Available online at www.sciencedirect.com
ScienceDirect
Forest Ecology and Management 248 (2007) 64–79
Forest Ecology and Management
www.elsevier.com/locate/foreco

Assessing trade-offs between carbon sequestration and timber production within a framework of multi-purpose forestry in Austria

Rupert Seidl [a,*], Werner Rammer [a], Dietmar Jäger [a], William S. Currie [b], Manfred J. Lexer [a]

[a] Institute of Silviculture, Department of Forest- and Soil Sciences, University of Natural Resource Management and Applied Life Sciences (BOKU), Peter Jordan Str. 82, 1190 Vienna, Austria

[b] School of Natural Resources & Environment, University of Michigan, 440 Church Street, Ann Arbor, MI 48109, USA

Accepted 8 February 2007

Abstract

Numerous studies have analyzed the carbon sequestration potential of forests and forest management. However, most studies either focused on national and supra-national scales or on the project level in the context of the flexible mechanisms of the Kyoto Protocol. Few studies are available which analyze the effects of alternative silvicultural strategies on carbon sequestration, timber production and other forest services and functions at the operational level of the forest management unit (FMU). The present study investigates effects of three alternative management strategies for secondary Norway spruce forests (*Picea abies* (L.) Karst.) (Norway spruce age class forestry; continuous cover forestry; conversion to mixed broadleaved forests) and an unmanaged control variant on C sequestration *in situ*, in wood products and through bioenergy production at the level of a private FMU in Austria, and analyses the interrelationships with timber production and key indicators of biodiversity. The hybrid patch model PICUS v1.4 and a wood products model are employed to simulate forest ecosystem development, timber production, carbon storage in the forest and in wood product pools. Results show that *in situ* C sequestration is sensitive to forest management with the highest amount of carbon stored in the unmanaged strategy, followed by the continuous cover regime. All three management strategies store substantial quantities of C in the wood products pool. Considering alternative biomass utilization focused on bioenergy production, substantial C offsets could be generated from potential substitution of fossil fuels. Opportunity cost estimates for C sequestration reveal that C sequestration through forest management can be a cost efficient way to reduce atmospheric CO_2, but the achievable quantities are limited due to biological limitations and societal constraints. The study emphasizes the importance of developing sustainable forest management strategies that serve the multiple demands on forests in the future.

Keywords: Sustainable forest management; Norway spruce conversion; Carbon storage; PICUS

1. Introduction

The role of forests as a carbon sink in mitigating climate change has been underpinned at the politically binding level by the Kyoto Protocol (UNFCCC, 1997), and guidelines for the inclusion of forest sector carbon sequestration in the national greenhouse gas balance have been developed (IPCC, 2003). Besides the human-induced changes in forest cover addressed by Article 3.3 of the Protocol, there has been much debate on the optional inclusion of sink enhancement by forest management under Article 3.4. In general there are three ways that existing forests can contribute to climate change mitigation via active management: through increased storage *in situ*, increased storage in wood product pools, or the substitution of fossil fuels by bioenergy. A number of recent studies on forest carbon sequestration have focused on *in situ* C storage, which has been investigated on varying scales, for different ecosystems and regions (e.g., Kurz et al., 1995; Liski et al., 2000, 2003; Thornley and Cannell, 2000; Lee et al., 2002; Pussinen et al., 2002; Dean et al., 2004; Howard et al., 2004; Pregitzer and Euskirchen, 2004; Backeus et al., 2005; Lasch et al., 2005). Results *inter alia* point towards considerable effects of management on forest carbon storage, however, quantitative impacts and economic feasibility vary. C storage in wood products is not always accounted for, especially since the wood product pools are not considered in the guidelines for the first Commitment Period under the Kyoto Protocol. However, considerable amounts of carbon are stored in long-lived wood

* Corresponding author. Tel.: +43 1 47654 4069; fax: +43 1 47654 4092.
E-mail address: rupert.seidl@boku.ac.at (R. Seidl).

0378-1127/$ – see front matter
doi:10.1016/j.foreco.2007.02.035

products (Karjalainen et al., 1994, 2002, 2003; Karjalainen, 1996; Winjum et al., 1998; Pingoud et al., 2001; Cote et al., 2002; Masera et al., 2003) and there is a call for an improved accounting methodology including such storage for post-2012 assessments (e.g., Marland and Marland, 2003). Another means to offset fossil fuel emissions is via an increased use of bioenergy, which has seen a revival lately. A number of studies point towards the positive aspects of the substitution of fossil fuels by renewable energy from forest biomass (Pingoud and Lehtila, 1997; Berndes et al., 2003; Kirschbaum, 2003; Kraxner et al., 2003; Sims, 2003). Several studies on bioenergy, however, have applied a broad top-down approach on potential extractable biomass (e.g., Hoogwijk et al., 2003; Parikka, 2004; Andersen et al., 2005) and have largely neglected ecological limitations, trade-offs with other forest products and services or restrictions to implementation.

There is a growing body of scientific knowledge on various aspects of forest carbon sequestration, but to operationally implement alternative forest management strategies these findings need to be transferred to the operational scale where actual management decisions are taken. Operational forest management in Central Europe is characterized by the multiple demands of a densely populated, heterogeneous landscape and a mostly small-scale forest ownership structure. The growing societal demand for forest services and functions beyond timber production contributes to the increasing complexity of forest management decision-making (cf. Lexer and Brooks, 2005; Rauscher et al., 2005).

In Central Europe, Norway spruce (*Picea abies* (L.) Karst.) has been promoted heavily as a productive timber species at sites naturally supporting broadleaved and mixed species forests. However, these secondary conifer forests are prone to an array of insect and disease organisms (e.g., Klimo et al., 2000) and are at particular risk in case of a warmer and possibly drier climate (e.g., Lexer et al., 2002; Matulla et al., 2002). Additionally, repeated rotations of pure Norway spruce may negatively affect soil productivity. To circumvent these problems alternative management strategies are discussed intensively. One option is the conversion of pure Norway spruce stands to mixed species stands to improve stand stability and resilience towards biotic and abiotic disturbances (e.g., Spiecker et al., 2004). Another strategy promotes continuous cover forestry and the transformation of even-aged conifer forests into uneven-aged vertically structured stands (e.g., Reininger, 2000). While there are several studies focusing on the economic analysis of stand conversion strategies (Hanewinkel, 2001; Knoke and Plusczyk, 2001), the inclusion of non-timber products and forest services such as carbon sequestration in an assessment of the costs and benefits of alternative forest management strategies has rarely been attempted.

Therefore, the primary objective of this contribution is to analyze carbon sequestration under alternative forest management strategies for secondary Norway spruce forests within a framework of multi-purpose forestry, using a private forest management unit in southern Austria as a case study. We consider above- and belowground forest carbon stocks by means of the hybrid forest patch model PICUS v1.4 (cf. Lexer and Hönninger, 2001; Seidl et al., 2005) as well as C storage in wood products and substitution effects of utilizing forest biomass for bioenergy by applying a recently modified wood products model (Briceno-Elizondo and Lexer, 2004). The specific objectives of the contribution are to (i) assess a combination of forest management and timber utilization scenarios with regard to timber production and carbon sequestration; (ii) evaluate scenario performance with regard to economic trade-offs; (iii) analyze scenario performance with regard to key indicators of forest biodiversity.

2. Methods and materials

2.1. Simulation models

2.1.1. PICUS v1.4

The model used in the study to track forest C flows and to project different forest management regimes is the hybrid forest patch model PICUS v1.4. The model is based on a three-dimensional structure of 10 m × 10 m patches extended by crown cells of 5 m height as described in Lexer and Hönninger (2001). The model layout is conceptually motivated by the findings of several authors (e.g., Mäkelä et al., 2000; Peng, 2000), that the hybridization of different modeling approaches is a suitable means to circumvent the limitations of the individual approaches. Building on the classical gap model PICUS v1.2 (Lexer and Hönninger, 2001), a process-based stand-level estimator of NPP derived from the 3-PG model (Landsberg and Waring, 1997) is applied to enhance the physiological foundation of the model. The hybridization aims at combining the abilities of gap models with regard to inter- and intra-specific competition, multi-species and multi-layered stand structure and general applicability with the benefits of a widely applied, robust stand-level estimate of forest production based on the concept of radiation use efficiency. The model coupling was described in detail by Seidl et al. (2005). Regeneration and mortality, key processes of forest dynamics, have been retained from the gap model approach of Lexer and Hönninger (2001). Tree mortality includes both an intrinsic as well as a stress-induced component (e.g., Keane et al., 2001). Dead trees, if not removed through forest management, are transferred stochastically from snags to wood detrital pools on the forest floor. A flexible management routine was incorporated to allow for individual-based harvesting interventions as well as for spatially explicit planting operations (Seidl et al., 2005). PICUS runs on monthly data of temperature, precipitation, radiation, and vapor pressure deficit. In an evaluation study (Seidl et al., 2005) the abilities of the hybrid model with regard to the simulation of potential natural vegetation composition as well as in the simulation of intensively managed, multi-species stands were tested. Seidl et al. (2005) found realistic results in the simulation of natural forest succession and equilibrium species composition along an environmental transect in the Eastern Alps, confirming the retained gap model strengths of the hybrid model approach. In addition, model tests against long-term growth and yield data of intensively managed, multi-species forests revealed the ability of the model approach to simulate complex management regimes at accuracy levels comparable to growth and yield models (Seidl et al., 2005).

In model variant 1.4, a process-oriented model of carbon and nitrogen cycling in soils has been incorporated into the PICUS framework to track belowground C storage and to obtain a dynamic update of site nutrient status. The soil submodel builds on the concept and algorithms used in the TRACE model (Tracer Redistributions Among Compartments in Ecosystems; Currie et al., 1999; Currie and Nadelhoffer, 1999). TRACE includes a detailed submodel of belowground N dynamics and C/N interactions because it was designed to simulate the redistribution of N isotopes over decadal-scale isotopic tracer experiments (in PICUS the isotope features were not used). The greatest strength of the TRACE-derived processes for the present analysis is that long-term feedbacks in plant production, soil nutrient status, and soil C storage are simulated. Carbon storage is calculated separately in the forest floor, mineral soil organic matter, and downed woody debris, with humification of foliar, root and woody litter contributing to slow-turnover humus pools. Pools of soil organic C and N are modeled as microbial–detrital pools containing microbial biomass implicitly and storing or releasing N based on C/N ratios in the forest floor and mineral soil organic matter separately. Fine litter enters the forest floor detrital pools according to C-classes (acid-insoluble, acid-soluble, extractives, cf. Ryan et al., 1990) and undergoes processes of decomposition, humification and production of dissolved organic C and N. Soil N transformations, leaching, and plant uptake of NH_4^+ and NO_3^- are simulated separately, with soil N availability exerting a strong control on plant production on a monthly time-step. Recently, the TRACE modeling approach has been successfully tested against field data (Currie et al., 2004) and across biomes (Moorhead et al., 1999) and is applied to simulate and forecast the effects of elevated nitrogen deposition on carbon storage in deciduous and coniferous forests of the Eastern USA (Currie et al., 2004).

2.1.2. Wood products model WPM

The model WPM (Briceno-Elizondo and Lexer, 2004) tracks carbon stored in the wood product pools by means of an approach first presented by Karjalainen et al. (1994), following the C flow in harvested timber through production processes and its storage in wood-based commodities until it is released to the atmosphere (Karjalainen et al., 1994; Briceno-Elizondo and Lexer, 2004). WPM considers four production lines (PL1 = sawmill industry, PL2 = particle board/plywood industry, PL3 = pulp and paper industry, and PL4 = fuelwood) and a number of intermediate products, end products and by-products. For each product group, a lifespan function based on work by Eggers (2002) is used to define the annual percentage taken out of use, to be either recycled to other product groups, burned for energy production or disposed in landfills. The landfill disposal releases carbon at a constant rate to the atmosphere, whereas C allocated to combustion is released immediately. The model includes detailed recycling loops for paper products and has been parameterized for Austrian conditions with data from national statistics and yearbooks of the wood processing industry (see Briceno-Elizondo and Lexer, 2004). Model applications include an evaluation study at the level of a forest enterprise in Austria (Briceno-Elizondo and Lexer, 2004) as well as a C sequestration assessment for several sites across Europe (Gracia et al., 2005) using country-specific parameter sets. For the study presented here the model has been applied as described in Briceno-Elizondo and Lexer (2004).

2.2. Simulation data

2.2.1. Study area

The study was conducted for a 248.7 ha forest enterprise in the province of Carinthia, Austria (Fig. 1), situated at approximately 550 m a.s.l. (latitude 46.78N, longitude 14.37E). Climate is characterized as subcontinental. Geological conditions are dominated by crystalline sediments of the last glacial stage which are sparsely penetrated by calcite formations. Geomorphology is smooth, allowing for a good forest road infrastructure (see Fig. 1) and the application of fully mechanized harvesting technology. The potential natural vegetation consists mainly of deciduous tree species (*Quercus* sp., *Fagus sylvatica* L.) with co-dominance by conifers (e.g., *P. abies*, *Pinus sylvestris* L.), mainly differentiated by soil conditions (see Mayer, 1974; Kilian et al., 1994).

2.2.2. Climate data

Climate data for the simulation experiment are represented by a 100-year time series based on the de-trended observed climate 1961–1990. Climate parameters required as input for the simulations had been interpolated to the study site from nearby weather stations of the Austrian weather service (ZAMG, 2001). Mean annual temperature of the climate

Fig. 1. Map of the 248.7 ha forest management unit. Site types are indicated in the 103 inventory compartments.

scenario is 7.6 °C and mean annual precipitation sum is 1013 mm, whereof approximately 50% occurs during the vegetation period. In the scenario simulations, the same climate data were used for all stands.

2.2.3. Soil data

Soils of the study area are mainly characterized by fertile Cambisols over crystalline gravel layers with medium to high water holding properties. A small area in the south of the forest management unit (FMU) is characterized by shallow rendzic Leptosol over dolomitic bedrock (Steiner, 1998). For the simulation, the forest area was grouped into three site types according to soil properties, where site types ST1 and ST2 represented eutric Cambisols, mainly differing with regard to soil water holding capacity (field capacity − permanent wilting point), and ST3 was parameterized as rendzic Leptosol with low water holding properties (Table 1, Fig. 1). Carbon and nitrogen data for the site types had been derived from laboratory analyses of soil samples from the study site. For organic matter and N content in the forest floor statistical relationships with stand characteristics had been established that allowed for a stand-specific initialization of the forest floor pools (Table A1, Appendix A). Mineral soil pools were not differentiated for stands within a site type (Table 1).

2.2.4. Stand data

The FMU holds 93% *P. abies* and 6% *P. sylvestris* (related to basal area). The age class distribution is skewed, with only a few stands below age 20 or above age 80. The FMU consists of 103 stands, for which a complete set of inventory data were available (Unegg, 1999). To reduce computing time, the 103 stands were clustered (method: partitioning around medoids, R Development Core Team, 2006) into 25 stand types according to the stand variables age, estimated mean annual increment over 100 years (MAI_{100}) of the inventory (de-trended due to strong age trend), stand density, share of *P. abies*, basal area weighted mean diameter, and existing regeneration. For each cluster, the stand most similar to the cluster average of the stand variables was selected for the simulation. Selected characteristics of the 103 stands are displayed in Fig. 2, major variables for the 25 stand types are given in Appendix A (Table A1).

Table 1
Properties of the mineral soil for the three site types (ST1–3) as derived from 20 soil samples

	ST1	ST2	ST3
Soil type	Eutric Cambisol	Eutric Cambisol	Rendzic Leptosol
pH (H_2O)	4.3	4.1	6.2
WHC (mm)	161	120	60
C (t ha^{-1})	82.03	95.75	66.30
N (t ha^{-1})	5.847	5.922	3.350
Soil depth (cm)	80	80	40

WHC: water holding capacity.

2.3. Experimental design

2.3.1. Silvicultural management strategies

Three alternative management strategies (MS) were defined over a time horizon of 100 years. The first strategy, MS1, reflects the current practice of the forest owner (used here as a baseline for comparison), while the other three represent hypothetical alternative strategies. MS1 is a Norway spruce (*P. abies*) age class management regime with a rotation age of 90 years. This strategy includes natural regeneration of mainly *P. abies* by means of a shelterwood system with a regeneration period of approximately 10 years, a pre-commercial thinning to control for stand density, and subsequent selective thinnings from above (Schädelin, 1942; Johann, 1987). The second strategy (MS2) represents a management strategy aimed at a transformation to a continuous cover management regime by applying ‘‘structural thinnings’’ (heavy thinnings from above,

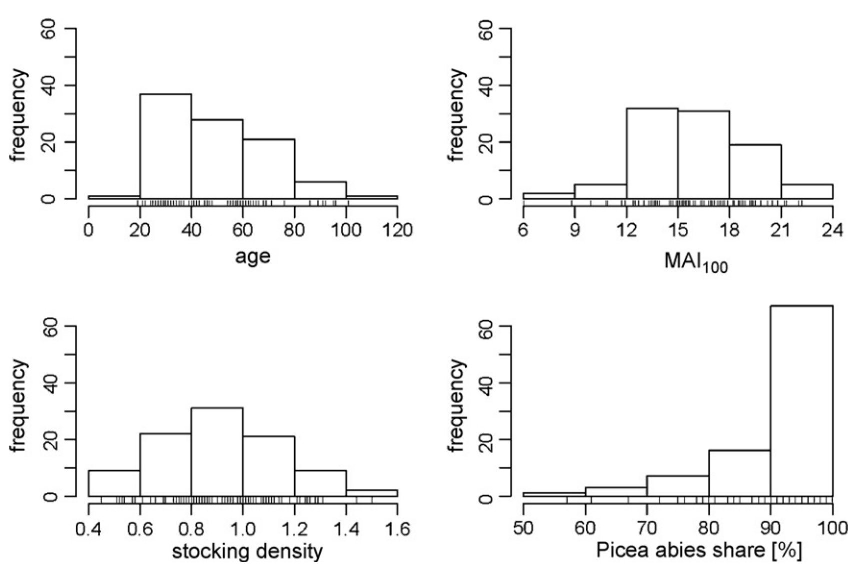

Fig. 2. Summary statistics of the 103 stands as recorded by Unegg (1999). MAI_{100} refers to mean annual increment (m^3 ha^{-1} a^{-1} gross volume over bark) at age 100 and is calculated from yield tables, stocking density is given relative to yield table estimates (Marschall, 1975). Share of *Picea abies* is based on stand basal area.

see Reininger, 2000) in younger stands with a subsequent shift to target diameter harvesting and continuous natural regeneration of mainly Norway spruce. Strategy MS3 is a conversion strategy, aimed at bringing about a moderate species change by introducing native broadleaved species. In this strategy, the current Norway spruce rotation period was reduced to 80 years. *F. sylvatica* and *Quercus robur* (L.) are the main species introduced by planting. Depending on the initial share of admixed species, site type and stand age, the stands are either (i) converted to *F. sylvatica* (on ST2) or *Q. robur* (on ST2, ST3) after clearcutting the current Norway spruce stand, or (ii) *F. sylvatica* is introduced by advance planting in groups below the shelter of Norway spruce aiming at a mixed future stand of *P. abies* and *F. sylvatica* (on ST1) (see Table A2, Appendix A). In addition to the three alternative management strategies a ‘‘do-nothing’’ variant (MS4) was simulated as reference, featuring no active management interventions.

All three management strategies were fully specified for every simulated stand and adopted according to initial stand conditions; for example, if the timeline of a scenario suggested a thinning in the second year of the simulation but the stand already had a low stocking density, the thinning was skipped or applied with a lower intensity. Harvesting interventions were specified as the removed percentage of standing volume in five relative diameter classes (class width = one-fifth of the difference between the largest and smallest values of dbh [diameter at breast height] in the simulated stand). A scheme of the timeline and management interventions in the strategies is given in Appendix A (Tables A3 and A4). The costs of introducing deciduous trees for the conversion to mixed forests (MS3) varies according to the conversion variant, from € 2150 ha^{-1} to € 7000 ha^{-1} including protection against browsing by game (see Table A2). Assumptions on timber prices are presented in relation to the biomass utilization scenarios in Section 2.3.2.

Based on data in Stampfer (2001), harvesting costs assume a fully mechanized harvesting system with slightly lower costs in MS2 due to a larger mean diameter per harvested volume (MS1 and MS3: conifers = € 23 m^{-3}, deciduous = € 25 m^{-3}, MS2: conifers = € 20 m^{-3}, deciduous = € 22 m^{-3}).

2.3.2. *Forest biomass utilization scenarios*

For every silvicultural management strategy, three biomass utilization scenarios (BMU) were investigated with regard to C sequestration and economic implications for the forest owner. In all scenarios only timber with a minimum diameter larger than 7 cm over bark was extracted from the forest, harvest residues below that threshold were left on site. Simulated harvested timber was graded into dimensional assortments based on individual tree dimensions according to Sterba and Griess (1983) and Sterba et al. (1986). In the present study a biomass utilization scenario consisted of the species-specific assignment of a certain proportion of an assortment to the four production lines (PL) of the WPM. In defining the allocation coefficients for production lines, regional expert knowledge on the expected quality of produced timber assortments and the demands of timber markets was employed. Species-specific dimensional and quality-related timber prices in Austria had been collected for the period 1990–2000 and were related to the year 2000 employing the consumer price index. In the economic evaluation, decadal average timber prices were used to factor out inter-annual variability in timber prices. Prices and costs were considered as exogenous variables and kept constant throughout the simulation period (with the exception of BMU2, see below). Aggregated values of the applied timber prices can be found in Table A5 (Appendix A).

The biomass utilization scenario BMU1 reflected current business-as-usual conditions concerning timber use (cf. Briceno-Elizondo and Lexer, 2004). BMU2 and BMU3 differed mainly with regard to an increased use of biomass for bioenergy compared to BMU1. Whereas BMU1 and BMU3 assumed a static economic environment (demand, prices) throughout the simulation period, in BMU2 changes in demand in bioenergy and consequently changing bioenergy prices were taken into account for the 100-year study period. The scenario assumptions for BMU2 were based on a storyline by Haas and Kranzl (2002), which predicts an oil price shock in 2010 followed by a distinct increase in prices for oil and subsequently bioenergy. In 2010, biomass prices reached a level of 150% of the current situation and stabilize at 120% in the year 2020 (Haas and Kranzl, 2002). Prices for saw timber and pulp- and paperwood assortments were, however, kept constant. Assuming rational economic behavior of the forest owner, more timber is allocated to the bioenergy sector at the cost of the particle board/plywood industry (PL2) and the pulp and paper industry (PL3) in the simulations. By assumption, at the highest biomass price level 30% of PL2 and PL3 are allocated to bioenergy (PL4). This percentage is reduced gradually to 20% in 2020 (see Fig. A1, Appendix A). The third biomass utilization scenario (BMU3) assumed an investment of the forest owner in a local heating plant operated with forest biomass. Thus, in BMU3 20% of the timber going to PL2 and PL3 under BMU1 was re-directed to the heating plant (e.g., PL4). The basic assignment of assortments to different production lines under BMU1 can be found in Tables A6 and A7 (Appendix A). Changes in BMU2 and BMU3 are understood relative to these figures. To derive an energetic proxy for PL4 a lower bound caloric value of 3.46 kWh kg^{-1} timber dry mass was used. To visualize the effect in terms of carbon sequestration, the energetic value was converted to C emitted from potentially substitutable fossil fuel. An emission factor of 0.109 t C MWh^{-1} (light fuel oil, GEMIS, 2005) was assumed. However, the analysis did not aim at a full net emission/reduction analysis, for which the fossil emissions of timber harvest, transport and the wood processing industry would have had to be accounted for.

2.3.3. *Analysis methods*

The issue of forest C accounting has intensively been discussed recently (IPCC, 2000; Kirschbaum et al., 2001; Kurz et al., 2002) and although the good practice guidance for land use, land-use change and forestry (GPG-LULUCF, IPCC, 2003) proposes a coherent accounting scheme for the first commitment period (CP1) of the Kyoto Protocol, future accounting rules may differ significantly (cf., Kirschbaum et al., 2001; Cacho et al., 2004; Kirschbaum and Cowie, 2004). Because the time frame of the current study extends far beyond the CP1, we did not address formal aspects of C accounting under the current Kyoto rules and regulations. Instead we employed three general C accounting approaches that have been proposed in the literature (see Newell and Stavins, 2000; Richards, 2004). In presenting the C sequestration potential of forest management on a per hectare basis we used (i) the mean storage approach, comparing mean C stocks over the simulation period; (ii) the flow summation approach (in short: flow approach), summing up all C flows in the study period on annual time-steps; and (iii) the levelization approach, where the annual C flows calculated as in (ii) were discounted with an assumed social interest rate of 2% (e.g., Hoen and Solberg, 1994). Carbon sequestration is analyzed in three hierarchical levels of aggregation: (A) *in situ* carbon storage, separated into aboveground (stem-, branch-, leaf-, and standing deadwood C) and belowground (soil organic carbon, litter, humified matter, fine woody debris and downed dead wood C) components; (B) *in situ* carbon and carbon stored in wood product pools; and (C) *in situ* C, carbon in wood product pools and C from potential fossil fuel substitution by bioenergy from the forest.

To assess the potential costs of C sequestration through forest management, we applied an opportunity cost approach based on costs and revenues from timber production. Two indicators were used to represent economic performance of the alternative MS regarding to timber production. A contribution margin (CMII) focusing on operational cost of timber production and neglecting administrative and maintenance costs was computed according to Eq. (1), reflecting the net balance of the nominal cash flow over the entire simulation period:

$$\mathrm{CMII} = \sum_{t=1}^{100} (R_t - C_t - \mathrm{s}C_t) \tag{1}$$

where R is the harvest revenue (€ ha^{-1}), C the harvesting cost (€ ha^{-1}), sC the silvicultural cost (€ ha^{-1}), CMII the contribution margin (€ ha^{-1}), and t is the simulation year (1–100).

To account for temporal effects of monetary flows, as a second approach the equivalent annual income (EAI) was calculated as the annualized net present value (NPV) of cash flows including the potential liquidation value of the stand at the end of the simulation period (Eqs. (2) and (3)), applying an annual interest rate of 2%.

$$\mathrm{NPV} = \sum_{t=1}^{100} \frac{R_t - C_t}{(1+p)^t} + \frac{\mathrm{LV}_{100}}{(1+p)^{100}} \tag{2}$$

$$\mathrm{EAI} = \mathrm{NPV}\frac{p(1+p)^t}{(1+p)^t - 1} \tag{3}$$

Opportunity costs were then calculated by relating the differences in economic performance between a C sequestration strategy and the baseline strategy (MS1 and BMU1) to the difference in the sequestered carbon where p is the interest rate (0.02), LV_{100} the liquidation value of stand at end of simulation (€ ha^{-1}), NPV the net present value of cash flows from timber production, including stumpage value of standing stock in year 100 (€ ha^{-1}) where EAI is the annualized NPV (€ $\mathrm{ha}^{-1}\,\mathrm{a}^{-1}$)

As an example for non-wood forest functions, key indicators for biodiversity were selected since recently the compatibility of the aims of increased C sequestration and conservation of biodiversity has been debated intensively (e.g., Matthews et al., 2002; Boscolo and Vincent, 2003; Caparros and Jacquemont, 2003; Huston and Marland, 2003). The selected indicators include (i) naturalness of tree species composition, (ii) tree species diversity, and (iii) standing dead wood, all assessed as average values over the 100-year simulation period. Naturalness of tree species composition (NTS) was evaluated by comparing simulated vegetation composition and structure with the potential natural vegetation (PNV) as reported by Kilian et al. (1994) at the level of site types according to the penalty point system of Grabherr et al. (1998). Penalty points characterize a possible mismatch of actual species abundance and expected species abundance of the PNV. The classification resulting from this evaluation ranges from natural (9) to artificial (1). An FMU-level area-weighted estimate was calculated over the 25 stand types in the simulation. The Shannon index SI (see Magurran, 1988) was calculated as a proxy for tree species diversity (Eq. (4)) from forest level species-specific aboveground biomass.

$$\mathrm{SI} = -\sum_{i=1}^{n} \mathrm{ps}_i \ln \mathrm{ps}_i \tag{4}$$

where ps_i the share of species (i) on total aboveground biomass.

As additional indicator for (saprophytic and faunal) diversity (e.g., Jonsell et al., 1998; Humphrey et al., 2002; Lohr et al., 2002; Kappes and Topp, 2004) the mean standing deadwood pool over the simulation period was evaluated.

3. Results

3.1. Timber production

Mean annual cuts (MAC, merchantable volume without bark) over the simulation period were comparable for the management strategies MS1–3 with the lowest MAC under the continuous cover strategy MS2 (9.3 $\mathrm{m}^3\,\mathrm{ha}^{-1}\,\mathrm{a}^{-1}$). Harvest levels were in the same range for MS1 and MS3 (10.6 and 10.1 $\mathrm{m}^3\,\mathrm{ha}^{-1}\,\mathrm{a}^{-1}$, respectively). While under the current management practice (MS1) and the continuous cover strategy (MS2) the share of broadleaves and *P. sylvestris* in harvested timber was very low, the MAC of MS3 already reflects the results of the conversion strategy (Fig. 3). Furthermore, the management strategies differed substantially with regard to the economic performance indicators. Averaged over the entire simulation period, the continuous cover management strategy (MS2) yielded the highest contribution margin CMII (€ 350 $\mathrm{ha}^{-1}\,\mathrm{a}^{-1}$) compared to MS1 (€ 287 $\mathrm{ha}^{-1}\,\mathrm{a}^{-1}$) and MS3 (€ 197 $\mathrm{ha}^{-1}\,\mathrm{a}^{-1}$). The lower value in CMII for MS3 is due to the establishment costs of mixed species stands. The EAI did not change the ranking of

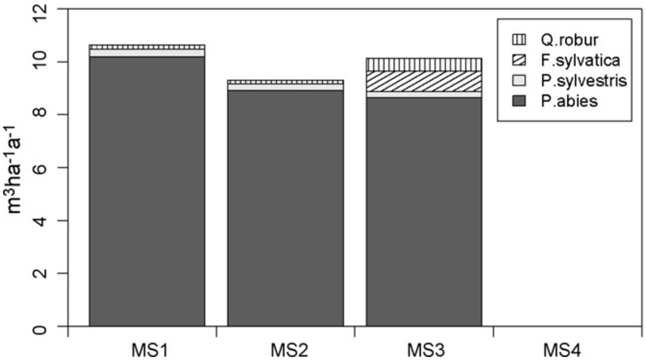

Fig. 3. Mean annual cut [merchantable volume without bark] of the three analyzed management strategies (MS1: Norway spruce age class, MS2: Norway spruce continuous cover, MS3: conversion to mixed coniferous-broadleaf stands) and the control variant MS4 (do-nothing, i.e., no harvest or other management activity).

the management strategies compared to the results of the CMII (Table 2). Allocating more harvested biomass into bioenergy production (BMU2 and BMU3) reduced the contribution margin (CMII) between 7.1% (MS3) and 3.1% (MS2), and the EAI between 7.4% (MS3) and 3.7% (MS2). In the do-nothing variant MS4 the CMII is zero. The EAI for MS4 is exclusively based on the potential liquidation value at the end of the simulation period. Differences among the biomass utilization scenarios for MS4 are due to different assumptions on timber utilization and consequently different timber prices under the BMU scenarios.

3.2. Carbon sequestration

As expected, the mean *in situ* C stock was highest in the do-nothing variant MS4 due to the continuing growth and the accumulation of deadwood pools on site. In the management strategies, mean aboveground C storage was highest in MS2 and almost identical in MS1 and MS3. Mean belowground C stocks differed moderately between all four strategies (±14.5 t C ha^{-1}, mean storage approach) and were highest under MS4. Compared to the initial above- plus belowground forest C stock of 256.6 t C ha^{-1}, MS1 and MS3 showed a moderate decrease in mean forest C stocks over the simulation period (−26.9 and −11.5 t C ha^{-1}, respectively), whereas stocks increased moderately to strongly in strategies MS2 and MS4 (+27.1 and +134.9 t C ha^{-1}, respectively). The flow approach showed somewhat contrasting results. Whereas the results in MS1, MS2 and MS4 correspond to those of the mean storage calculation, MS3 turned out as a small C sink instead of a small source. When the temporal development of flows is taken into account by discounting the C flows (levelization approach), MS3 was again a small C source (Tables 3a–3c).

Extending the scope of the analysis to C stored in wood products, the superior performance of the unmanaged reference strategy MS4 was put into perspective. It could be demonstrated that a significant amount of carbon is stored in the wood products pool in management strategies MS1–3 under all C accounting schemes (Tables 3a–3c). Increased use of biomass for bioenergy (BMU2 and BMU3) resulted in lower flows of wood into the plywood (PL2) and pulp and paper (PL3) streams, with consequent decreases in C stored in wood products. Under MS1, for instance, BMU2 and BMU3 resulted

Table 2
Economic performance indicators for the analyzed strategies MS1–4 over 100 years under three biomass utilization scenarios (BMU1–3)

	BMU1		BMU2		BMU3	
	CMII	EAI	CMII	EAI	CMII	EAI
MS1	286.6	344.1	274.3	331.0	268.6	322.7
MS2	350.0	371.9	342.8	363.7	339.2	358.2
MS3	196.5	261.1	190.5	252.7	182.5	241.8
MS4	0.0	136.6	0.0	134.2	0.0	133.4

CMII: contribution margin including harvesting and silvicultural cost and timber revenues (€ ha^{-1} a^{-1}); EAI: annualized net present value including stumpage value of standing stock in year 100 (p = 2%) (€ ha^{-1} a^{-1}).

Table 3a
C sequestration (t C ha^{-1}) according to the mean storage approach in the management strategies (biomass utilization scenario: BMU1) over 100 years

	A				B	
	ag	bg	*In situ* C	CS_A	wp	CS_B
MS1	78.9	150.8	229.7	−26.9	83.6	+56.7
MS2	135.1	148.6	283.7	+27.1	73.1	+100.2
MS3	88.2	156.9	245.1	−11.5	76.2	+64.7
MS4	228.4	163.1	391.5	+134.9	0.0	+134.9

The initial mean C-stock equals 256.6 t C ha^{-1}. CS gives the changes in mean C stocks to the initial value where the subscripts denote the corresponding levels of aggregation (A: *in situ*; B: *in situ* plus wood products). ag: aboveground; bg: belowground (SOM, roots); wp: wood products.

Table 3b
C sequestration (t C ha^{-1}) according to the flow approach in the management strategies (biomass utilization scenario: BMU1) over 100 years

	A			B	
	ag	bg	CS_A	wp	CS_B
MS1	−22.0	14.0	−8.0	74.5	+66.5
MS2	37.7	8.3	+46.0	116.1	+162.1
MS3	−3.2	24.3	+21.1	57.2	+78.3
MS4	218.7	35.4	+254.1	0.0	+254.1

CS gives the corresponding summarized C-flows where subscripts denote the levels of aggregation (A: *in situ*; B: *in situ* plus wood products). ag: aboveground; bg: belowground (SOM, roots); wp: wood products.

Table 3c
C sequestration (t C ha^{-1}) according to the levelization approach in the management strategies (biomass utilization scenario: BMU1) over 100 years

	A			B	
	ag	bg	CS_A	wp	CS_B
MS1	−22.5	6.5	−16.0	72.9	+56.9
MS2	22.7	5.0	+27.7	63.6	+91.3
MS3	−18.4	11.1	−7.3	68.3	+61.0
MS4	102.8	17.0	+119.8	0.0	+119.8

CS gives the corresponding summarized C-flows where subscripts denote the levels of aggregation (A: *in situ*; B: *in situ* plus wood products). ag: aboveground; bg: belowground (SOM, roots); wp: wood products.

Table 4
Potential fossil fuel emissions substituted by bioenergy production over the simulation period according to the flow approach (t C ha^{-1})

Management strategy	BMU1	BMU2	BMU3
MS1	0.49	20.29	21.92
MS2	0.29	12.23	13.31
MS3	2.47	25.24	27.49
MS4	0.00	0.00	0.00

BMU1–3: alternative biomass utilization scenarios.

in a reduced C-flow into wood products of −6.3 and −6.1 t C ha^{-1} compared to BMU1. However, as shown in Table 4 for the flow approach, the increased substitution potential of BMU2 and BMU3 compared to BMU1 more than offsets the corresponding reduction in C stored in wood products. Fig. 4 summarizes C sequestration according to the flow approach for all management strategies and biomass utilization scenarios at three hierarchical levels of aggregation.

3.3. Trade-offs between timber production and carbon sequestration

Trade-offs between timber production and C sequestration were assessed by means of an opportunity cost approach where the business as usual management MS1 under BMU1 was used as the baseline scenario. Using the C flow approach and the economic indicator CMII, the costs for additional storage of one ton C in the forest (strategies MS1, MS3 and MS4) ranged from € 1.1 t C^{-1} a^{-1} to € 3.6 t C^{-1} a^{-1}, and from € 0.8 t C^{-1} a^{-1} to € 3.5 t C^{-1} a^{-1} when the annualized net present value ($p = 2\%$) was used. If C storage in products and through fossil fuel substitution is considered as well, the opportunity costs per additional ton of C were € 0.9 t C^{-1} a^{-1} to € 6.6 t C^{-1} a^{-1} for CMII, and € 1.0 t C^{-1} a^{-1} to € 6.1 t C^{-1} a^{-1} for EAI ($p = 2\%$). Under any biomass utilization scenario and C storage accumulation level, MS2 resulted in negative opportunity costs (at best € −1.2 t C^{-1} a^{-1} with CMII, € −0.5 t C^{-1} a^{-1} with EAI) due to higher C storage and economic efficiency compared to MS1. Generally, increasing the level of aggregation for C sequestration increased the opportunity cost per additional ton of sequestered C (cf. Table 5).

Table 5
Opportunity costs of C sequestration relative to the business as usual management strategy MS1 in the corresponding level of aggregation, calculated from C flows and two economic indicators under three biomass utilization scenarios

Level of aggregation	BMU1		BMU2		BMU3	
	OC-CM	OC-EAI	OC-CM	OC-EAI	OC-CM	OC-EAI
MS1						
A	–	–	–	–	–	–
B	–	–	NA	NA	NA	NA
C	–	–	0.91	0.97	1.17	1.40
MS2						
A	−1.17	−0.51	−1.04	−0.36	−0.97	−0.26
B	−0.66	−0.29	−0.61	−0.21	−0.57	−0.15
C	−0.66	−0.29	−0.54	−0.19	−0.50	−0.13
MS3						
A	3.10	2.86	3.31	3.14	3.58	3.52
B	7.68	7.08	17.51	16.65	17.15	16.87
C	6.57	6.06	3.18	3.02	3.15	3.10
MS4						
A	1.09	0.79	1.09	0.80	1.09	0.80
B	1.53	1.11	1.53	1.12	1.53	1.12
C	1.53	1.11	1.53	1.12	1.53	1.13

Levels of aggregation: (A) *in situ* C storage; (B) *in situ* C storage plus C stored in wood product pools; (C) *in situ* C, C in products plus C substituted by bioenergy. OC-CM: related to the contribution margin (€ t C^{-1} a^{-1}); OC-EAI: related to the annualized net present value ($p = 2\%$) (€ t C^{-1} a^{-1}). NA indicate combinations of lower C storage than the reference strategy, for which no opportunity costs of C sequestration can be derived.

3.4. Biodiversity

A set of biodiversity indicators was used to represent an additional non-timber forest function. The tree species composition over the simulation period was evaluated for naturalness and diversity. The conversion strategy MS3 resulted in a share of 25% *F. sylvatica* and 8% *Q. robur* (relative to standing stock) at the end of the simulation period, with *P. abies* still being the dominating species at the FMU-level. The strategies MS1, MS2 and the ''do-nothing'' variant MS4 resulted in almost pure stands of *P. abies* with less than one percent of admixed *P. sylvestris* and various deciduous species (e.g., *Quercus* sp.). Naturalness of tree species composition (NTS) for the whole forest according to Grabherr

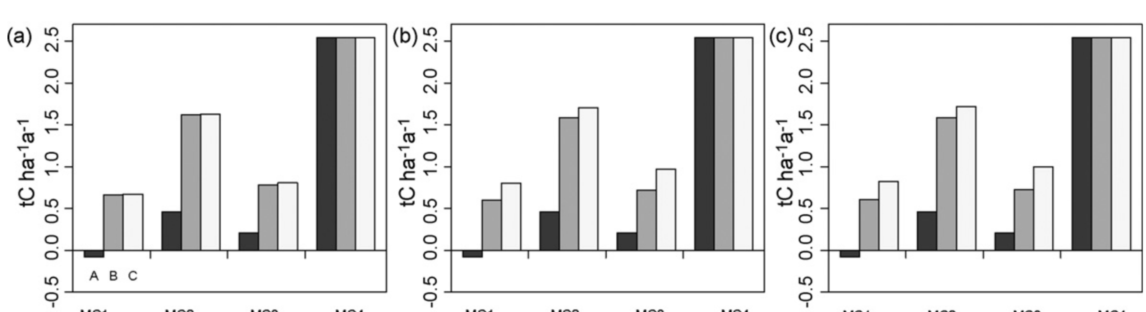

Fig. 4. C sequestration (flow approach) in the biomass utilization scenarios (a) BMU1; (b) BMU2; (c) BMU3. Bars denote the three levels of aggregation: (A) *in situ* C storage; (B) *in situ* storage and storage in wood products; (C) *in situ* C, carbon stored in wood products and substituted C emissions through bioenergy.

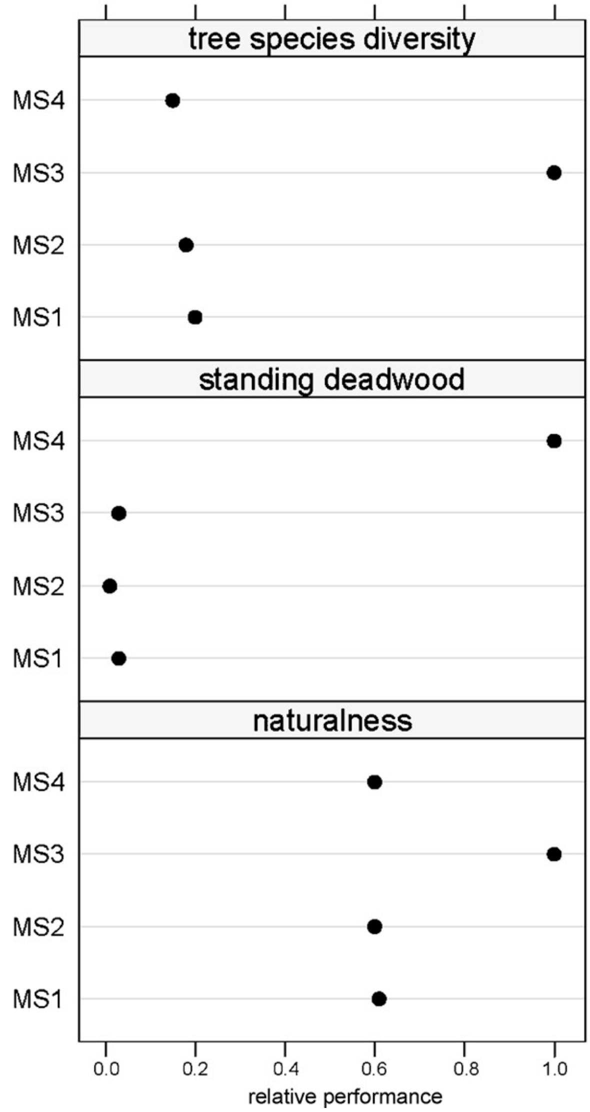

Fig. 5. The performance of three management strategies (MS1: Norway spruce age class forestry, MS2: Norway spruce continuous cover forestry, MS3: conversion to mixed broadleaved stands) and the unmanaged control variant (MS4) relative to the management strategy with the best performance with regard to three key indicators of biodiversity (see text for details).

et al. (1998) thus yielded a fairly low rating of NTS = 1.53 for MS3, and even lower with NTS = 1.02 for the other investigated strategies, indicating major deficits regarding to naturalness even for MS3. Tree species diversity calculated with the Shannon index (SI) was highest under MS3 (SI = 0.59) as well and lowest under MS4 (SI = 0.09), with slightly better results for MS1 and MS2 (SI = 0.11). As an additional key indicator for biodiversity, the average standing deadwood stock was assessed. As expected, the standing deadwood pool was considerable in the do-nothing variant MS4 (58.5 m^3 ha^{-1}) and very low in the management strategies (MS1: 1.6 m^3 ha^{-1}; MS2: 0.6 m^3 ha^{-1}; MS3: 1.8 m^3 ha^{-1}). The performance of the four strategies relative to the best strategy with regard to the three indicators of biodiversity is summarized in Fig. 5.

4. Discussion and conclusion

This study aimed at tackling the issue of carbon sequestration from the operational perspective of a forest management unit (FMU), displaying the interaction of C storage with other forest functions in Central European forests by means of an exemplary FMU. Three management strategies and an unmanaged control variant were investigated over a time horizon of 100 years. The simulated strategies were designed to reflect alternative silvicultural treatments currently discussed in practical forestry (e.g., Reininger, 2000) as well as in the scientific literature (Spiecker et al., 2004; Knoche, 2005; Knoke et al., 2005; Loewenstein, 2005; Rojo and Orois, 2005), besides the business as usual strategy (MS1) and a do-nothing control variant (MS4). As such, the study did not search for a management strategy with maximum C sequestration but rather investigated selected silvicultural strategies with regard to their C sequestration capacity over a period of 100 years and analyzed the trade-offs with regard to timber production and key indicators of biodiversity. Similarly, our study design did not facilitate the comparison of management strategies per se, such as different rotation periods for Norway spruce in MS1 and MS3.

4.1. Evaluation of model plausibility

Before specific results and possible consequences thereof will be discussed, the credibility of the employed simulation models will be addressed. The core component of the analysis was the hybrid patch model PICUS v1.4, which was used to simulate stand-specific silvicultural treatments and forest development under the four strategies investigated. In an earlier study (Seidl et al., 2005), PICUS had been extensively evaluated and had been found capable of reproducing observed development of mixed and vertically structured stands over several decades. For the present study, simulated soil C stocks were compared to those obtained from other process model estimates (Lasch et al., 2005) which showed good agreement of the response of soil C to management (not shown in this paper). However, an in-depth evaluation of belowground processes in PICUS v1.4 would further add to the credibility of the simulated soil carbon pools and their interpretation.

Judging the credibility of the stand growth projections cannot be separated from the stand treatment programs simulated for each stand type of the FMU within each MS. While strategy MS1 reflects the current age-class management practice, continuous cover forestry (MS2) has recently been proposed to achieve a more diverse stand structure and circumvent particular drawbacks of age class forestry such as high tending costs, a substantial share of low dimension timber and subsequently less efficient harvesting operations (e.g., Reininger, 2000), and high risk of windthrow and attacks by biotic agents (e.g., Schütz, 2001). Conversion of pure Norway spruce forests to mixed broadleaved species stands better adapted to the prevailing site conditions (MS3) is seen as a means to reduce the amount of salvage due to abiotic and biotic disturbances (e.g., Mayer, 1992; Olsthoorn et al., 1999) and is widely acknowledged to improve the adaptation potential of forests to climate change (e.g., Kienast et al., 1996).

The operational definition of stand treatment programs was based on literature and practical field experiences (e.g., Schädelin, 1942; Abetz, 1975; Johann, 1987; Reininger, 2000). The FMU harvest level was not constrained by an *ex ante* defined annual allowable cut but consists of the aggregated harvests of all individually simulated stands according to the silvicultural prescriptions (‘‘silvicultural harvest level’’). Despite this unconstrained bottom-up approach, the resulting mean annual cuts (MAC) for all management strategies (MS1–3) were highly plausible. For instance, for MS1, representing business as usual management, the simulated MAC of 10.6 $m^3\,ha^{-1}\,a^{-1}$ merchantable volume corresponds well to the reported average MAI of the enterprise (15.7 $m^3\,ha^{-1}\,a^{-1}$, gross volume over bark, Unegg, 1999), and sustainable harvest levels from recent management plans (Anonymous, 1949, 1960).

In assessing the realism of our estimates of economic costs, comparing the contribution margins (CMII) for MS1 calculated from simulated harvests and observed price and cost data with results from the Austrian report on forests and forestry (Anonymous, 2004) showed good agreement and further strengthened credibility of the results. The CMII for MS2, a strategy aiming at transformation of an even-aged forest into continuous cover stands, was very similar to data for coniferous uneven-aged forests reported by Hanewinkel (2001). Similarly, the results regarding volume production and financial performance of the conversion strategy MS3 are confirmed by several studies from the literature (e.g., Kenk and Guehne, 2001; Knoke et al., 2005). The reasons for lower values in CMII and EAI for MS3 are the high cost of introducing broadleaves (throughout the simulation period) and lower average net revenue per m^3 broadleaved timber in later phases of the planning period. Recently, Knoke et al. (2005) confirmed that mixed forests of *F. sylvatica* and *P. abies* are economically preferable over pure *P. abies* forests only if the uncertainty of future net revenue flows due to high disturbance risk is taken into account. In the current study, disturbances by biotic or abiotic risk agents have not been considered, and therefore the economic results for MS3 appear plausible. Overall, we are confident that the applied forest simulation model in combination with the employed algorithms to derive net revenues of a MS is capable of simulating stand development and timber production under the management strategies analyzed in this study.

4.2. Sensitivities in simulated C sequestration

Forest carbon sequestration was highly sensitive to the investigated strategies with the highest amount of C stored in the unmanaged variant (MS4). However, MS4 has to be seen as a ‘‘biological’’ reference run rather than a feasible management alternative. Also the continuous cover strategy (MS2) resulted in a considerably increase of aboveground C stocks relative to the baseline management strategy. Over the planning period of 100 years, MS1 and MS3 sustained their standing stock amazingly well, considering that no forest level constraint on the harvest level had been defined. Both MS2 and MS4 intentionally increased the standing stock. Over the entire simulation period, MS2 showed an average standing stock of ca. 475 m^3 (merchantable volume). Reports from the literature suggest that a continuous cover management strategy with Norway spruce may be possible also at a lower average standing stock (e.g., Schütz, 2001). However, given the climatic site conditions, both MS2 and MS4, being strongly dominated by mature *P. abies*, are likely to be at high risk due to storm events and bark beetle damage, which had not been taken into account in this assessment. Seidl et al. (in press) *inter alia* assessed the C storage effects of disturbances by the European spruce bark beetle *Ips typographus* (Scol. L.) which is a main disturbance agent in secondary spruce forests in Central Europe (Spiecker et al., 2004; Wermelinger, 2004) and has recently led to severe damages at low elevation sites in Austria. For the same study area Seidl et al. (in press) found a pronounced effect of biotic disturbances on C storage with particularly negative implications under climatic change. This is in general agreement with various findings pointing at the importance of disturbances on forest C storage (e.g., Li et al., 2003; Thornley and Cannell, 2004; Thürig et al., 2005). In general, the full range of disturbance agents, of which wind is the most important in Europe (Schelhaas et al., 2003), and their interactions (e.g., storm damage and bark beetle gradation) have the potential to strongly alter the undisturbed forest development as simulated in MS4. Furthermore, the ecological and C storage benefits of, for instance, a continuous cover forestry regime might be partly offset by increased efforts in forest protection routines. Considering the possibility of increasing pressure from disturbances as mediated through climate change, a continuous cover forestry regime would have to promote a tree species composition better adapted to the prevailing site conditions to circumvent negative effects for forest management and C sequestration.

Uncertainties remain concerning belowground forest C storage. For all four strategies an increase in average belowground C stock was predicted, with the highest increase occurring in MS4 (+21.4%). For MS4, this increase can partly be explained through the increased deadwood input to the soil. The increase in soil C pools under any of the MS may be generally due to past land-use practices such as litter raking and grazing, subsequently resulting in soil degradation (e.g., Glatzel, 1999). In a similar simulation study in Scots pine forests in Brandenburg (Germany), Fürstenau et al. (2007) report comparable soil C increases over the course of stand conversion strategies.

Although not accounted for in the Kyoto Protocol (UNFCCC, 1997), C storage in wood products has been assessed in this study. The wood product pools were a considerable forest sector C sink in all management strategies (MS1–3) and biomass utilization regimes (BMU1–3) of the study. This once more points at the fact that the assumptions of the GPG-LULUCF (IPCC, 2003) of immediate emission of harvested C is rather crude and needs revision, if the forest sector is to be accounted for beyond the first Commitment Period of the Protocol. Especially for the intensive forest management regimes of Central Europe, the increase in *in situ* C storage is limited by resource demands of the timber processing industry and because of the important role of forest management in providing income for rural populations. However, a societal shift to an increased use of wood products would have positive effects for forestry and forest-related industries, and it would also increase the C stored in the products pool. In addition, with the inclusion of wood product pools, the superiority of the unmanaged variant regarding the C sequestration potential diminished considerably. If mean C storage is considered, MS2 under business as usual biomass utilization (BMU1) stored only 34.7 t C ha^{-1} less over 100 years than the control variant MS4.

Both analyzed alternative biomass utilization scenarios (BMU2 and BMU3) feature an increased use of biomass for bioenergy at the cost of PL2 and PL3, which decreased C stored in wood products. In turn, BMU2 and BMU3 showed a strong increase in bioenergy derived from the forest, which has the potential to directly substitute fossil fuels. If the decrease of C in the wood product pools in BMU2 and BMU3 (between −3.6 and −6.3 t C ha^{-1} over 100 years according to the flow approach) is related to the increased substitution potential (considering light fuel oil, substitution of 12.2–27.5 t C ha^{-1}), net benefits for BMU2 and BMU3 were found. However, the study did not include the fossil fuel emissions of the individual production chains in the wood processing industry, which might reduce the estimates in the wood product pools to a certain degree and favor the biomass for energy approach even more. Moreover, offsets generated by substitution of fossil fuels with CO_2-neutral fuels are permanent compared to the reversible nature of C stocks in the forest and in products. Additionally, in the long run the *in situ* C storage is strongly constrained by ecological limits whereas positive effects of bioenergy can be sustained. An extended review of the potential and effects of bioenergy extraction from the forest would, however, have to consider the utilization of slash residuals and a full resource competition of bioenergy production with other timber processing industries. In this context it is important to note that in the current study, the allocation of forest biomass to production lines was an external input to the analysis.

Three accounting methods were applied to evaluate rates of C sequestration in the forest and in wood products. The general picture over the accounting regimes is quite consistent, but nevertheless there are remarkable differences, pointing at the influence of the applied accounting methodology. *In situ* C sequestration was highest in MS4 for all accounting methods, similarly the ranking of the management strategies was consistent over all accounting methods. However, whereas MS1 was a small C source and MS2 and MS4 are C sinks in all accounting regimes, the behavior of the transition to mixed-forest strategy (MS3) varied. It constituted a small C source under the mean storage approach but, in contrast, a C sink under the flow approach. If the temporal development of the flows is taken into account through discounting (our levelization approach), the transition to mixed-forest strategy (MS3) constitutes a source due to the harvests triggered early in the simulation by a reduced rotation period for Norway spruce. Interestingly, the flow to wood products under MS2 differed significantly between the flow and the levelization approach, which is due to the fact that considerable C flows occur towards the end of the simulation period, when forest structure already allows for full target diameter harvesting. For the resource utilization strategies BMU2 and BMU3, which differed only slightly with regard to C storage in wood product pools, the accounting method affected the ranking of the two scenarios. In general, the absolute values of C sequestration differed significantly in the three accounting methods investigated, which points at the importance of a consistent and well documented methodology related to forest C storage (e.g., Richards, 2004). Further uncertainty lies in the estimation of the interest rate for the levelization approach, which has a strong influence on the result under this method.

4.3. Relationships between forest functions

In deciding about the efficiency of sink enhancement through forest management, the potential cost of such an approach as well as the quantities of C storage have to be considered. To estimate trade-offs between C sequestration and timber production, we undertook an opportunity cost approach in which differential costs relative to the present-day management strategy (MS1 and BMU1) were calculated. Differences in the contribution margin from timber production were related to additionally sequestered C applying the flow accounting method. Opportunity costs were found to be positive in MS3 and MS4 and negative under MS2. Under BMU2 and BMU3, where bioenergy production is favored over other fiber use, opportunity costs were higher if C storage *in situ* and in products is considered, especially under MS3 due to the lower contribution margins from a higher share of moderately priced energy wood. This effect was, however, partly offset by increased C storage efficiency of utilizing biomass for bioenergy production, if this C storage pathway is considered. Opportunity costs ranged from € −1.2 to 17.5 t C^{-1} a^{-1} for a period of 100 years depending on the approach to characterize the economic performance and the pathways of C storage considered. A direct comparison to other studies is strongly limited by the variety of approaches and boundary conditions (see Richards, 2004). However, if results from Richards and Stokes (2004) for the temperate forest biome and C sequestration through forest management are taken as annual values, the range of € 0.85–40 t C^{-1} corresponds well to our findings.

Nevertheless, it is important to note that there are considerable uncertainties related to the economic assessment approach. The present study generally assumes a static socio-economic environment regarding prices and costs. The definition of scenarios for prices and costs may seem as the logical extension of the presented analysis. However, a scenario of future harvesting cost, for instance, beyond increasing labor costs will largely depend on assumptions about improved harvesting technology and future rationalization. The current analysis did not indigenously account for an eventually increasing price for biomass due to competition between the bioenergy sector and other fiber-dependant industries. To indicate such a development, in BMU2 the revenues from biomass for bioenergy and the resource allocation were changed in the course of the simulation as an exogenous input. Nevertheless, the presented approach gives an idea of the relationships between timber production and C sequestration. The results showed that even negative opportunity costs may be achievable, e.g., that both an increase in revenue from timber production and additional C sequestration are possible (compare also Richards and Stokes, 2004). The calculated opportunity costs for C sequestration indicate the potential for incentives to enhance C sinks within a national climate protection policy.

Today, the paradigm of sustainable forest management (SFM) as, for instance, outlined in the resolutions of the Ministerial Conference for the Protection of Forests in Europe (MCPFE, 1993, 1998) provides the frame for multi-purpose forest management. In this context, other objectives beyond timber production and climate protection through C sequestration may be considered important. In this study, forest biodiversity was considered by means of key indicators to demonstrate the multi-purpose dimension of silvicultural decision-making. In the analysis of tree species diversity and naturalness of species composition strong advantages of the conversion strategy MS3 were found. Standing deadwood in turn was considerably higher under strategy MS4. This demonstrates that some key parameters of biodiversity may be improved via a changed management regime (from MS1 to MS3), while others (e.g., deadwood) are not affected and require additional measures to meet all demands of sustainable forest management, such as dead-wood management.

As an overall conclusion, the study provided insights into the complex interrelations of forest services and functions at the FMU level, where C sequestration might be an emerging additional marketable forest function. Although overall quantities of forest C sequestration at the FMU level in our example were limited (+115 t C a^{-1} for the FMU *in situ* under MS2 according to the flow approach) compared to other sequestration approaches (see Lackner, 2003), the inclusion of the wood products pool and C offsets from bioenergy production contributed strongly to a better and unbiased view of forests and forest management with regard to climate change mitigation. Moreover, the study could show that for a consistent evaluation of alternative forest management strategies within the frame of SFM, the climate protection function needs to be jointly incorporated into management decisions at the operational level of the forest owner (i.e., FMU level) to (i) address involved trade-offs with management objectives and other forest functions; (ii) account for the specific socio-economic and ecological situation of the forest (Plantinga and Wu, 2001; van Kooten et al., 2004). Further work should include the effects of disturbances and the uncertainty regarding a possible climate change.

Acknowledgements

The authors are grateful to H. and G. Kleinszig for data on the FMU used in this study and continuing support. Further thanks go to P. Lasch and F.W. Badeck for their support in a model comparison with the 4C model. Climate scenario data were provided by the Potsdam Institute of Climate Impact Research within the FP5 project SilviStrat. The study was partly funded by the Austrian Federal Ministry for Agriculture, Forestry, Environment and Water Management (grant GZ54 3895/140-V/4/03) and the FP6 research project Integrated Sink Enhancement Assessment (INSEA) of the European Commission (grant SSP1-CT-2003-503614). We furthermore like to thank two anonymous reviewers for their remarks helping to improve an earlier version of the manuscript.

Appendix A

See Fig. A1 and Tables A1–A7.

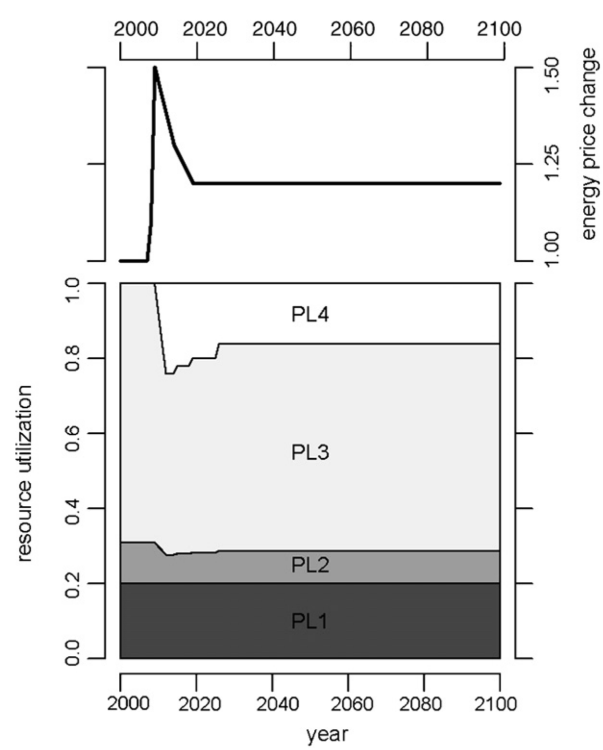

Fig. A1. Relative changes in energy prices in scenario BMU2 (upper panel) and exemplarily changes in resource allocation to the four main production lines (PL1–4) for assortment Norway spruce 20–29 cm (lower panel, see Table A6). PL1: sawmill industry; PL2: particle board/plywood industry; PL3: pulp and paper industry; PL4: bioenergy production.

Table A1
Characteristics of the 25 stand types as used for model initialization

#	n	ST	C_{ff} (t ha^{-1})	N_{ff} (t ha^{-1})	MAI_{100} (m^3 ha^{-1})	Age	Density	*P. abies* (%)	d_g (cm)
1	1	2	37.24	1.497	18.8	19	0.85	71.8	11.4
2	3	1	41.71	1.663	21.3	22	0.53	92.0	14.5
3	10	2	33.90	1.374	15.2	24	1.01	100.0	13.2
4	3	1	30.92	1.277	19.8	26	1.04	84.8	13.7
5	5	2	30.38	1.277	15.3	35	1.09	97.5	15.0
6	9	1	30.57	1.274	20.5	27	1.07	100.0	17.2
7	6	1	29.03	1.282	20.8	30	1.28	85.5	18.1
8	1	1	30.46	1.276	19.3	36	0.84	56.6	19.2
9	1	2	39.90	1.596	13.9	37	0.54	93.7	17.6
10	1	1	32.06	1.310	19.3	39	0.70	100.0	21.9
11	13	2	30.54	1.274	15.0	41	0.93	90.6	20.8
12	7	2	30.31	1.280	14.7	58	0.80	94.7	27.7
13	4	1	26.92	1.241	19.4	57	0.94	83.3	35.1
14	3	2	34.92	1.411	13.6	57	0.52	88.5	26.5
15	3	1	25.48	1.206	18.9	42	1.21	78.8	25.6
16	2	2	29.73	1.288	15.0	55	0.92	67.4	27.5
17	9	2	28.32	1.271	14.5	62	0.95	89.0	28.4
18	4	2	30.26	1.281	13.0	76	0.74	100.0	37.6
19	2	1	30.50	1.275	15.0	60	0.73	100.0	30.2
20	3	2	31.35	1.287	12.4	61	0.66	61.4	26.8
21	5	1	26.08	1.221	17.6	61	0.96	100.0	35.9
22	1	3	38.35	1.816	8.8	68	1.29	81.3	21.4
23	3	1	30.94	1.278	13.0	96	0.57	80.5	34.6
24	3	2	30.26	1.281	9.9	86	0.79	83.9	25.6
25	1	3	40.08	1.603	6.0	101	0.51	84.3	25.5

Forest floor C and N content were derived from statistical relationships with stand-level parameters: $DM = 0.138BA^2 - 6.5565BA + 161.37$, $R^2 = 0.536$, $n_{ss} = 9$; $N\% = -0.0382BA + 2.5993$, $R^2 = 0.605$, $n_{ss} = 9$; $C\% = -1.0301BA + 66.335$, $R^2 = 0.513$, $n_{ss} = 9$, where DM is the dry mass (t ha^{-1}), BA the basal area (m^2 ha^{-1}), N% the nitrogen content, C% the carbon content, n_{ss} the number of soil samples, n the number of stands represented by a stand type, ST the site type (see Table 1), C_{ff} the carbon in the forest floor, N_{ff} the nitrogen in the forest floor, MAI_{100} the mean annual increment at age 100 as estimated from yield tables (gross volume over bark), density the stocking density relative to yield table basal area, *P. abies* the share of *P. abies* (relative to basal area), and d_g is the basal area weighted mean diameter.

Table A2
Stand conversion variants within MS3 and corresponding costs for the introduction of deciduous species, including protection against browsing and tending

Conversion variant	Target share of deciduous species (%)	FMU area (%)	Establishment cost (€ ha^{-1})
Quercus	100	21.1	7000
Fagus	100	4.5	7000
Picea–Fagus (1)	30	68.6	4250
Picea–Fagus (2)	20	5.8	2150

Picea–Fagus variant (2) is applied in stands with existing natural regeneration of *Picea abies*. FMU: forest management unit.

Table A3
Percent volume removal in the relative diameter classes (RDC) for the silvicultural interventions applied

Intervention	RDC1	RDC2	RDC3	RDC4	RDC5
PCT	40	40	40	30	30
THA	–	10	10	25	15
THB	–	10	10	10	5
THS	–	10	15	30	20
SWC	–	25	30	35	10
CLC	100	100	100	100	100
TDH	–	–	–	10	75

Values are average values and are adopted to varying initial stand conditions and species. PCT: pre-commercial thinning (timber is not removed from site); THA: thinning from above; THB: light thinning from below; THS: structural thinning according to Reininger (2000); SWC: shelterwood cut; CLC: clearcut; TDH: target diameter harvest.

Table A4
The scheduling of management interventions in the strategies given at approximate stand age

Intervention	MS1	MS2	MS3	MS4
PCT	20	20	20	–
THA	40; 50; 60	–	40; 50; 60	–
THB	70	–	70	–
THS	–	40; 50; 60	–	–
SWC	80	–	–	–
CLC	90	–	80	–
TDH	–	75; 90; . . .	–	–

Values are average values and are adopted to varying initial stand conditions and species (differences in MS3 for the *Quercus*, *Fagus* and *Picea*/*Fagus* variant). TDH is carried out in 15-year intervals.

Table A5
Weighted average price (€ m^{-3}) over assortments (dimension, quality) for diameter classes

	P. abies	*Pinus sylvestris*	*Fagus sylvatica*	*Quercus robur*
Residue 1	31.45	26.85	36.97	36.97
Residue 2	44.68	35.52	36.97	36.97
15–19 cm	46.00	36.91	36.97	36.97
20–29 cm	49.12	37.72	40.82	41.46
30–39 cm	68.98	51.52	47.63	51.78
40–49 cm	69.98	51.52	58.84	69.61
>50 cm	65.00	47.50	53.00	60.50

Table A6
Resource allocation to the production lines (PL) of the wood products model WPM for conifers under BMU1

	PL1	PL2	PL3	PL4
Residue1	0.00	0.07	0.43	0.50
Residue2	0.20	0.11	0.69	0.00
15–19 cm	0.20	0.11	0.69	0.00
20–29 cm	0.20	0.11	0.69	0.00
30–39 cm	0.70	0.04	0.26	0.00
40–49 cm	0.70	0.04	0.26	0.00
>50 cm	0.70	0.04	0.26	0.00

Table A7
Resource allocation to the production lines (PL) of the wood products model WPM for deciduous species under BMU1

	PL1	PL2	PL3	PL4
Residue1	0.00	0.13	0.77	0.10
Residue2	0.00	0.13	0.77	0.10
15–19 cm	0.00	0.13	0.77	0.10
20–29 cm	0.10	0.11	0.69	0.10
30–39 cm	0.70	0.04	0.26	0.00
40–49 cm	0.70	0.04	0.26	0.00
>50 cm	0.70	0.04	0.26	0.00

References

Abetz, P., 1975. Eine Entscheidungshilfe für die Durchforstung von Fichtenbeständen. Allg. Forstztg. 30, 666–667.

Andersen, R.S., Towers, W., Smith, P., 2005. Assessing the potential for biomass energy to contribute to Scotland's renewable energy needs. Biomass Bioenerg. 29, 73–82.

Anonymous, 1949. Forsteinrichtung Kleinszig. Operat des Revieres Wolschart 1949–1958, 305 pp.

Anonymous, 1960. Forsteinrichtung Kleinszig. Operat des Revieres Wolschart 1960–1969, 247 pp.

Anonymous, 2004. Nachhaltige Waldwirtschaft in Österreich. Österreichischer Waldbericht—Datensammlung. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien.

Backeus, S., Wilkström, P., Lämas, T., 2005. A model for regional analysis of carbon sequestration and timber production. For. Ecol. Manage. 216, 28–40.

Berndes, G., Hoogwijk, M., van er Broek, R., 2003. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass Bioenerg. 25, 1–28.

Boscolo, M., Vincent, J.R., 2003. Nonconvexities in the production of timber, biodiversity, and carbon sequestration. J. Environ. Econ. Manage. 46, 251–268.

Briceno-Elizondo, E., Lexer, M.J., 2004. Estimating carbon sequestration in the wood products pool: model adaptation and application for Austrian conditions. Cent.bl. gesamte Forstwes. 121 (2), 99–119.

Cacho, O.J., Wise, R.M., Macdicken, K.G., 2004. Carbon monitoring costs and their effect on incentives to sequester carbon through forestry. Mitigat. Adaptat. Strat. Global Change 154, 273–293.

Caparros, A., Jacquemont, F., 2003. Conflicts between biodiversity and carbon sequestration programs: economic and legal implications. Ecol. Econ. 46, 143–157.

Cote, W.A., Young, R.J., Risse, K.B., Constanza, A.F., Tonellia, J.P., Lenocker, C., 2002. A carbon balance method for paper and wood products. Environ. Pollut. 116, S1–S6.

Currie, W.S., Nadelhoffer, J.K., 1999. Dynamic redistribution of isotopically labeled cohorts of nitrogen inputs in two temperate forests. Ecosystems 2, 4–18.

Currie, W.S., Nadelhoffer, J.K., Aber, J.D., 1999. Soil detrital processes controlling the movement of ^{15}N tracers to forest vegetation. Ecol. Appl. 9, 87–102.

Currie, W.S., Nadelhoffer, K.J., Aber, J.D., 2004. Redistribution of ^{15}N highlight turnover and replentishment of mineral soil organic N as a long-term control on forest C balance. For. Ecol. Manage. 196, 109–127.

Dean, C., Roxburgh, S., Mackey, B.G., 2004. Forecasting landscape-level carbon sequestration using gridded, spatially adjusted tree growth. For. Ecol. Manage. 194, 109–129.

Eggers, T., 2002. The impact of Manufacturing and Utilization of Wood Products on the European Carbon Budget. European Forest Institute, Joensuu, 90 pp.

Fürstenau, C., Badeck, F.W., Lasch, P., Lexer, M.J., Lindner, M., Mohr, P., Suckow, F., 2007. Multiple-use forest management in consideration of climate change and the interests of stakeholder groups. Eur. J. For. Res. 126, 225–239.

GEMIS, 2005. Global Emission Model for Integrated Systems. http://www.oeko.de/service/gemis/en/index.htm (November 3, 2005).

Glatzel, G., 1999. Historic forest use and its possible implications to recently accelerated tree growth in Central Europe. In: Karjalainen, T., Spiecker, H., Laroussinie, O. (Eds.), Causes and consequences of accelerating tree growth in Europe, EFI Proceedings 27, European Forest Institute, Joensuu, Finland, pp. 65–74.

Grabherr, G., Koch, G., Kirchmeir, H., Reiter, K., 1998. Hemerobie Österreichischer Waldökosysteme. Österreichische Akademie der Wissenschaften. Wagner, Innsbruck, 493 pp.

Gracia, C., Sanchez, A., Pla, E., Sabate, S., Lexer, M.J., Jäger, D., 2005. Adaptive forest management strategies. In: Kellomäki, S., Leinonen, S. (Eds.), Management of European forests under changing climate conditions. Research Notes 163. University of Joensuu, Finland, ISBN: 952-458-652-5.

Haas, R., Kranzl, L., 2002. Bioenergie und Gesamtwirtschaft: Analyse der volkswirtschaftlichen Bedeutung der energetischen Nutzung von Biomasse für Heizzwecke und Entwicklung effizienter Förderstrategien für Österreich. Austrian Federal Ministry for Transport, Innovation and Technology, Vienna, 239 pp.

Hanewinkel, M., 2001. Economic aspects of the transformation from even-aged pure stands of Norway spruce to uneven-aged mixed stands of Norway spruce and beech. For. Ecol. Manage. 151, 181–193.

Hoen, H.F., Solberg, B., 1994. Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. For. Sci. 4, 429–451.

Hoogwijk, M., Faaij, A., van den Broek, R., Berndes, G., Gielen, D., Turkenburg, W., 2003. Exploration of the ranges of the global potential of biomass for energy. Biomass Bioenerg. 25, 119–133.

Howard, E.A., Gower, S.T., Foley, J.A., Kucharik, C.J., 2004. Effects of logging on carbon dynamics of a jack pine forest in Saskatchewan, Canada. Global Change Biol. 10, 1267–1284.

Humphrey, J.W., Davey, S., Peace, A.J., Ferris, R., Harding, K., 2002. Lichens and bryophyte communities of planted and semi-natural forests in Britain: the influence of site type, stand structure and deadwood. Biol. Conserv. 107, 165–180.

Huston, M.A., Marland, G., 2003. Carbon management and biodiversity. J. Environ. Manage. 67, 77–86.

IPCC, 2000. Intergovernmental Panel on Climate Change: Special Report on Land Use, Land-Use Change and Forestry. http://www.grida.no/climate/ipcc/land_use/index.htm (November 4, 2005).

IPCC, 2003. Intergovernmental Panel on Climate Change: Good Practice Guidance for Land Use, Land-Use Change and Forestry. http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm (November 3, 2005).

Johann, K., 1987. Standraumregulierung bei der Fichte. Schriftreihe der Forstlichen Bundesversuchsanstalt Wien No. 22. Österreichischer Agrarverlag, Wien, 66 pp.

Jonsell, M., Weslien, J., Ehnström, B., 1998. Substrate requirements of redlisted saproxylic invertebrates in Sweden. Biodivers. Conserv. 7, 749–764.

Kappes, H., Topp, W., 2004. Emergence of Coleoptera from deadwood in a managed broadleaved forest in Central Europe. Biodivers. Conserv. 13, 1905–1924.

Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G.J., Eggers, T., Lapvetelainen, T., Kaipainen, T., 2003. Scenario analysis of the impact of forest management and climate change on the European forest sector carbon budget. For. Policy Econ. 5, 141–155.

Karjalainen, T., 1996. Dynamics and potentials of carbon sequestration in managed stands and wood products in Finland under changing climatic conditions. For. Ecol. Manage. 80, 113–132.

Karjalainen, T., Kellomäki, S., Pussinen, A., 1994. Role of wood based products absorbing atmospheric carbon. Silva Fenn. 28 (2), 67–80.

Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G.J., Erhard, M., Eggers, T., Sonntag, M., Mohren, G.M.J., 2002. An approach towards an estimate of the impact of forest management and climate change on European forest sector carbon budget: Germany as a case study. For. Ecol. Manage. 162, 87–103.

Keane, R.E., Austin, M., Dahlman, R., Field, C., Huth, A., Lexer, M.J., Peters, D., Solomon, A.M., Wyckoff, P., 2001. Plant mortality in gap models. Clim. Change 51, 509–540.

Kenk, G., Guehne, S., 2001. Management of transformation in Central Europe. For. Ecol. Manage. 151, 107–119.

Kienast, F., Brzeziecki, C., Wildi, O., 1996. Long-term adaptation potential of Central European mountain forests to climate change: a GIS-assisted sensitivity assessment. For. Ecol. Manage. 80, 133–153.

Kilian, W., Müller, F., Starlinger, F., 1994. Die forstlichen Wuchsgebiete Österreichs, vol. 82. Forstliche Bundesversuchsanstalt Wien, Berichte, 60 pp.

Kirschbaum, M.U.F., 2003. To sink or to burn? A discussion of the potential contributions of forests to greenhouse gas balances through storing carbon or providing biofuels. Biomass Bioenerg. 24, 297–310.

Kirschbaum, M.U.F., Cowie, A.L., 2004. Giving credit where credit is due: a practical method to distinguish between human and natural factors in carbon accounting. Clim. Change 67, 417–436.

Kirschbaum, M.U.F., Schlamadinger, B., Cannell, M.G.R., Hamburg, S.P., Karjalainen, T., Kurz, W.A., Prisley, S., Schulze, E.D., Singh, T.P., 2001. A generalized approach of accounting for biospheric carbon stock changes under the Kyoto Protocol. Environ. Sci. Policy 4, 73–85.

Klimo, E., Hager, H., Kulhavy, J. (Eds.), 2000. Spruce monocultures in Central Europe—problems and prospects. EFI Proceedings 33, European Forest Institute, Joensu, p. 208.

Knoche, D., 2005. Effects of stand conversion by thinning and underplanting on water and element fluxes of a pine ecosystem (*P. sylvestris* L.) on lignite mine spoil. For. Ecol. Manage. 212, 214–220.

Knoke, T., Plusczyk, N., 2001. On economic consequences of transformation of a spruce (*Picea abies* (L.) Karst.) dominated stand from regular to irregular age structure. For. Ecol. Manage. 151, 163–179.

Knoke, T., Strimm, B., Ammer, C., Moog, M., 2005. Mixed forests reconsidered: a forest economics contribution on an ecological concept. For. Ecol. Manage. 213, 102–116.

Kraxner, F., Nilsson, S., Obersteiner, M., 2003. Negative emission from bioenergy use, carbon capture and sequestration (BECS)—The case of biomass production by sustainable forest management from semi-natural temperate forests. Biomass Bioernerg. 24, 285–296.

Kurz, W.A., Apps, M., Banfield, E., Stinson, G., 2002. Forest carbon accounting at the operational scale. For. Chron. 78 (5), 672–679.

Kurz, W.A., Apps, M.J., Beukema, S.J., Lekstrum, T., 1995. 20th Century carbon budget of Canadian forests. Tellus 47B, 170–177.

Lackner, K.S., 2003. A guide to CO_2 sequestration. Science 300, 1677–1678.

Landsberg, J.J., Waring, R.H., 1997. A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. For. Ecol. Manage. 95, 209–228.

Lasch, P., Badeck, F.W., Suckow, F., 2005. Model-based analysis of management alternatives at stand and regional level in Brandenburg (Germany). For. Ecol. Manage. 207, 59–74.

Lee, J., Morrison, I.K., Leblanc, J.D., Dumas, M.T., Cameron, D.A., 2002. Carbon sequestration in trees and regrowth vegetation as affected by clearcut and partial harvesting in a second-growth boreal mixedwood. For. Ecol. Manage. 169, 83–101.

Lexer, M.J., Brooks, R.T., 2005. Decision support for multiple purpose forestry. For. Ecol. Manage. 207, 1–3.

Lexer, M.J., Hönninger, K., 2001. A modified 3D-patch model for spatially explicit simulation of vegetation composition in heterogeneous landscapes. For. Ecol. Manage. 144, 43–65.

Lexer, M.J., Hönninger, K., Scheifinger, H., Matulla, C., Groll, N., Kromp-Kolb, H., Schadauer, K., Starlinger, F., Englisch, M., 2002. The sensitivity of Austrian forests to scenarios of climate change: a large-scale risk assessment based on a modified gap model and forest inventory data. For. Ecol. Manage. 162, 53–72.

Li, Z., Apps, M.J., Kurz, W.A., Banfield, E., 2003. Temporal changes of forest net primary production and net ecosystem production in West Central Canada associated with natural and anthropogenic disturbances. Can. J. For. Res. 33, 2340–2351.

Liski, J., Karjalainen, T., Pussinen, A., Nabuurs, G.J., Kauppi, P., 2000. Trees as carbon sinks and sources in the European Union. Environ. Sci. Policy 3, 91–97.

Liski, J., Korotkov, A.V., Prins, C.F.L., Karjalainen, T., Victor, D.G., Kauppi, P.E., 2003. Increased carbon sink in temperate and boreal forests. Clim. Change 61, 89–99.

Loewenstein, E.F., 2005. Conversion of uniform broadleaved stands to an uneven-aged structure. For. Ecol. Manage. 215, 103–112.

Lohr, S.M., Gauthreaux, S.A., Kilgo, J.C., 2002. Importance of coarse woody debris to avian communities in loblolly pine forests. Conserv. Biol. 16 (3), 767–777.

Magurran, A.E., 1988. Ecological Diversity and its Measurement. Princeton University Press, Princeton, 179 pp.

Mäkelä, A., Landsberg, J.J., Ek, A.R., Burk, T.E., Ter-Mikaelian, M., Agren, G.I., Oliver, C.D., Puttonen, P., 2000. Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. Tree Physiol. 20, 289–298.

Marland, E., Marland, G., 2003. The treatment of long-lived carbon-containing products in inventories of carbon dioxide emissions to the atmosphere. Environ. Sci. Policy 6, 139–152.

Marschall, J., 1975. Hilfstafeln für die Forsteinrichtung. Österreichischer Agrarverlag, Wien, 199 pp.

Masera, O.R., Garza-Caligaris, J.F., Kanninen, M., Karjalainen, T., Liski, J., Nabuurs, G.J., Pussinen, A., de Jong, B.H.J., Mohren, G.M.J., 2003. Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. Ecol. Model. 164, 177–199.

Matthews, S., O'Connor, R., Plantinga, A.J., 2002. Quantifying the impacts on biodiversity of policies for carbon sequestration in forests. Ecol. Econ. 40, 71–87.

Matulla, C., Groll, N., Kromp-Kolb, H., Scheiflinger, H., Lexer, M.J., Windmann, M., 2002. Climate change scenarios at Austrian national forest inventory sites. Clim. Res. 22 (2), 161–173.

Mayer, H., 1974. Wälder des Ostalpenraumes. Fischer, Stuttgart, 344 pp.

Mayer, H., 1992. Waldbau auf soziologisch-ökologischer Grundlage, 4th ed. Fischer, Stuttgart, 522 pp.

MCPFE, 1993. Ministerial Conference on Protection of Forests in Europe, Conference Proceedings, Ministry of Agriculture and Forestry, Helsinki, Finland.

MCPFE, 1998. Proceedings of the Third Ministerial Conference on Protection of the Forests in Europe. General Declaration and Resolutions Adopted, Ministry of Agriculture, Rural Development, and Fisheries, Lisbon, Portugal.

Moorhead, D.L., Currie, W.S., Rastetter, E.B., Parton, W.J., Harmon, M.E., 1999. Climate and litter quality controls on decomposition: an analysis of modeling approaches. Global Biogeochem. Cycles 13, 575–589.

Newell, R.G., Stavins, R.N., 2000. Climate change and forest sinks: factors affecting the cost of carbon sequestration. J. Environ. Econ. Manage. 40, 211–235.

Olsthoorn, A.F.M., Bartelink, H.H., Gardiner, J.J., Pretzsch, H., Franc, A. (Eds.), 1999. Management of Mixed-species Forests: Silviculture and Economics. IBN-DLO Scientific Contributions, Wageningen, NL.

Parikka, M., 2004. Global biomass fuel resources. Biomass Bioenerg. 27, 613–620.

Peng, C., 2000. Understanding the role of forest simulation models in sustainable forest management. Environ. Impact Asses. 20, 481–501.

Pingoud, K., Lehtila, A., 1997. Role of forest sector and bioenergy in limiting the carbon emissions of Finland. Biomass Bioenerg. 13, 413–420.

Pingoud, K., Perälä, A.L., Pussinen, A., 2001. Carbon dynamics in wood products. Mitigat. Adaptat. Strat. Global Change 6, 91–111.

Plantinga, A., Wu, J., 2001. Co-benefits from carbon sequestration in forests: An evaluation of the reductions in agricultural externalities from an afforestation policy in Wisconsin. Land Econ. 79 (1), 74–85.

Pregitzer, K.S., Euskirchen, E.S., 2004. Carbon cycling and storage in world forests: biom patterns related to forest age. Global Change Biol. 10, 2052–2077.

Pussinen, A., Karjalainen, T., Mäkipää, R., Valsta, L., Kellomäki, S., 2002. Forest carbon sequestration and harvests in Scots pine stand under different climate and nitrogen deposition scenarios. For. Ecol. Manage. 158, 103–115.

R Development Core Team, 2006. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. http://www.R-project.org (June 28, 2006).

Rauscher, H.M., Reynolds, K., Vacik, H., 2005. Decision support systems for forest management. Comput. Electron. Agric. 49 (1), 1–5.

Reininger, H., 2000. Das Plenterprinzip oder die Überführung des Altersklassenwaldes. Stocker, Graz, 238 pp.

Richards, K.R., 2004. A brief overview of carbon sequestration economics and policy. Environ. Manage. 33 (4), 545–558.

Richards, K.R., Stokes, C., 2004. A review of forest carbon sequestration cost studies: a dozen years of research. Clim. Change 63, 1–48.

Rojo, J.M.T., Orois, S.S., 2005. A decision support system for optimizing the conversion of rotation forest stands to continuous cover forest stands. For. Ecol. Manage. 207, 109–120.

Ryan, M.G., Melillo, J.M., Ricca, A., 1990. A comparison of methods for determining proximate carbon fractions of forest litter. Can. J. For. Res. 20, 166–171.

Schädelin, W., 1942. Die Auslesedurchforstung als Erziehungsbetrieb höchster Wertleistung, 3rd ed. Haupt, Berlin, 147 pp.

Schelhaas, M.-J., Nabuurs, G.-J., Schuck, A., 2003. Natural disturbances in the European forests in the 19th and 20th centuries. Global Change Biol. 9, 1620–1633.

Schütz, J.P., 2001. Der Plenterwald und weitere Formen strukturierter und gemischter Wälder. Parey, Berlin, 207 pp.

Seidl, R., Lexer, M.J., Jäger, D., Hönninger, K., 2005. Evaluating the accuracy and generality of a hybrid patch model. Tree Phys. 25, 939–951.

Seidl, R., Rammer, W., Jäger, D., Lexer, M.J., in press. Impact of bark beetle (*Ips typographus* L.) disturbance on timber production and carbon sequestration in different management strategies under climate change. For. Ecol. Manage.

Sims, R.E.H., 2003. Bioenergy to mitigate for climate change and meet the needs of society, the economy and the environment. Mitigat. Adaptat. Strat. Global Change 8, 349–370.

Spiecker, H., Hansen, J., Kilmo, E., Skovsgaard, J.P., Sterba, H., von Teuffel, K., 2004. Norway spruce conversion—options and consequences. EFI Research Report 18. Brill, Leiden, p. 320.

Stampfer, K., 2001. Harvester Leistungsdaten, MHT Robin, Neuson 11002 HV, Impex Königstiger, Untersuchungsergebnisse aus Aufnahmen bei Geländeneigungen von 20–60%. FPP Kooperationsabkommen Forst-Platte-Papier, Wien, 15 pp.

Steiner, C., 1998. Ein klimasensitives statisches Modell zur Beurteilung der Baumarteneignung. Diploma Thesis. University of Natural Resources and Applied Life Sciences, Vienna, 160 pp.

Sterba, H., Griess, O., 1983. Sortentafeln für Fichte. Österreichischer Agrarverlag, Wien, 151 pp.

Sterba, H., Kleine, M., Eckmüllner, O., 1986. Sortentafeln für Tanne, Lärche, Kiefer und Buche. Österreichischer Agrarverlag, Wien, 182 pp.

Thornley, J.H.M., Cannell, G.R., 2000. Managing forest for wood yield and carbon storage: a theoretical study. Tree Phys. 20, 477–484.

Thornley, J.H.M., Cannell, M.G.R., 2004. Long-term effects of fire frequency on carbon storage and productivity of boreal forests: a modeling study. Tree Phys. 24, 765–773.

Thürig, E., Palosuo, T., Bucher, J., Kaufmann, E., 2005. The impact of windthrow on carbon sequestration in Switzerland: a model-based assessment. For. Ecol. Manage. 210, 337–350.

Unegg, F., 1999. Erstellung und Anwendung eines Regelwerkes zur waldbaulichen Entscheidungsfindung in schneebruchgeschädigten, sekundären Fichtenbeständen. Diploma Thesis. University of Natural Resources and Applied Life Sciences Vienna, 113 pp.

UNFCCC, 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. http://unfccc.int/resource/docs/convkp/kpeng.pdf (November 3, 2005).

van Kooten, C.G., Eagle, A.J., Manley, J., Smolak, T., 2004. How costly are carbon offsets? A meta-analysis of carbon forest sinks. Environ. Sci. Policy 7, 239–251.

Wermelinger, B., 2004. Ecology and management of the spruce bark beetle *Ips typographus*—a review of recent research. For. Ecol. Manage. 202, 67–82.

Winjum, J.K., Brown, S., Schlamadinger, B., 1998. Forest harvest and wood products: sources and sinks of atmospheric carbon dioxide. For. Sci. 44 (2), 272–284.

ZAMG, 2001. Klimadaten von Österreich. Zentralanstalt für Meteorologie und Geodynamik Wien (CD-ROM).