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Does Conversion of Even-Aged, Secondary Coniferous Forests Affect Carbon Sequestration? A Simulation Study under Changing Environmental Conditions

Rupert Seidl, Werner Rammer, Petra Lasch, Franz-Werner Badeck and Manfred J. Lexer

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To circumvent problems associated with even-aged, pure coniferous stands propagated outside their natural range alternative management strategies and conversion programs are currently discussed in Central Europe. However, a mainstreaming of such adapted silvicultural systems with climate change mitigation objectives is missing to date. In this study the objective was to assess in situ C storage under conditions of climate change in a secondary Norway spruce (*Picea abies* (L.) Karst.) forest management unit in Austria. Four management strategies (Norway spruce age class forestry, transition to continuous cover forestry with Norway spruce, conversion to mixed conifer/broadleaved stands, no management) were investigated under current climate and two transient climate change scenarios in a simulation study. By comparing the results of two independent forest ecosystem models (PICUS v1.41, 4C) applied under identical forcings and boundary conditions we aimed at addressing uncertainties in model-based projections. A transition to continuous cover forestry increased C storage in all climate scenarios (+45.4 $tC \cdot ha^{-1}$ to +74.0 $tC \cdot ha^{-1}$ over the 100 year analysis period) compared to the approximately balanced C budget under the age class system. For the mixed conifer/broadleaved management variant predictions of the two models diverged significantly (+29.4 $tC \cdot ha^{-1}$ and –10.6 $tC \cdot ha^{-1}$ in PICUS and 4C respectively, current climate). With regard to climate change impacts both models agreed on distinct effects on productivity but lower sensitivity of C stocks due to compensation from respiration and adaptive harvest levels. In conclusion, considering the potential effects of silvicultural decisions on C stocks climate change mitigation should be addressed explicitly in programs advocating targeted change in management paradigms.

Keywords forest management, Norway spruce, climate change mitigation, PICUS, 4C, model comparison
Addresses *Seidl*, *Rammer* & *Lexer*: Institute of Silviculture, BOKU, Vienna, Austria; *Lasch* & *Badeck*: Potsdam Institute for Climate Impact Research e.V., Potsdam, Germany
E-mail rupert.seidl@boku.ac.at
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1 Introduction

Forests have the potential to play a considerable role in the mitigation of anthropogenic climate change (e.g. Liski et al. 2000, Janssens et al. 2003, Nabuurs et al. 2003, Woodbury et al. 2007). Consequently, forests and forest management are included in the Kyoto Protocol (KP, UNFCCC 1997) and are likely to be considered in post-KP treaties on climate protection (e.g. Benndorf et al. 2007, Schlamadinger et al. 2007a). Under the current KP regulations additional management-induced in situ C storage in existing forests can be accounted in national GHG balances (Höhne et al. 2007, Schlamadinger et al. 2007b). However, to operationally implement the climate protection function in forestry it is necessary to review potential trade-offs with other forest services within a framework of sustainable forest management (cf. MCPFE 1993, 1998). Furthermore, discussions on adapted management strategies in response to current problems in forest management (e.g., reducing vulnerabilities to disturbances) rarely account for climate change mitigation objectives. This is in conflict with the findings of the Intergovernmental Panel on Climate Change (cf. Sathaye et al. 2007), advocating the mainstreaming of climate change mitigation into programs and policies of sustainable development in order to facilitate greenhouse gas reduction.

A current challenge in Central European forestry is the sustainable management of even-aged, coniferous forests at sites naturally supporting deciduous forest vegetation types (cf. Spiecker et al. 2004). The approximate area covered by such secondary conifer forests in Europe was estimated to be between 5.7 mill. and 7.3 mill. hectares, mainly located in Germany, the Czech Republic and Austria (von Teuffel et al. 2004). These forests are prone to an array of diseases and pest organisms and may be particularly vulnerable to warmer and drier climatic conditions (e.g. Führer 1996, Tomiczek 2000, Kulhavy et al. 2004). Moreover, repeated rotations may result in decreasing productivity and soil quality (e.g. Englisch 2000, Glatzel et al. 2000, Kulhavy et al. 2004). Furthermore, even-aged management has been criticised recently for failing to realize the site-specific production potential (e.g. Reininger 2000, Lähde et al. 2001), producing large shares of low priced assortments (i.e. trees of low dimension), and being a sub-optimal management strategy with regard to biodiversity objectives (e.g. Humphrey et al. 2002). Addressing these problems several alternative management concepts for even-aged, coniferous forests are discussed among practitioners and in the scientific literature (e.g. Reininger 2000, Kenk and Guehne 2001, Pommerening and Murphy 2004, von Lüpke et al. 2004, von Teuffel et al. 2005, Kint et al. 2006, Price and Price 2006). Klimo et al. (2000) and Spiecker et al. (2004) provide a summary on problems and prospects of secondary coniferous forests in Europe. Yet to date potential effects of climate change are often only indirectly considered and climate change mitigation objectives are widely neglected in the discussion of alternative management strategies for such forest types.

Our aim in this study was to analyse how the interaction of forest management and climate may affect the C storage in a secondary coniferous forest. To capture the transient effects of a change in management as well as climate, the time horizon of the analysis extended over 100 years. Considering the time frame and ecological complexity of the task, uncertainties with regard to the current understanding of climate-management interactions require particular attention. We addressed this issue by proposing a multi-model study design, applying independent simulation models to a common set of input parameters and forcings (Badeck et al. 2001, Prisley and Mortimer 2004; see Schmid et al. (2006) for a recent example with regard to forest C storage). Requirements for models to be potentially applicable in the current study were 1) parameterization for Central European conditions (e.g. tree species); 2) sufficient physiological detail to project responses to climate change; the ability to simulate 3) multi-species stands, and 4) structured, uneven-aged management regimes. In this respect the models PICUS v1.4 (Seidl et al. 2005) and 4C (FORESEE – FOREst Ecosystems in a changing Environment, Lasch et al. 2005) were found suitable tools for this study. Both models are well evaluated and have been recently applied in studies assessing forest C storage in managed temperate forests (Fürstenau et al. 2007, Seidl et al. 2007).

As study region a Norway spruce forest management unit (FMU) in Austria was chosen. The specific objectives of our analysis were threefold: First, to evaluate the two models with available data from the study FMU. Second, to investigate forest C dynamics and storage in a simulation experiment over a set of climate scenarios and management strategies with both models. The four silvicultural alternatives analysed were 1) Norway spruce age class forestry (business as usual, MS1); 2) transition to Norway spruce continuous cover forestry (MS2); 3) conversion to mixed coniferous-deciduous forests (age-class system, MS3); and 4) an unmanaged control variant (MS4). And finally, to address uncertainties in the systems understanding of conversion effects under climate change in discussing divergences in projections of alternative simulation approaches.

2 Material and Methods

2.1 Study Site and Stand Data

The study was conducted for a FMU in the province of Carinthia, southern Austria (Lat. E14.37, Long. N46.78). The privately owned 248.7 ha FMU is situated in the submontane vegetation belt (altitude approximately 550 m asl) and has been subject to intensive management throughout the last centuries. As a result of past management practice current tree species composition is dominated by Norway spruce (*Picea abies* (L.) Karst.) and distinctly differs from the potential natural vegetation, which mainly consists of deciduous species (beech, *Fagus sylvatica* L. and oak, *Quercus robur* L., cf. Mayer 1985, Kilian et al. 1994). The current climate regime is subcontinental, and soil bedrock consists of crystalline glacial residues.

Soil conditions are primarily characterized by fertile Cambisols, covering 98.8% of the FMU (Steiner 1998). For the current analysis we focused on this soil type and distinguished two site types (ST), mainly differing with regard to soil water holding properties (ST1= high water holding capacity, ST2= medium water holding capacity, Table 1). A third site type not considered here is characterized by shallow rendzic Leptosols over calcite cliffs. Initial carbon and nitrogen pools were calculated based on laboratory analysis of soil samples which had been taken in all site types. Mineral soil properties were assumed to be constant within a site type (Table 1). Stand level forest floor C and N pools were derived by means of locally established empirical relationships using stand characteristics as explanatory variables (see Seidl et al. 2007).

Stand level inventory data of the 101 compartments of the FMU were available from Unegg (1999). Norway spruce is by far the dominating species (93% of basal area), followed by Scots pine (*Pinus sylvestris* L.) (6%) and a minor share of deciduous species (*Quercus robur*, *Acer* spp., *Salix* spp.). The age-class structure is strongly dominated by intermediate stand development stages, with only a minor share of stands older than 70 years. For the simulation the 101 compartments were aggregated to 23 stand types by means of a cluster analysis (partitional clustering, partitioning around medoids, Kaufman and Rousseeuw 1990, R Development Core Team 2006). Stands were first grouped by age-class and subsequently clustered according to the inventory estimates of mean annual increment over 100 years (MAI_{100}), stocking density (relative to yield table basal area), share of Norway spruce and basal area weighted mean diameter. A representative stand type per cluster was chosen for the simulation study. For details we refer to Seidl et al. (2007).

Table 1. Mineral soil properties of the two site types (ST). WHC = water holding capacity.

Properties	ST1	ST2
Soil type	Eutric Cambisol	Eutric Cambisol
pH (H_2O)	4.3	4.1
WHC [mm]	161	120
C [$t \cdot ha^{-1}$]	82.03	95.75
N [$t \cdot ha^{-1}$]	5.847	5.922
soil depth [cm]	80	80

2.2 Climate Scenarios

The simulation study was conducted for three climate scenarios, representing a de-trended baseline climate (CS1) and two transient climate change scenarios (CS2, CS3). The baseline climate scenario CS1 employed observed climate data for the period 1961 to 1990, interpolated from nearby weather stations of the Austrian Central Institute for Meteorology and Geodynamics. A de-trended 100 year climate series was generated from this data, forming the reference climate scenario for the study. Mean annual temperature of the baseline climate is 7.6°C, mean annual precipitation amounts to 1013 mm.

Two transient climate change scenarios, both derived from global circulation model (GCM) results and referring to the IS92a emission scenario of the IPCC (1995), were employed (time horizon 2001 to 2100): Scenario CS2 is based on ECHAM4-OPYC3 (Max-Planck-Institute for Meteorology and Deutsches Klimarechenzentrum GmbH, Hamburg, Germany, cf. Roeckner et al. 1996), climate scenario CS3 is derived from HadCM2 (Hadley Center, UK, cf. Johns et al. 1997). GCM climate parameter anomalies were spatially interpolated to the study site using Delaunay triangulation. Data were provided by the Potsdam Institute for Climate Impact Research (see Kellomäki et al. 2005). Both climate change scenarios show steady warming until the end of the 21st century (delta between first and last decade of the century CS2: +3.7°C; CS3: +3.1°C). Precipitation changes show distinct differences between the climate change scenarios: In scenario CS2 the mid-century increase in precipitation is more pronounced than in scenario CS3 (increase in mean annual precipitation for the period 2046–2060 compared to CS1: +271mm and +98mm respectively). In the second half of the 21st century precipitation levels decrease in both scenarios, with scenario CS3 resulting in a considerable drop under current levels in the last decades of the study period (change in mean annual precipitation in 2086–2100 compared to CS1: +21mm and –97mm for CS2 and CS3 respectively). Other climate drivers were assumed to have no climate change induced trend over the 21st century. A detailed description of the climate scenarios can be found in Seidl et al. (2008).

2.3 Management Strategies

Four alternative management strategies (MS1,2,3,4) were simulated. Strategy MS1 reflects current business as usual management, characterized by age-class management with a rotation period of 90 years. In this strategy Norway spruce was regenerated naturally through a shelterwood approach. A pre-commercial thinning was carried out at age 20 to control stand density. Subsequent thinnings were conducted as selective thinnings (thinnings from above).

Alternative management strategies focused on silvicultural options recently discussed in the literature and among practitioners (see Reininger 2000, Pommerening and Murphy 2004, Spiecker et al. 2004, von Teuffel et al. 2005).

Strategy MS2 represents continuous cover management. Structural thinnings (cf. Reininger 2000) were applied in young development stages in order to promote early differentiation of stand structure, followed by a transition to a target diameter harvesting regime with harvesting intervals of approximately 10 years.

Strategy MS3 aims at the conversion to mixed deciduous stands. In MS3 the rotation period of the current Norway spruce stands was reduced to 80 years and beech and oak were introduced in several conversion variants, depending on site and initial stand conditions. In total on 74.9% of the FMU area beech was underplanted in small groups below the canopy of Norway spruce, aiming at mixed stands of Norway spruce and beech. A conversion to oak by afforestation after clear cutting was implemented on 20.6% of the forest area, 4.5% were converted to pure beech stands. In addition to the three actively managed strategies a "do nothing" variant (MS4) was simulated, featuring a total abandonment of management interventions. In MS4 deadwood was left on site.

All management interventions within the strategies were specified as percent volume removals in five relative diameter classes (RDC) and were individually adapted to the conditions of each stand type. In the actively managed strategies merchantable dead trees (dbh > 10cm) were removed in the year of death, mimicking current forest protection routines. A detailed description of the management strategies is given in Seidl et

Table 2. Characterisation of the stand treatment programs in the management strategies. Removals are expressed in percent volume removed in relative diameter classes (RDC, class-width = largest dbh minus smallest dbh divided by five) from the lowest (RDC1) to the highest class (RDC5).

Management strategy	Description of intervention	Stand age, years	Removal, % volume RDC1	RDC2	RDC3	RDC4	RDC5
MS1	pre-commercial thinning	20	40	40	40	30	30
	thinning from above	40 ; 50 ; 60	–	10	10	25	15
	light thinning from below	70	–	10	10	10	5
	shelterwood cut	80	–	25	30	35	10
	clearcut	90	100	100	100	100	100
MS2	pre-commercial thinning	20	40	40	40	30	30
	structural thinning	40 ; 50 ; 60	–	10	15	30	20
	target diameter harvest	10–15 year interval	–	–	–	10	75
MS3	pre-commercial thinning	20	40	40	40	30	30
	thinning from above	40 ; 50 ; 60	–	10	10	25	15
	light thinning from below	70	–	10	10	10	5
	clearcut	80	100	100	100	100	100

al (2007), Table 2 summarizes the main features of the simulated strategies.

2.4 Simulation Models

2.4.1 The Model PICUS v1.4

PICUS v1.4 is a hybrid forest patch model combining elements of classical patch models and physiological production models. The spatial resolution is given by 10m · 10m patches extended into the third dimension by 5m crown cells. This resolution is, in contrast to classical patch models (e.g. Shugart 1984, Botkin 1993), utilized to compute a detailed three-dimensional light environment for every patch of the stand, explicitly taking interactions between patches (i.e. stand structure) into account (Lexer and Höninger 2001). Inter- and intraspecific competition among individuals is simulated following the patch model approach from Lexer and Hönninger (2001). Stand level productivity is estimated by means of a simplified model of radiation interception and light use efficiency (Landsberg and Waring 1997). In the simulation of forest growth temperature, radiation, vapour pressure deficit, soil water and nutrient supply are considered as environmental factors. Redistribution of assimilates to trees, assuming constant respiration losses (Landsberg and Waring 1997), is accomplished according to the relative competitive success of the individuals within the patch model environment. A detailed description of hybridising a patch model with a stand level production model is given in Seidl et al. (2005). Regeneration and mortality are retained from the gap model approach of Lexer and Hönninger (2001).

PICUS v1.4 simulates closed carbon and nitrogen cycles in forest ecosystems by integrating a process model of soil dynamics into its simulation environment. The soil submodule builds on concepts and algorithms presented by Currie et al. (1999) and Currie and Nadelhoffer (1999), simulating C and N dynamics in the forest floor and mineral soil. Humification of foliar, root and woody litter contributes to slow-turnover humus pools. Soil organic C and N pools are simulated as microbal-detrital pools containing microbal biomass implicitly. Soil N transformations, leaching, and plant uptake of NH_4^+ and NO_3^- are simulated separately with soil N availability exerting a strong feedback on plant production. More information on the simulated soil processes can be found in Moorhead et al. (1999) and Currie et al (2004); Seidl et al. (2007) give a more detailed description with regard to the incorporation in PICUS.

PICUS contains a flexible management module allowing for harvesting interventions as well as planting operations on the level of individual trees. The time-step of the simulation is monthly with annual integration. The model has been tested against growth and yield data (Seidl et al. 2005), confirming the ability of the model to simulate managed, structured multi-species stands. Long-term simulations of potential natural species composition (PNV) over an extended ecological gradient in the eastern Alps revealed good agreement with expert assessments of PNV. In addition, the climate response of the model was compared against a detailed process model of forest production and found highly plausible (Lindner et al. 2005, Seidl et al. 2005). Recent applications include an assessment of silvicultural options under climate change (Kellomäki and Leinonen 2005) as well as the analysis of the trade-offs between carbon sequestration and other forest functions under climate change at the forest management unit level with particular consideration of biotic disturbances (Seidl et al. 2007, 2008).

2.4.2 The Model 4C

The model 4C ('FORESEE' – Forest Ecosystems in a Changing Environment) has been developed to investigate long-term forest behaviour under changing environmental conditions (Bugmann et al. 1997, Schaber et al. 1999). It describes processes on tree and stand level based on findings from eco-physiological experiments (e.g. Medlyn and Jarvis 1999), investigations of tree growth and architecture (e.g. Burger 1948), and physiological modelling (e.g. Haxeltine and Prentice 1996). The model simulates tree species composition, forest structure, leaf area index, as well as ecosystem carbon and water balance. Establishment, growth and mortality of tree cohorts are explicitly modelled on individual patches, on which horizontal homogeneity is assumed. Start and end of the vegetation period are estimated as functions of air temperature and day length (Schaber and Badeck 2003). A mechanistic formulation of net photosynthesis as a function of environmental factors (temperature, water and nitrogen availability, radiation, and CO_2) is used, where the physiological capacity is calculated based on optimisation theory (modified after Haxeltine and Prentice 1996). The calculation of total tree respiration follows the concept of constant annual respiration fraction as proposed by Landsberg and Waring (1997). The allocation patterns are modelled with a combination of pipe model theory (Shinozaki et al. 1964), the functional balance hypothesis (Davidson 1969), and several allometric relationships extended to respond dynamically to water and nutrient limitations. Mortality is caused by stress due to negative leaf mass increment in a number of successive years.

The soil model of 4C consists of a water, temperature, and C/N sub-model (Grote et al. 1999). Following the soil horizons (organic layer and mineral soil horizons) the soil is divided into layers of varying thickness. The physical and chemical soil parameters and the initial C and N pools, as sum of soil organic matter and dead organic matter (litter), are determined either from measurements or from profile information available for soil maps. The C and N dynamics are driven by litter input, which is separated into five fractions (stems, twigs and branches, foliage, fine roots and coarse roots) for each species type. The turnover of all litter fractions and of the soil organic matter compartment is described as first order reaction kinetics (Grote et al. 1999). The processes are controlled by litter type and species-specific reaction coefficients and modified by soil moisture, temperature and pH value. Reaction coefficients of the soil organic matter, and the five litter fractions of the considered species are derived from the literature. Its performance was analysed and compared successfully with ROMUL, RothC, and Yasso in the framework of a soil model comparison study (Thürig et al. 2008).

Currently the model is parameterised for the six most abundant tree species of Central Europe (beech, Norway spruce, Scots pine, sessile oak (*Quercus robur* L.), common oak (*Qercus petraea* Liebl.), and birch (*Betula pendula* Roth)). With 4C, the management of mono- and mixed species forests can be simulated. For this purpose, a number of thinning, harvesting, and regeneration strategies are implemented, including changes in species composition.

The model has been evaluated for different forest stands in Germany with short-term data of water budgets (Suckow et al. 2001) and long-term stand growth data (Lasch et al. 2005). Moreover, 4C has been applied in several climate change

Table 3. The main features of simulation models PICUS v1.41 and 4C.

Properties	PICUS v1.41	4C
MAIN MODEL FEATURES		
Objectives	Dynamic forest succession, long-term simulations, climate change impacts, various management regimes, disturbances	Dynamic forest growth, long-term simulations, climate change impacts, includes water dynamic, various management regimes
Management options	Thinning, harvest, planting (all on individual tree level), natural regeneration, nitrogen fertilization	Thinning, harvest, planting (all on cohort level), natural regeneration, nitrogen fertilisation
SYSTEM STRUCTURE (ECOSYSTEM)		
Stand structure	Individual trees, multi-species systems, multi-layered systems	Average tree cohorts, multi-species systems, multi-layered systems
Tree structure	Crown, foliage, stem, roots	Crown, foliage, stem, roots
Soil structure	2 layers (forest floor, mineral soil), C-compartments, organic matter	Multiple layers, C-compartments, organic matter, texture
Water balance	Precipitation (liquid, solid), interception, evaporation, transpiration	Precipitation (liquid, solid), interception, evaporation, transpiration, infiltration, runoff
MODEL STRUCTURE (TYPE, SPATIAL AND TEMPORAL RESOLUTION, DRIVING VARIABLES)		
Model type	Hybrid patch model, stochastic	Mechanistic model, deterministic
Ecosystem	Temperate, alpine, Central European	Temperate, Central European
Spatial resolution	Patch/tree	Stand/cohort
Timestep	Month (primary production, soil), year (structural variables)	Day (phenology, soil), week (photosynthesis, respiration), year (structural variables)
Environment – atmosphere	Temperature, precipitation, radiation, vapor pressure deficit, nitrogen deposition	Temperature, precipitation, radiation, humidity, wind speed, CO_2-concentration
Environment – soil	Soil water availability, AET, nitrogen availability, carbon content, pH-value	Soil water availability, soil moisture, temperature, nitrogen availability, carbon content, pH-value
FUNCTIONING OF THE MODEL (DESCRIPTION OF MAIN PRECESSES)		
Photosynthesis	3-PG approach (Landsberg and Waring 1997)	Farquhar biochemical model (Farquhar et al. 1980)
Autotrophic respiration	Fixed ratio	Growth respiration as fraction of growth, maintenance respiration
Tree mortality	Dynamic (environment, density, age), bark beetle-induced (*Ips typographus*)	Dynamic (environment, density, age)
Heterotrophic losses soil	Dynamic (AET, litter quality)	Dynamic (soil temperature, soil water, litter quality)
MODEL PARAMETERS AND EVALUATION		
Parameters	Literature, national forest inventory	Literature
Evaluation	Lexer and Hönninger (2001, 2004), Seidl et al. (2005)	Mäkelä et al. (2000), Sievänen et al. (2000), Lasch et al. (2002)

impact assessments (Lasch et al. 2002, Gerstengarbe et al. 2003) as well as in a study on climate sensitivity (Lindner et al. 2005) and an assessment of climate change impacts on forest management (Kellomäki and Leinonen 2005, Fürstenau et al. 2007).

The main features of the two models applied in this study are compared in Table 3, following the structure proposed by Freeman et al. (2005). A common sensitivity analysis of PICUS and 4C with regard to management and climate drivers can be found in Lindner et al. (2005).

2.5 Study Design and Analysis

2.5.1 Model Evaluation under Current Climate

The performance of the models was evaluated with regard to two key C cycle variables. Observed Norway spruce stemwood productivity, a proxy for total aboveground biomass productivity, was compared to simulations at the level of site types. Observations were derived from mean annual stemwood increment data (MAI_{100}) from yield tables (Marschall 1975) based on observed dominant height and stand age (Unegg 1999). Since a strong age trend in MAI_{100} was detected within the site types (compare Spiecker et al. 1996), a linearly de-trended record of MAI_{100} was employed. MAI_{100} was converted to stem carbon productivity applying a species specific gross biomass density, shrinkage percentage and C content (cf. Weiss et al. 2000). Corresponding model simulations were designed for compliance with the underlying yield table concept: For every site type a mono-species stand of Norway spruce was simulated over 100 years (initial age 10 years) with regular light thinnings from below.

Forest floor C is the soil C pool most sensitive to changes in management and productivity (cf. Jandl et al. 2007) and was thus a focus in evaluating model performance. In the absence of disturbances (e.g. extractive activities as litter raking, cf. Prietzel und Kaiser 2005, Prietzel et al. 2006) empirical studies have found stand structure and development stage to have the strongest influence on forest floor C (e.g. Sogn et al. 1999, Böttcher and Springob 2001, Jandl et al. 2007). Since the time horizon of the study covers approximately a rotation period under business as usual management (MS1), the age structure of the FMU after the 100 year simulation period is comparable to the initial conditions. Furthermore, no litter raking was reported for the FMU (Forsteinrichtung Kleinszig 1949, 1960). Thus we tested the hypothesis that the forest floor C pools at the end of the study period (current climate CS1, MS1) do not differ from the values of the initial soil inventory.

Considering the strong influence of structural traits on forest floor C pools potential changes in stand structure over the study period need to be accounted for in such comparison. Thus locally established empirical relationships between stand basal area and the forest floor (cf. Seidl et al. 2007) were employed to update forest floor C pools according to the model-projected stand structure at the end of the study period. The dynamically simulated forest floor C estimates of PICUS and 4C were subsequently tested against this static update.

2.5.2 Scenario Analysis

In relation to climate change mitigation the main target variable of the analysis was in situ net C stock change over the study period. Analysed C pools were stem-, branch-, leaf- and standing deadwood carbon (subsumed as aboveground C pools) as well as root-, mineral soil, forest floor and downed deadwood C pools (henceforward referred to as belowground C pools). Correspondence between the two dynamic models was assessed by a pair-wise comparison at stand level for every combination of climate scenario and management strategy (Wilcoxon signed rank sum test). For strategies with significant divergence between the models we further investigated the source of deviation by resolving simulated C stock changes into above- and belowground compartments. Equal weights were applied in the analysis of the 23 simulated stand types (i.e. neglecting their spatial representation in the FMU) in order to omit weighting-effects in the interpretation of differences. The median over all FMU stand types is reported except where stated otherwise.

Climate change impacts were, in addition to C stock changes, analysed with regard to effects on stem C productivity in order to resolve climate sensitivities at a finer scale. Finally, potential interactions between factors influencing C storage (i.e. climate scenario, management strategy) were tested by means of a generalized linear model with first order interactions (GLM, function: glm( ), error distribution: gaussian, link: identity, contrasts: contr.treatment, R Development Core Team 2006). For the GLM in Eq. 1,

$$\Delta C_{ijk} = \mu + MS_i + CS_j + Mod_k + (MS \cdot CS)_{ij} + (MS \cdot Mod)_{ik} + (CS \cdot Mod)_{jk} + (MS \cdot CS \cdot Mod)_{ijk} + \varepsilon_{ijk} \quad (1)$$

containing the factors management (MS_i, $i=1$–4), climate (CS_j, $j=1$–3) and model (Mod_k, $k=$PICUS, 4C) as well as their interaction terms as explanatory variables, an analysis of variance (ANOVA) of net C stock changes (ΔC_{ijk}) over all stand level simulations was conducted.

3 Results

3.1 Model Evaluation under Current Climate

Simulated Norway spruce stem C productivity compared well to the observed values for ST2, the site type holding the largest share of the FMU (see Fig. 1). On the more fertile site type ST1 both models predicted lower productivities than the observed average, but only 4C exceeded the confidence interval of the observations (–16.1% compared to the observed mean stem C productivity).

Both models projected a slight increase in forest floor C stocks over the 100 year simulation period (Table 4) under current climate (CS1) and business as usual management (MS1). Compared to the initial soil inventory increases were significant for PICUS only ($p=0.0307$; 4C: $p=0.112$). Reviewing the statically updated forest floor C based on local empirical relationships showed that simulated stand structure is contributing to this accumulation. Testing the dynamic simulation results against the static updates revealed no significant differences for both PICUS and 4C (Table 4). Consequently the process-based soil modules of PICUS and 4C realistically captured the interactions between stand structure and forest floor C as represented in the local empirical model.

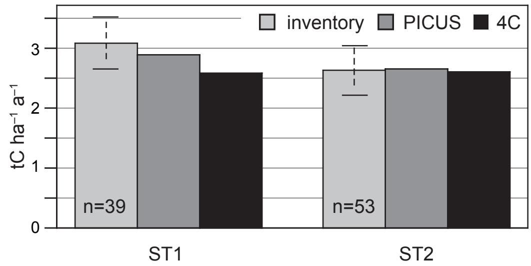

Fig. 1. Simulated mean annual stem C productivity for Norway spruce on the two site types (ST) of the forest management unit, compared to inventory estimates. For the inventory records, the number of stands (n) and the corresponding 95% confidence interval are indicated.

3.2 Scenario Analysis

3.2.1 C Cycle Effects under Current Climate

Under the baseline management regime (MS1) and current climate the FMU carbon budget was approximately balanced. Both models agreed remarkably well on this finding with no significant differences in the pairwise comparison ($\alpha=0.05$). The transition to continuous cover forestry as simulated in strategy MS2 resulted in a decrease in harvest level compared to MS1 (PICUS: –9.6%, 4C: –7.5%) but also in structural changes of standing stock and harvest (i.e. target diameter harvesting replacing shelterwood age-class management). Ultimately MS2 resulted in increased average standing volume (PICUS: +70.9%, 4C: +70.4%) and positive net C stock changes compared to MS1 (see Fig. 2, lower panels). A pairwise comparison of stand level results between PICUS and 4C indicated no significant differences ($\alpha = 0.05$) in the projection of the C response to these structural changes.

In contrast to MS2 the main differences between MS3 and the business as usual management were in tree species composition instead of vertical stand structure. Under current climate MS3 resulted in a share of deciduous species of 23.9% and 22.0% (percent of total standing stock) after 100 years in PICUS and 4C respectively. The net C stock changes in MS3 were smaller than in MS2 for both models, with PICUS and 4C predicting contrasting trends in C stocks (significant at $\alpha = 0.05$). While PICUS simulated an increase in C storage after 100 years (+29.4 $tC \cdot ha^{-1}$), 4C estimated moderate C losses (–10.6 $tC \cdot ha^{-1}$). Both models agreed on an increase in mean belowground C stocks in MS3. However, effects were stronger in PICUS (mean belowground C stock change +24.5 $tC \cdot ha^{-1}$) compared to 4C (+4.6 $tC \cdot ha^{-1}$). Aboveground C stocks increased

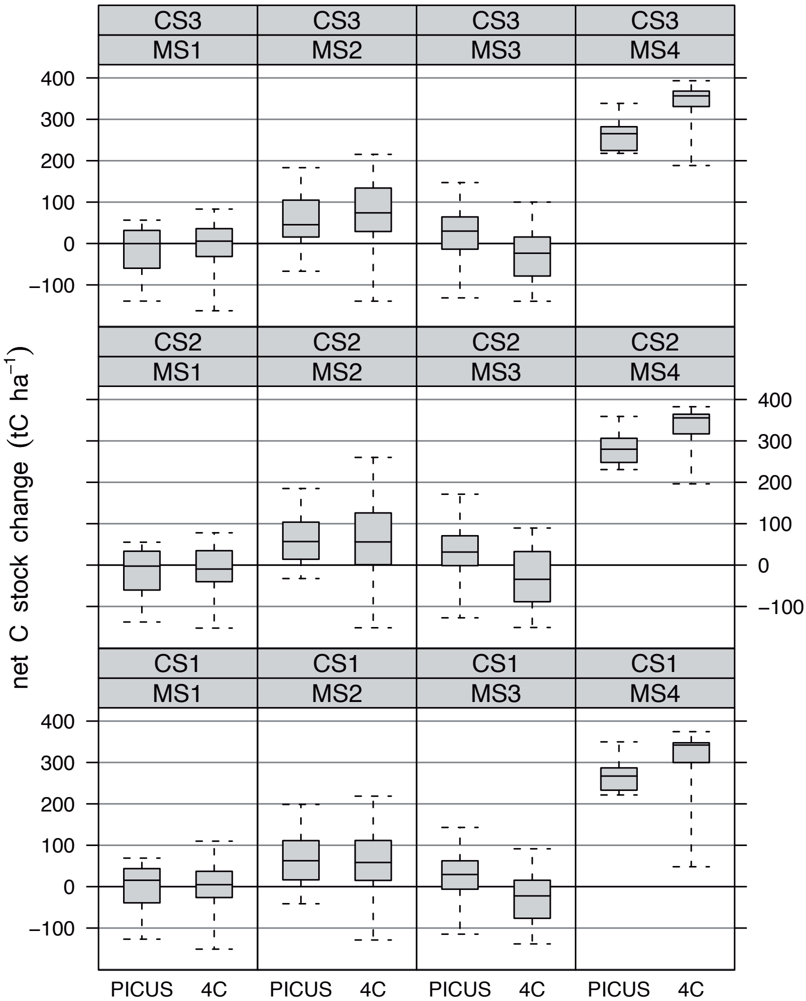

Fig. 2. Net C stock changes over the 100 year simulation period for the 23 stand types of the forest management unit, simulated with the models PICUS and 4C. Rows denote the climate scenarios (CS1–CS3), columns the management strategies (MS1–MS4). Boxes indicate the interquartile range, whiskers extend to the most extreme data point, the central line represents the median value.

slightly in the projections with PICUS while a loss was estimated by 4C (–20.8 $tC \cdot ha^{-1}$).

Overall, the largest positive C cycle effects were simulated under the unmanaged variant MS4. Although this ranking was consistently retained by both models 4C predicted significantly higher C stock increases than PICUS. Both above (PICUS: +229.5 $tC \cdot ha^{-1}$, 4C: +278.8 $tC \cdot ha^{-1}$) and belowground (PICUS: +34.0 $tC \cdot ha^{-1}$, 4C: +60.1 $tC \cdot ha^{-1}$) pools accumulated C in MS4. The most distinct differences between the models were found with regard to deadwood pools: The average deadwood pool (standing + downed deadwood) at the end of the simulation amounted to 15.8 $tC \cdot ha^{-1}$ in PICUS, whereas 4C predicted 111.9 $tC \cdot ha^{-1}$ stored in deadwood.

Table 4. Evaluation of forest floor carbon pools [t C · ha^{-1}] for the FMU. The results of the dynamic simulation experiment over 100 years under current climate and business as usual management (dynamic model) were compared to the initial values of the soil inventory as well as to a static update of forest floor C with empirical relationships based on simulated stand structure (Wilcoxen rank sum tests, * = significant; n.s. = not significant; significance level α = 0.05; sd: standard deviation).

Estimate	Year	PICUS		4C	
		mean	sd	mean	sd
Dynamic model	100	35.5	±6.4	36.3	±11.9
Inventory	1	29.0	±9.5 *	29.0	±9.5 n.s.
Static update	100	33.9	±8.4 n.s.	32.0	±10.0 n.s.

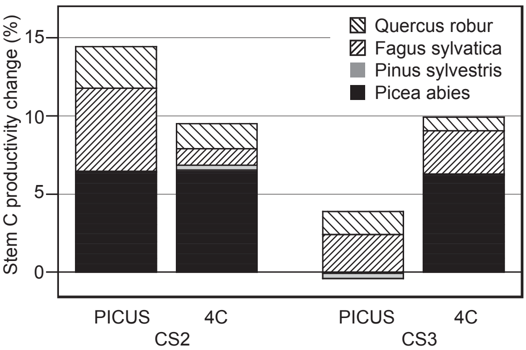

Fig. 3. Mean stem C productivity change relative to current climate (CS1) in the climate change scenarios (CS2, CS3) for the conversion strategy MS3. Bar-compartments indicate the contributions of tree species to the average productivity change over all simulated stand types.

3.2.2 Climate Change Impacts and Interactions with Management

The climate change scenarios had a distinct impact on stem C productivity in both models. In PICUS, the combined effect of higher temperatures and decreasing precipitation in scenario CS3 reduced Norway spruce stem C productivity in all management strategies (–0.5% to –3.4%), whereas scenario CS2 (higher temperatures, increased precipitation) enhanced productivity (+8.2% to +9.3%). With the model 4C productivity benefited from climate change in both scenarios (+8.0% to +17.7% compared to CS1). For the conversion strategy MS3 the introduced deciduous tree species showed a remarkably high contribution to the climate-induced overall increases in productivity despite their relatively limited share on total stocking (Fig. 3).

However, effects of changing productivities on C stocks were largely offset by simultaneously increasing harvest levels (up to 11.6% and 12.4% under CS2 in PICUS and 4C respectively). Climate change scenarios did not alter the ranking of management strategies with regard to net C cycle effects compared to results under current climate (PICUS: MS4 > MS2 > MS3 > MS1; 4C: MS4 > MS2 > MS1 > MS3). No significant interaction between management and climate (*CS·MS*) was found in the ANOVA of the GLM (Eq. 1). In PICUS the warmer and drier scenario CS3 reduced C storage over all management regimes (median –7.6 tC · ha^{-1} compared to CS1) while scenario CS2 resulted in a slightly positive effect (median +2.0 tC · ha^{-1}). Simulations with the model 4C suggested a reversed pattern of the same magnitude, with CS3 being the more favourable climate change scenario (see also Fig. 2). However, a pairwise test of simulated stand level responses to the climate change scenarios relative to CS1 did not reveal significant differences between the models. Moreover, scrutinizing climate response in the ANOVA no significant divergence in climate response pattern of PICUS and 4C could be found. Both the overall interaction model × climate (*CS·Mod*) and the individual coefficients were not significant at α=0.05. Nonetheless, the main effect of the factor model and the interaction between the factors model and management (*MS·Mod*) were found significant and underline the differences between the models as discussed in Section 3.2.1 (significant coefficients of the interaction *MS·Mod* for strategies MS3 and MS4).

4 Discussion and Conclusion

4.1 Model Evaluation

Both models had been successfully scrutinized in designated model evaluation experiments prior to this study (compare Table 3). Considering that for the current work no site specific calibration had been carried out, the comparison of simulated stemwood productivity with local data confirmed the general applicability of the models. Although homogeneous climatic conditions were assumed for the whole study FMU, PICUS was able to reproduce the observed gradient between the two site types realistically whereas 4C predicted similar productivities for both site types. This finding points at higher sensitivity of PICUS with regard to water availability, since the site types differed mainly with regard to soil water holding capacity (see also discussion on sensitivity to climate change in Section 4.3 below).

Simulated forest floor C stocks at the end of the 100 year simulation period were moderately higher than current observations. Since forest floor C pools are strongly driven by stand structure and management (cf. Jandl et al. 2007) it was analyzed whether this response was consistent with the simulated stand structure. The findings confirmed the ability of the models to reproduce the present forest floor dynamics. It is noteworthy that both models agreed remarkably well with regard to the forest floor C pools and that the observed variability between the stand types was reproduced well over the 100 year simulation period.

Overall, reviewing two key ecosystem processes of high sensitivity, the model evaluation experiments for the study FMU revealed satisfactorily results. Notwithstanding the value of further evaluation – particularly as detailed C inventories (i.e. C compartments, time series) become available in the future – the eligibility of PICUS and 4C for a scenario analysis of C cycle effects could not be rejected based on the currently available data.

4.2 C Cycle Implications of Management Alternatives

The study showed that a transition to continuous cover forestry has considerable potential with regard to increased C storage in the forest ecosystem. This finding is remarkably robust in both simulation models, considering the structural complexity of multi-layered, uneven-aged stands. It confirms the results of recent studies that found continuous cover forestry to be an efficient strategy to achieving multiple goals of SFM (e.g. Seidl et al. 2007). However, the continuous cover forestry variant simulated in this study may also be prone to increased risk from disturbances due to high accumulated standing stock levels (cf. Seidl et al. 2008). Nonetheless, positive C cycle effects of a continuous forest cover would be retained even at substantially lower average stocking levels.

Disturbances, not considered in this study, may also strongly affect the C stock increase in the unmanaged variant (MS4). Although representing the strongest positive C cycle effect among the analysed strategies, MS4 has to be seen as an ecological reference run in the context of this study. A total abandonment of management would fail to fulfil the increasing demands on forests under the umbrella of SFM, especially in areas of intensive land use and resource demands as in Central Europe. While both models agreed on a strong in situ C stock increase resulting from total abandonment of management, significant differences between the absolute levels were detected. The considerably higher net C stock changes simulated by 4C under MS4 appeared to be mainly an effect of differences in deadwood dynamics. The average amount of deadwood C over all unmanaged runs in the model 4C was more than six times higher than in PICUS. Diverging snag dynamics (e.g. simulating the process from standing to downed dead wood) and differences in deadwood decomposition in the soil pools were the main processes contributing to this difference in the models. This points at future research needs with regard to the representation of deadwood dynamics in the models (compare Rock 2007).

The introduction of deciduous tree species within an age class management regime (MS3) showed only a moderate response of forest C stocks in both models. PICUS and 4C projected contrasting results on the direction of C stock response to MS3. This is particularly interesting since the models showed good agreement in the prediction of C stock development under the current management regime (MS1), and stand treatment programs in MS1 and MS3, apart from tree species composition, differed only slightly. Nonetheless, simulated dynamics of both above- and belowground ecosystem compartments diverged in the models, revealing considerable uncertainty in the effects of tree species change. While a detailed analysis of model equations to track down these differences was beyond the scope of this contribution a review of empirical evidence from other studies highlights the considerable complexities in tree species change effects on C storage. Scarascia-Mugnozza et al. (2000), for instance, found higher carbon stocks in beech forests compared to Norway spruce over a latitudinal transect of paired experimental plots (spruce and beech) in Europe. However, the authors stressed the different management histories of the compared sites which might limit comparability. Berger et al. (2002) investigated soil C stocks in pure Norway spruce stands and adjacent mixed stands of Norway spruce and beech. Their findings range from no significant differences to higher C stocks in pure Norway spruce stands, differing with bedrock material. Koch and Makeschin (2004) investigated a conversion transect consisting of conifer (Norway spruce and Scots pine) stands, coniferous stands with underplanting of beech and oak, and pure deciduous stands. They reported increasing soil organic layer thickness and total soil organic carbon stocks along this conversion sequence at lowland sites. Furthermore, Koch and Makeschin (2004) emphasized the influence of stand structure on soil organic carbon storage, finding higher C stocks in the two-storied stands of the conversion phase.

4.3 Interactions with Climate Change

Although the studied climate change scenarios had a distinct influence on stem C productivity, FMU C stock changes were found to be relatively insensitive to climatic changes as represented by CS2 and CS3. One reason for this insensitivity of C stocks were increased respiratory losses in response to rising temperatures, due to which improved growing conditions (e.g. longer vegetation period) did not result in proportionally increased ecosystem C stocks. However, an additional aspect that needs to be highlighted is the level and fate of C removals by harvest interventions. Harvest intensities were defined relative to the respective standing volume (silvicultural harvest level), aiming at high operational realism in the design of the management strategies, but potentially dampening the in situ C stock changes. Furthermore, wood products constitute a considerable C pool (cf. Karjalainen et al. 1994, Pingoud et al. 2001). Thus, notwithstanding the Kyoto-perspective (restriction to in situ changes) adopted in this study, management decisions might influence both the quantity (e.g. harvest level) and structure (e.g. harvested assortments, timber utilization and life-spans) of C storage in wood products. Furthermore it has to be noted that potential climate-induced changes in the disturbance regime (e.g. bark beetle disturbances) and related impacts on forest C stocks (cf. Seidl et al. 2008) have not been addressed in this study.

Simulated climate change responses in this study were generally in line with the results of Lindner et al. (2005), performing an in-depth review of climate sensitivity for five different models including PICUS and 4C. Whereas the general climate response pattern and magnitude was comparable, Lindner et al. (2005) found a stronger sensitivity to combined changes in precipitation and temperature in PICUS compared to 4C. In this study simulated stem C productivity changes were in the same order of magnitude for both models with PICUS predicting a stronger response to decreased precipitation levels in CS3 than 4C. However, with regard to C stock changes no significant climate × model interaction (i.e. diverging climate response of the models) was found in the analysis. This underlines the robustness of the predictions under the investigated transient climate change scenarios with regard to the scope of this study.

4.4 Conclusions

Alternative management options for the vast areas of secondary coniferous forests in Central Europe are a matter of intensive debate, inter alia to reduce vulnerabilities to future climate change. Since productivity in these forests is generally high and forest infrastructure supports intensive management, such sites may be in a focal point of conflicting management interests in the future. Thus in promoting targeted management change the full range of forest services, including climate change mitigation, should be addressed. This study demonstrated that generic alternative management strategies, as for instance continuous cover forestry, have the potential to positively affect in situ carbon storage. It, however, also highlighted remaining limitations in understanding the effects of simultaneous transitions in management and climate, particularly in mixed and unmanaged forest ecosystems.

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