. (2004) investigated the response of Black spruce to increased proportions of aspen.

We referred to the well-acknowledged example of Kennel (1965) and adjusted the growth of the mixed forest stand according to his results. He pointed out that Norway spruce gains an additional volume increment of 15%, while European beech looses 13% in a mixed stand of 50% Norway spruce and 50% European beech. More recent investigations of Pretzsch (2005) confirmed the result of Kennel (1965). Although the effect of mixing tree species is generally very site specific (Pretzsch, 2005), we exemplarily based our investigation on the results obtained by Kennel (1965). We defined the maximum effect of the tree mixture on volume growth using a 50:50 (%) mixture and adjusted the effect linearly according to changing proportions of tree species. A factor formed the basis

**Table 1 – Factors to adjust net revenues according to changes in volume growth and timber quality in mixed European beech and Norway spruce stands**

| Factor to adjust net revenues | Fraction of Norway spruce (%) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 10 | 20 | 30 | 40 | 50[a] | 60 | 70 | 80 | 90 | 100 |
| According to changed volume growth | | | | | | | | | | | |
| European beech | 1.00 | 0.97 | 0.94 | 0.91 | 0.89 | 0.87 | 0.87 | 0.87 | 0.87 | 0.87 | – |
| Norway spruce | – | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.12 | 1.09 | 1.06 | 1.03 | 1.00 |
| According to changed timber quality | | | | | | | | | | | |
| European beech | 1.00 | 0.98 | 0.96 | 0.94 | 0.92 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | – |
| Norway spruce | – | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.96 | 0.97 | 0.98 | 0.99 | 1.00 |

[a] Values obtained from the literature (volume growth from Kennel, 1965) or by theoretical consideration (timber quality). Other values are linear interpolations.

to correct the financial returns proportionally to the changed volume growth (Table 1).

### 2.2.3. *Timber quality*

It is well known that the timber quality in mixed stands often declines in the border zone, where the mixed tree species interact (Röhrig et al., 2006, p. 187). Typical effects of mixture on Norway spruce when mixed with beech are longer crowns, which also show more green knots (Seifert, 2004). The same can be stated for the ratio of branch to stem biomass, as shown by the same author. Based on a study of the crown development of beech, Seifert et al. (submitted for publication) were able to identify a significantly higher crown variability and asymmetry of beech with an increase in the proportion of the tree species in the mixture. This may also be the cause of curved stems. Crown asymmetry and stem curvature could induce an implicit biomechanical stress to the stem. Based on newer results we can anticipate a negative influence on timber quality because of the amount of growth stresses, cracks and tension wood (Beimgraben, 2002; Bleile, 2006).

However, the effects on wood quality are strongly determined by the specific type of mixture. Especially the aggregation of tree species in mixed stands takes a direct influence on the degree of interdependence. Consequently, we estimated the proportion of border trees when mixing groups of different tree species by means of the edge length of the groups. Finally, we reduced the net revenue flows accordingly.

In the case of European beech 20% of the trees were located at the border of the group, while in the case of Norway spruce, due to wider spacing, a proportion of 25% resulted. According to the experience of the professionals, we reduced the net revenues for border trees by 50% (European beech) and 20% (Norway spruce). These assumptions led to a maximum decline in net revenues, due to the decrease in timber quality by 10% (European beech) or 5% (Norway spruce) for a 50:50 (%) mixture. Starting with this maximum decline in timber quality we developed factors to adjust net revenue flows, which depended on the changing percentages of border trees for various mixtures (Table 1).

Our modelling of the ecological effects of interdependent tree species on timber quality is rather conservative. In fact positive effects may also occur on timber quality by admixture of different species as shown in Seifert (2004). Here, the competition with beech led to an earlier loss of dead branches for Norway spruce, even if the crown ratios were bigger. The proportion of stem wood for the total height in beech was increased when mixed with spruce, because a more slender growth with a later bifurcation was observed. Consequently, no final statement can be made regarding the effects of mixture on wood quality. Nevertheless, a rather conservative modelling with anticipated negative effects of tree species mixture on timber quality avoids too optimistic results.

## 2.3. *Existing data from Monte Carlo simulation (MCS): the reference situation*

The biophysical and financial data of our reference (mixtures of large blocks) were adopted from MCS done by Knoke and Wurm (2006) (Table 2) and later extended by the ecological effects derived in Section 2.2 (see Section 2.4). The basic data material resulted from projections by means of growth models, which were evaluated from a financial point of view under biophysical risks (wind throw, snow breakage and insect damage), modelled timber price volatility and the assumption of independent tree species by means of 1000 scenarios.

The growth simulations based on site conditions for southern Germany (growing area “Tertiärhügelland”). Rather conservative silvicultural operations were assumed, such as thinning from below for Norway spruce and random selection of thinning trees for European beech. As a consequence, the simulated standing volumes were mostly close to the values of appropriate yield tables (Table 3).

Biophysical risks were simulated by means of the survival probabilities adopted from existing studies (Möhring, 1986; König, 1995; Kouba, 2002 and Fig. 1). Due to the conservative stand treatment, the historically derived survival probabilities should fit well to the growth and yield data. Moreover, the simulations considered a timber price volatility based on

**Table 2 – Standing timber volumes and densities according to yield tables**

| Age (years) | Standing timber volume ($m^3$ $ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | European beech | | | Norway spruce | | |
| | Simulated | Yield table | Density | Simulated | Yield table | Density |
| 40 | 180 | 123 | 1.46 | 200 | 234 | 0.85 |
| 50 | 230 | 193 | 1.19 | 289 | 340 | 0.85 |
| 60 | 273 | 261 | 1.05 | 384 | 439 | 0.87 |
| 70 | 317 | 321 | 0.99 | 480 | 527 | 0.91 |
| 80 | 349 | 366 | 0.95 | 575 | 603 | 0.95 |
| 90 | 389 | 404 | 0.96 | 663 | 665 | 1.00 |
| 100 | 427 | 437 | 0.98 | 740 | 713 | 1.04 |

According to the simulated average volume increment we used the yield table of Wiedemann (1931, in BSELF, 1990), yield class I.0, moderate thinning, for European beech and the yield table of Assmann and Franz (1972), yield class 34, for Norway spruce as references. The densities resulted from the quotient ‘simulated standing volume:standing volume yield table’.

**Table 3 – Harvest volumes of timber and net revenues (adopted from Knoke and Wurm, 2006, with alterations)**

| Age | European beech | | | | Norway spruce | | | |
|---|---|---|---|---|---|---|---|---|
| | Timber harvest ($m^3\,ha^{-1}$) | | Net revenue (Euro $ha^{-1}$) | | Timber harvest ($m^3\,ha^{-1}$) | | Net revenue (Euro $ha^{-1}$) | |
| | Scheduled | Under risk | Scheduled | Simulated under risk | Scheduled | Under risk | Scheduled | Simulated under risk |
| 0 | 0 | 0 | −3,000 | −3,000 | 0 | 0 | −2,000 | −2,000 |
| 21 | 0 | 0 | 0 | −6 | 4 | 5 | 42 | −19 |
| 31 | 0 | 0 | 0 | −11 | 20 | 24 | 146 | 98 |
| 41 | 30 | 31 | 219 | 205 | 34 | 42 | 441 | 473 |
| 51 | 35 | 36 | 880 | 888 | 44 | 57 | 1,097 | 1,392 |
| 61 | 40 | 42 | 1,499 | 1,464 | 51 | 69 | 2,147 | 2,395 |
| 71 | 50 | 52 | 2,008 | 1,953 | 53 | 78 | 3,153 | 3,142 |
| 81 | 60 | 62 | 2,338 | 2,354 | 49 | 81 | 3,308 | 3,368 |
| 91 | 50 | 54 | 2,421 | 2,492 | 38 | 80 | 2,364 | 2,714 |
| 101 | 427 | 373 | 27,390 | 24,400 | 740 | 422 | 34,039 | 19,917 |
| NPV (Euro $ha^{-1}$) | | | 2,916 | 2,507 (±1,380) | | | 5,942 | 3,403 (±2,473) |
| Coefficient of correlation between NPVs | | | | | | +0.022 | | |

NPV: net present value, sum of net revenues discounted at 2% in Euro $ha^{-1}$.

autoregressive models derived from data of the historical time series from the Bavarian timber market. The assumptions on timber quality were drawn according to the average results for log grading derived by the Bavarian forest service. While we simulated the timber price of Norway spruce by means of an autoregressive model, we modelled the timber price of European beech as a dependent variable by means of a linear regression using the price for Norway spruce as the independent. The following regression curves were used (Eqs. (2) and (3), see Knoke and Wurm, 2006):

$$P_t(S) = 24.10(10.94) + 0.71(0.13)P_{t-1}(S) \pm s_p \quad (2)$$

where $P_t(S)$ is the timber price of Norway spruce, $P_{t-1}(S)$ the timber price of Norway spruce from the previous year and $s_p$ is the stochastic term.

The stochastic term, $s_p$, contains the dispersion not explained by the model, which resulted in ±Euro 7.91/$m^{-3}$. The expected mean timber price of this model was Euro 83.1/$m^{-3}$ achieving an $r^2$ of 0.57. Standard errors of parameters are given in parentheses.

The timber price correlation between Norway spruce and European beech was considered by a linear regression:

$$P_t(B) = 136.66(13.28) - 0.57(0.16)P_t(S) \pm s_p \quad (3)$$

where $P_t(B)$ is the timber price of European beech, $P_t(S)$ the timber price of Norway spruce and $s_p$ is the stochastic term.

For European beech the stochastic term, $s_p$, was ±Euro 8.89/$m^{-3}$. The expected mean timber price of this model was Euro 90.07/$m^{-3}$ achieving an $r^2$ of 0.38. A detailed description on the generation of these stochastic prices is given by Knoke and Wurm (2006).

The growth simulation showed a greater biophysical yield of the conifer Norway spruce, which agrees with other studies (e.g., Möhring, 2004). Ignoring risk the growth model yielded an average volume increment of 10.30 $m^3\,ha^{-1}$/year for Norway spruce, while European beech showed a value of only 6.92 $m^3\,ha^{-1}$/year. Moreover, in a scenario without risks, the net revenues for Norway spruce were greater than that of European beech during the thinnings (operations in younger stands) and for the final crops (Table 2).

The scheduled net present value (sum of all discounted net revenues, NPV) of Norway spruce was almost twice the NPV for European beech. Even if risks were included the NPV of Norway spruce was still about 35% higher than that of European beech (Table 2). The earlier mentioned studies of Knoke et al. (2005) and Knoke and Wurm (2006) showed that effects of risk compensation between both tree species and a risk-averse attitude of the decision-maker would lead to optimum proportions of European beech mixed with Norway spruce between 30 and 60%. However, the cited results considered no effects of ecologically interdependent tree species.

### 2.4. *Conceptual modelling approach*

Considering the interdependencies of European beech and Norway spruce in a mixed stand (Section 2.2) we carried out new computer runs. The new simulations were based on the

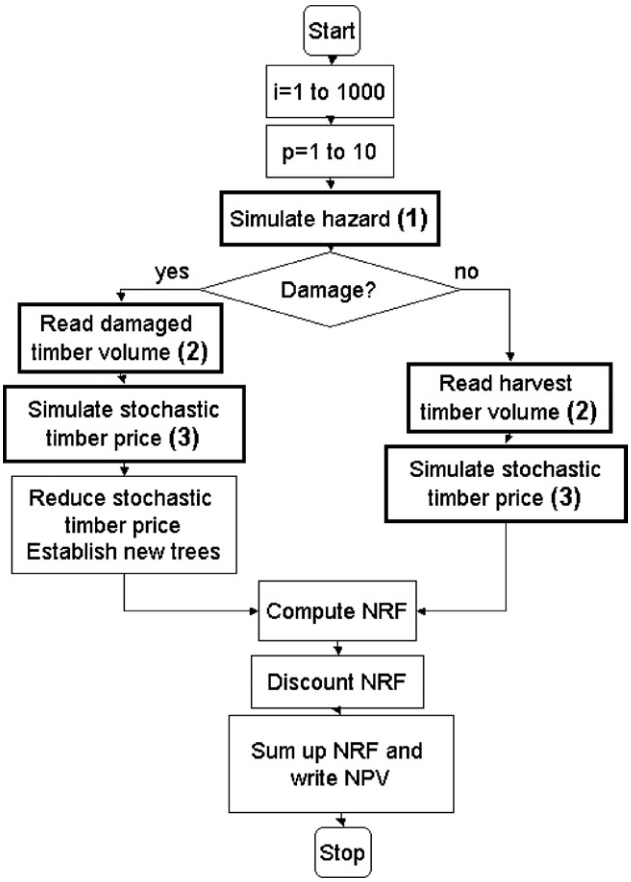


**Fig. 3 – Schematic flow chart of Monte Carlo simulations. NRF: net revenue; NPV: net present value (Euro ha$^{-1}$), i.e. the sum of all discounted NRF.**

existing MCS of the earlier study (Knoke and Wurm, 2006) but the net revenues were adjusted by means of changed survival probabilities or appropriate factors according to the altered resistance, volume growth and timber quality in a mixed stand (Fig. 2 in combination with Table 1). While comparing the results on financial risk and return of the new simulations with the existing MCS, which represented the practice of mixing tree species in large blocks, the study followed a comparative approach to evaluate the financial consequences of ecological effects of mixing tree species.

In order to increase the analytical power of the investigation, we simulated tree species interdependence separately and explicitly based on the plausible effects described in Section 2.2. A simplified flow chart shows the entries for tree species interaction in the modelling (Fig. 3).

First, the model analysed the consequence of an increased resistance of Norway spruce, when mixed with European beech, by assuming increased survival probabilities (entry 1). Secondly, we adjusted the net revenues according to expected changes in the volume increment of a mixed Norway spruce and European beech stand (entry 2). And finally, the possible impact of tree mixing on timber quality deduced by a geometrical consideration (Section 2.2) modified the simulated timber prices and thus the net revenues (entry 3).

### 2.5. *The financial model*

In economic theory the standard deviation of financial returns commonly quantifies volatility and risk, the last of which when non-desirable realisations are focused. Given a specific mean expected financial return, a greater standard deviation implies a higher probability of loss. If investors mix two or more investments, which show an independent variability of financial returns, they benefit from diversification effects such as risk compensation. This means that one investment may achieve an unexpectedly high financial return, while that of the other investment is lower than expected and vice versa. In this situation of independent investments, the coefficient of correlation ($k$) between financial returns is zero ($k = 0$). Note that the present argumentation does not imply for $k = 0$. Even greater risk compensation occurs, if financial returns correlate negatively among investments ($k < 0$). Even though the diversification effect is smaller when there is a positive correlation between the assets, every combination causes reduction of risk to some extent, unless the correlation is perfect ($k = 1$). The following equation expresses mathematically the described effect of mixed risk:

$$\sigma_P = \sqrt{\sum_{i\in N} f_i^2\sigma_i^2 + \sum_{i\in N}\sum_{\substack{j\in N\\ j\neq i}} f_i f_j k_{i,j}\sigma_i\sigma_j},$$

$$\sum_{i\in N} f_i = 1, \qquad k_{i,j}\sigma_i\sigma_j = \mathrm{cov}_{i,j} \tag{4}$$

where $\sigma_P$ is the standard deviation of portfolio financial return (set of risky asset), $i$, $j$ and $N$ the indices for a specific asset, set of possible assets, $f_i$ the fraction of a specific asset, $\sigma_i$ the standard deviation of financial return for a specific asset, $k_{i,j}$ the coefficient of correlation between asset $i$ and asset $j$ and $\mathrm{cov}_{i,j}$ is the covariance between asset $i$ and asset $j$.

Eq. (4) shows that the aggregate risk of a portfolio (mixture of several investments) depends not only on the risk in single investments but also on the covariance of all possible pairs of investments. In summary, for all $k < 1$, the risk of mixtures is smaller than proportional to the risks of single investments. It was Markowitz (1952) who first described these financial effects, called "effect of diversification" (Elton and Gruber, 1995).

If we apply utility curves, the calculations on optimum mixtures are based on the risk aversion as demonstrated, e.g., in Knoke and Wurm (2006). For our research it was nevertheless sufficient to analyse the possible impact of tree species interdependence on financial return and risk.

## 3. Results

### 3.1. *Mixtures with ecologically independent tree species (reference)*

The study done by Knoke and Wurm (2006) provided the data for Fig. 4. The figure depicts the basic financial effects of mixing tree species in large blocks at the forest enterprise level, which largely avoids tree species interdependence. The devel-

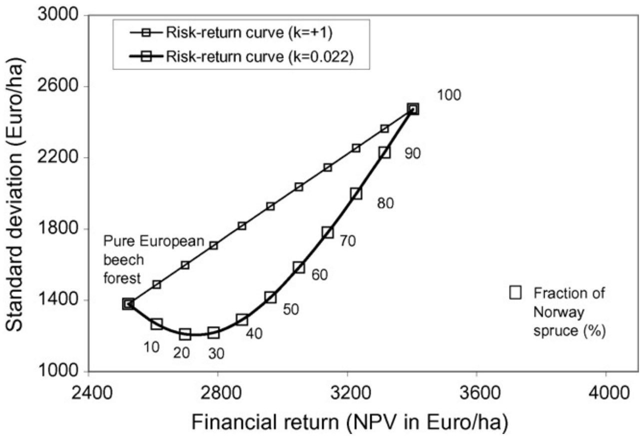


**Fig. 4 – Combinations of risk and return without tree species interaction.**

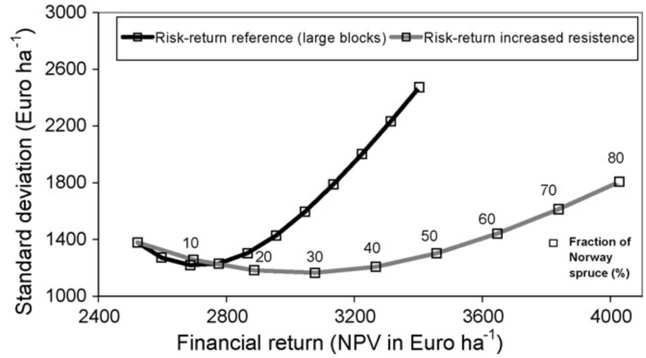


**Fig. 5 – Combinations of risk and return under the assumption of an increased resistance of Norway spruce in a mixed stand.**

oped two-species model combined the financial return of two ecologically independent single-species models proportionally. Yet, the model considered possible interdependence of financial flows due to slightly negatively correlated timber prices and only weakly correlated biophysical risks of the two tree species (Knoke et al., 2005). The approach thus linked the financial risks of the two ecologically independent tree species not proportionally. Rather a significant compensation of financial risk occurred in the above-mentioned studies (see Knoke et al., 2005; Knoke and Wurm, 2006).

As mentioned earlier the NPV is the indicator for financial return and its standard deviation quantifies the financial risk. Both variables define the values of both tree species and their combination in Fig. 4. A forest containing 100% European beech limits the left range, while a forest of 100% Norway spruce forms the right limit. In the case of no effect of risk compensation when mixing species (complete positive correlation of risks) the straight fine line represents all combinations of risk and return of the possible tree species mixtures (risk–return curve for $k = +1$). Here financial risk and return simply grow proportional to the fraction of Norway spruce.

In contrast, under a coefficient of correlation of about zero varying the proportions ($f_i$, $f_j$) of European beech and Norway spruce forms a different curve of financial risk depending on the average financial return (risk–return curve for $k = 0.022$). As mentioned before, a coefficient of correlation of around zero resulted from slightly negatively correlated timber prices and just weakly correlated biophysical risks (see Knoke et al., 2005; Knoke and Wurm, 2006).

From the perspective of a forest consisting of 100% Norway spruce an admixture of European beech reduces financial risk more intensively than the financial return. Vice versa, mixing the high-risk species Norway spruce into a low-risk European beech forest reduces risk, too, because of compensatory effects. Simultaneously to the risk reduction, the financial return increases. A clear effect of diversification is obvious for the forest formed of two tree species. Here, we realise the impact of tree species mixing on financial risk being not proportional, while the financial return grows proportional to the fraction of Norway spruce.

### 3.2. *Possible effects of ecologically interdependent tree species*

#### 3.2.1. *Impact of increased stand resistance*

Applying a curve of increased survival probability to Norway spruce in a mixed stand showed a great impact on financial risk and return. In contrast to the reference any admixture of Norway spruce into a European beech forest increased financial return more than proportional to the return of pure Norway spruce. For a proportion of 20% and higher of Norway spruce, the mixed stand achieved the same financial return as the reference at a lower standard deviation and at lower proportions of Norway spruce (Fig. 5).

A mixture of 50% European beech and 50% Norway spruce led to a greater financial return than that of pure Norway spruce. The financial risk, however, was comparable to that of pure European beech. Up to a proportion of 80% of Norway spruce the financial return increased steadily, while the standard deviation increased only moderately.

#### 3.2.2. *Impact of changed volume growth*

Assuming changed volume growth led to a similar risk–return curve as the modelling without ecological effects of mixing the tree species. Yet, given a specific financial return, Norway spruce proportions beyond 50% produced only a smaller

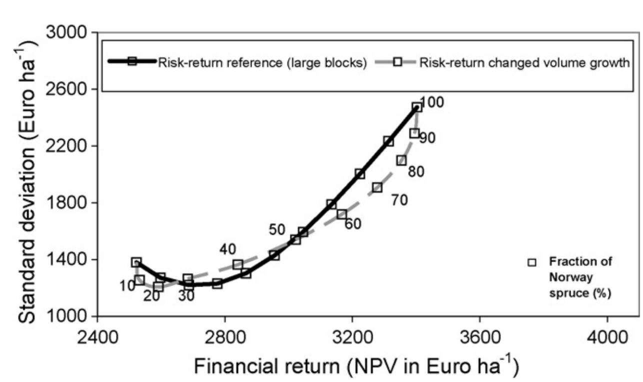


**Fig. 6 – Combinations of risk and return under the assumption of a changed volume growth in a mixed stand.**

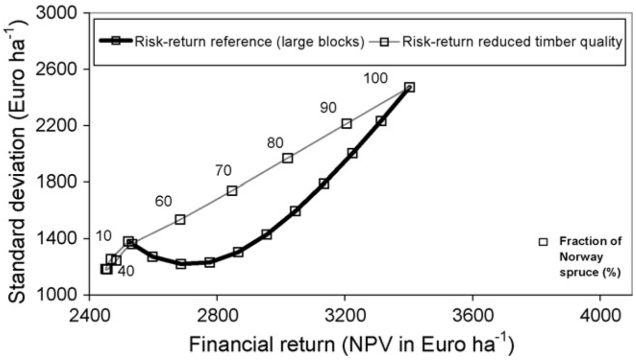


**Fig. 7 – Combinations of risk and return under the assumption of a decreased timber quality in a mixed stand.**

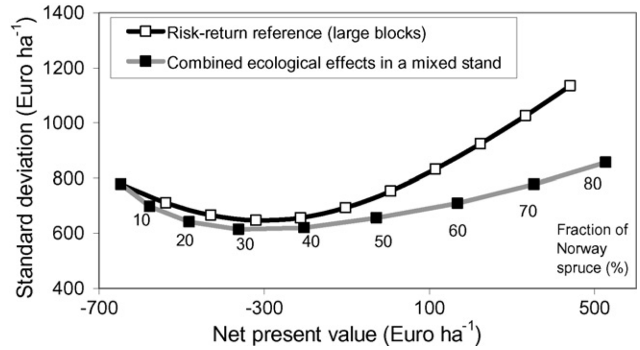


**Fig. 9 – Combinations of risk and return when combining tree species interdependencies for an increased interest (3%).**

standard deviation than in the case of mixing pure blocks of both species (Fig. 6). Under an increasing proportion of Norway spruce, the effect of a changed volume growth resulted in a more than proportional increase of the financial return up to a proportion of 50% Norway spruce.

### 3.2.3. *Impact of reduced timber quality*

A reduced timber quality may worsen the financial effects of tree species mixtures significantly (Fig. 7). Mixed stands with Norway spruce proportions less than 50% even showed a financial return less than pure European beech. Thereafter, the risk–return curve under a reduced timber quality followed almost exactly the curve describing the case of no risk compensation (under perfect correlation of risks, with $k = +1$).

A reduced timber quality can therefore abolish positive effects of risk compensation in mixed forests, if no other effects, like an increased resistance, compensate the effect of declined timber quality.

### 3.2.4. *Combining the ecological effects*

Combining all separately analysed effects investigated so far, showed a dominating position of the factor “increased stand resistance” (Fig. 8). Despite the negative effect of a reduced timber quality the mixed stand's performance was clearly superior, when compared to the reference, if Norway spruce had a proportion of at least 40%. In the forest stand where group mixture of tree species was simulated, a given financial return could be achieved at a significantly reduced standard deviation. Any proportion above 40% of Norway spruce in mixed forest stands yielded greater financial return than the corresponding mixture of pure blocks.

Given a combination of 60% Norway spruce and 40% European beech, the mixed forest stand already achieved a greater financial return than pure Norway spruce, with a standard deviation not much greater than that of pure European beech. It is obvious that these effects result predominantly from the improved resistance of Norway spruce. This effect clearly outbalanced the effects of a changed volume growth and declined timber quality.

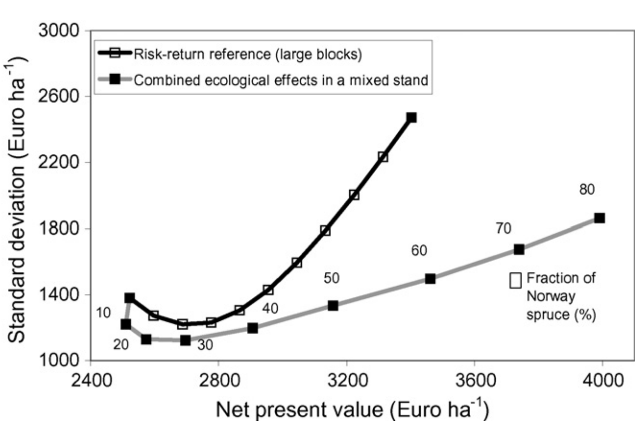


**Fig. 8 – Combinations of risk and return when combining tree species interdependencies.**

## 3.3. *Combined effects under an increased interest*

It is clear that the described ecological effects of interdependent tree species mainly concern financial flows arising a long time after the establishment of the forest stand. As we used a comparatively low interest of 2%, which is recommended for extremely long-term decision periods (Heal et al., 1996), the effect of discounting was only moderate. However, an increased interest might eliminate the presented financial effects or change the pattern of the risk–return curve. In order to test the sensitivity of our model against an increased interest we repeated our simulations with a 3% interest (Fig. 9).

Although we obtained negative NPV under an interest of 3% for stands dominated by European beech, the effect of a reduced financial risk for every financial return remained evident. Still the effect of an increased resistance dominated the shape of the risk–return curve. Similar to discounting with 2%, we received greater financial return than with independent tree species (mixing in large blocks) for fractions of Norway spruce of 40% and higher in the mixed stand. In addition, a still greater (positive) financial return than from pure Norway spruce was possible with a stand level mixture of 20% European beech and 80% Norway spruce. Given an increased interest, however the effects of interdependent tree species which concern predominantly the older stands were significantly reduced.

## 4. Conclusions and future research

While the results clearly supported the first hypothesis of this paper, "The financial results derived from two bioeconomic models, one which considers while the other ignores possible ecological effects of tree mixing, will differ significantly", the second hypothesis, "Possible ecological effects of tree mixing, such as increased resistance, changed productivity and decreased timber quality, are of the similar financial importance", could be rejected.

Given the financial results of mixing tree species in large blocks as a reference, each of the tested effects, improved resistance, changed volume growth and decreased timber quality, resulted in changed financial risks and returns. While improved resistance and decreased timber quality moved the risk–return curves significantly, changed volume growth had merely a moderate impact.

### 4.1. *Limitations*

Modelling future tree growth, hazard risks and timber prices is always subject to severe uncertainty. Our modelling relied on models parameterised with historical data. Hence, our predictions will only be valid if the future would not lead to changed hazard risks, tree growth and market development. Yet, the differences between the modelling excluding tree species interdependence and that which considers effects of interdependent tree species would remain valid in principle, if the future changes would enhance or diminish hazard risks, growth and timber prices of the compared modelling variants to the same extent. Critical changes may be expected, if the relation of the survival curves, the tree growth and the timber prices between the tree species and between pure and mixed stands would change. However, severe uncertainty pervades very often in long-term predictions of purely ecological models. For further research the info-gap models proposed by Ben-Haim (2006) are highly interesting. Info-gap models consider severe uncertainty largely independent from historical data. An application of an info-gap model in order to evaluate the robustness of the results of a bioeconomic forest model was given by Knoke (2007).

### 4.2. *Implications for forest growth modelling*

To enhance the analytical power of the study, the possible ecological effects of tree mixing were explicitly tested. This can be justified for several reasons. Up to now it has not been proved that Central European growth models (e.g., Sterba and Monserud, 1997; Pretzsch et al., 2002) can describe the effects of mixing tree species on volume growth reliability. Although some growth models already contain species dependent competition effects (Pretzsch et al., 2002), the empirical results on changed volume growth have hardly been confirmed by growth simulations. Furthermore, it is a fact that the impact of mixing tree species on stand resistance and timber quality cannot be completely simulated by means of the available models. For this reasons the combination of growth predictions with exogenous and risk driven survival models, as well as external volume growth and timber quality adjustments are beneficial as a first step.

Survival models and adjustments used for our study may principally be combined with growth predictions of Central European growth models like SILVA (Pretzsch et al., 2002), PROGNAUS (Sterba and Monserud, 1997) or BWIN (Nagel, 1996). For growth models parameterised with data of other areas (e.g., Chumachenko et al., 2003) different survival curves and adjustments for growth interdependence will be necessary. However, even for the Central European area our rather general modelling will not apply to every site and stand condition. Consequently, further intensive ecological research is necessary (see Section 4.3).

Although we think that our modelling has rather clearly shown the significance of ecological effects when integrated in bioeconomic models, the direct implementation of these effects into the existing growth models should be a long-term objective. Our results could serve as a reference to test the plausibility of a future implicit consideration of ecological interdependence between the tree species by means of developed growth models. Particularly, abiotic and biotic damages must be modelled reliably, if possible at the single-tree level.

Besides the importance of modelling tree survival, our simulations made clear that the effect of decreased timber quality might obviously be serious and could detract from mixing tree species in groups. Further research should indeed concentrate on the modelling of timber quality (e.g., Seifert, 2003), its financial implications (e.g., Knoke, 2002, 2003; Knoke et al., 2006) and the integration in growth models.

### 4.3. *Implications for ecological research*

It was not our intention to model all possible tree species interdependencies under every site condition, as well as multiple interactions of tree species mixture and silvicultural treatment, together with all the subsequent effects on stand resistance, volume growth and timber quality. Instead of modelling all the possible effects of interdependent tree species, our aim was primarily to test the importance of ecological effects for bioeconomic models.

Although a variety of studies showed evidence for an enhanced resistance of mixed stands, the comprehensive knowledge is still lacking. Schütz et al. (2006), for instance, identified the same reduction of storm damage for mixed stands with admixtures of broadleaves of only 20% when compared to almost pure broadleaved stands (proportion of broadleaves above 80%). This contradicts with the study of Schmid-Haas and Bachofen (1991), who found an effect of the proportion of admixed broadleaves on damages in mixed stands.

Further, we expect an influence of the silvicultural treatment on stand resistance. Yet, we also find partly contradicting results on this topic. For example, Mason (2002) and Cucchi et al. (2005) modelled rather negative effects of thinning on the stand resistance, while Munishi and Chamshama (1994) could prove a clear positive impact by means of empirical data. The study of Cucchi et al. (2005), which relied on the GALES model developed for Northern Europe (Gardiner et al., 2000), included no information on either root system or tree adaptation to wind loading. Moreover, Hale et al. (2004) confirmed that especially widely spaced stands are out with the bounds of ForestGALES. This means that still some important aspects of stand resistance against wind are not completely considered in wind models. Particularly, a sound differentiation between short-term (possibly reducing stand resistance) and long-term effects (probably enhancing stand resistance) of thinning would be necessary.

### 4.4. *Implications for bioeconomic modelling in forest science*

It can be stressed as an important result that bioeconomic modelling would benefit from the inclusion of species interdependence. Our model gained more biological realism and the inclusion of species interaction implied richer but more complex results. Principally, these effects were already pointed out by Bulte and van Kooten (1999).

Especially from the perspectives of practical decisions on ecosystem management and the acceptance of economic research, realistic bioeconomic models are extraordinary important. At least for the example of forest science, we can say that research in ecological and economic sub-disciplines often largely takes place independent of one another. While most sub-disciplines predominantly focus on ecological aspects of forest management, the sub-discipline of forest economics is mainly concerned with transferring economic theory to forestry. If bioeconomic models are used for the purpose of forest economics, they often lack biological realism. At least in Germany, this situation leads to an increasing loss of management relevance in the case of forest research and, simultaneously, to little acceptance of too theoretical forest economics in practice. The whole discipline of forest science suffers from this situation since the transfer of new scientific knowledge to forest managers is disturbed. Thus, a closer connection between ecological and economic research is certainly necessary to improve this situation.

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