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Carbon budget of Swiss forests: evaluation and application of empirical models for assessing future management impacts

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Table of contents

Summary

Forests play an important role in the global cycle of carbon. As negotiated in the Kyoto Protocol (Article 3.4), managed forests can be included in the national carbon budgets. However, there is insufficient knowledge on the future long-term development of carbon storage in forests under different management scenarios and the time span for which forests might act as carbon sinks. The present study focused on these issues using Switzerland as a case study.

The aim of this thesis was (1) to evaluate and apply two empirical forest models and a soil carbon model to assess the mid- to long-term (50-100 years) development of the above- and belowground carbon pools in forests, (2) to assess the influence of forest management and windthrow on the carbon budget, and (3) to compare projections of carbon pools and fluxes for the 21st century as obtained from the different models under the assumption that the environmental conditions would remain constant. To assess the aboveground carbon budget, the models MASSIMO and EFISCEN were selected, while the belowground carbon budget was estimated by linking the soil carbon model YASSO to the model MASSIMO.

In chapter I, the individual-based forest growth model MASSIMO that had been derived from the Swiss National Forest Inventories (NFI) I and II was evaluated with independent data. MASSIMO was found to predict the basal area increment fairly accurately, with some differences in the projections of the larger tree dimensions due to the low precision of input variables such as stand age. These variables should either be omitted from the model, or be estimated more precisely.

In chapter II, the large-scale matrix (volume/stand-age classes) model EFISCEN was evaluated. This study indicated that the model accurately estimated the growing stock for the entire study region in Switzerland. However, within that region major differences occurred mainly with respect to the spatial distribution of the harvesting amount, the mortality and the age class distribution. Moreover, the management practices common in Switzerland and especially in the Alpine region could not be represented by EFISCEN because the options for implementing management in EFISCEN did not offer enough flexibility. Therefore, EFISCEN was not used in the model comparison of chapter IV.

Chapter III deals with the application of MASSIMO linked to the soil carbon model YASSO for assessing the impacts of windthrow and management on the carbon budget for the next 40 years. Specifically, the effect of clearing after windthrow on the soil carbon amount was investigated. The validation of YASSO showed that measured soil carbon values were fairly accurately reproduced. Assuming a "business as usual" forest management scenario with a slightly increased harvesting amount (111% of current harvesting amount) and a moderate storm frequency of 15 years, the annual increase of aboveground carbon stock, averaged over the 40 simulation years, were estimated at 135 g m^{-2} yr^{-1}, and the increase of the belowground carbon stock was estimated at 20 g m^{-2} yr^{-1} with clearing after a windthrow and 27 m^{-2} yr^{-1} without.

In chapter IV, MASSIMO as linked to YASSO and the process-based, ecophysiological model Biome-BGC (partner PhD thesis by Stéphanie Schmid, in prep.) were applied to assess the influence of different management practices as well as different model assumptions on projections of future carbon storage in selected Swiss forests areas. The results indicated that the carbon fluxes estimated by the two models had very similar dynamics, thus enhancing our confidence in the projections. According to the models, in the absence of large-scale disturbances forest biomass and soil carbon could be increased and Swiss forests could therefore be used as carbon sinks. The sinks were estimated to last for approximately 80-100 years. Differences between results under the different management practices are due to the different time periods for which carbon sequestration is aimed to be maximized: the increase of the carbon stock can be maximized either at the short (30-40 years) or the long term (100 years or more). Although the dynamics of the fluxes were similar, the carbon pools projected by the models differed somewhat, and these differences can be attributed to model-specific responses to the strongly heterogeneous Swiss climatic conditions and to different model assumptions.

This thesis shows that the management regime maximizing carbon pools or fluxes depends strongly on site conditions such as soil quality or growth conditions and the initial situation. In the case of poor soil conditions with a high biomass as in the Alps, the loss of biomass and carbon sequestration due to harvesting of old trees may not be compensated by the enhanced growth of the remaining forest for a long time. In the Plateau, however, where growth conditions are much more favourable, it may be more advantageous to keep forests in a state of maximum increment and to use the harvest either for long-lived construction purposes or to substitute fossil fuels. To optimize the strategy for climate protection rather than maximum C sequestration alone, it would be quite important to take into account wood products and especially the substitution of fossil fuels in the assessment.

If models are to simulate the influence of forest management on future carbon pools and fluxes in a realistic way, they should include information about tree species and stand structure. The empirical individual-based forest model used in this thesis contains such structural information and was therefore suitable for this research. The drawback of empirical models, however, is that they are often based on parameter constancy rather than mechanism constancy, contrary to process models. Consequently, empirical models cannot usually be used to assess the impacts of changing environmental conditions such as temperature, precipitation, atmospheric CO_2 and nitrogen concentration, which are likely to have a crucial influence on future carbon storage.

Assessing the potential of Swiss forests to act as a carbon sink/source depends on which carbon stocks are accounted for under the Kyoto Protocol. If a so-called "full accounting

system" was applied, changes in carbon sequestration since 1990 of almost the entire Swiss forest area would be counted as sinks or sources. Extrapolating the results from chapter III to the productive forest area of approximately 8,000 km^2 would result in an annual carbon sequestration of 1.24 Mt C. This sink effect would be expected to last for the next 50-80 years. However, if the so-called "partial accounting system" was applied, the carbon fluxes would be much smaller.

Although the models were found to be useful for predicting future forest carbon development, uncertainties still remain. Each biotic sink has an upper limit as indicated in chapter IV, and therefore no biotic sink offers a sustainable solution to the CO_2 problem, but it just forms an interim strategy for the coming decades during which solutions for reducing human CO_2 emissions have to be developed and implemented.

Zusammenfassung

Die Wälder spielen im globalen Kohlenstoffkreislauf eine bedeutende Rolle. Gemäss Kyoto Protokoll (Artikel 3.4) können bewirtschaftete Wälder zu einem gewissen Teil dem nationalen Kohlenstoffhaushalt als Senken/Quellen angerechnet werden. Die langfristige Entwicklung des Waldes als Kohlenstoffsenke, abhängig von verschiedenen Waldbewirtschaftungsszenarien, ist jedoch weitgehend unbekannt.

Ziel dieser Dissertation war es, (1) zwei empirische Waldmodelle und ein Boden-Kohlenstoffmodell zu evaluieren und anzuwenden, um die mittel- sowie die langfristige (50-100 Jahre) Entwicklung über- und unterirdischer Kohlenstoffspeicher abzuschätzen, (2) den Einfluss von Waldbewirtschaftung und Windwurf abzuschätzen sowie (3) Kohlenstoffreservoirs und -flüsse verschiedener Modelle für das 21. Jahrhundert zu vergleichen. Für alle Abschätzungen wurden die Klimabedingungen als konstant angenommen. Um den oberirdischen Kohlenstoffhaushalt abzuschätzen, wurden die Modelle MASSIMO und EFISCEN ausgewählt, der unterirdische Kohlenstoffhaushalt wurde mit dem Bodenmodell YASSO, verbunden mit MASSIMO, abgeschätzt.

In Kapitel I wurde das empirische, individuenbasierte Waldwachstumsmodell MASSIMO, welches vom Schweizerischen Landesforstinventar (LFI) abgeleitet ist, anhand von unabhängigen Daten evaluiert. Es konnte gezeigt werden, dass MASSIMO gute Resultate für den Basalflächenzuwachs lieferte, wobei Differenzen hauptsächlich beim Schätzen der dickeren Bäume aufgrund ungenauer erklärender Variablen, wie zum Beispiel des Bestandesalters, entstanden. Diese Variablen sollen für das Modell entweder nicht verwendet oder präziser geschätzt werden.

In Kapitel II wurde das grossflächige Matrixmodell (Alters-Volumen Klassen) EFISCEN evaluiert. Diese Studie zeigte, dass das Modell den Holzvorrat für die ganze Studienregion in der Schweiz gut schätzen konnte. Innerhalb verschiedener Regionen zeigten sich jedoch Unterschiede zwischen dem gemessenen und dem modellierten Vorrat. Insbesondere wurden Unterschiede bezüglich der räumlichen Verteilung der Erntemengen, der Mortalitäten sowie der Altersklassenverteilung gefunden. Zusätzlich ergaben sich Probleme bei der Implementierung der Waldbewirtschaftungen, welche in der Schweiz und vor allem in den Alpenregionen angewendet werden, weil die Bewirtschaftungstools in EFISCEN nicht genügend flexibel sind. Aus diesen Gründen wurde EFSCEN im Modellvergleich von Kapitel IV nicht berücksichtigt.

In Kapitel III wurde MASSIMO mit dem Bodenkohlenstoffmodell YASSO verbunden, um den Einfluss von Windwurf und Waldbewirtschaftung auf den Kohlenstoffhaushalt der nächsten 40 Jahre abzuschätzen. Im Besonderen wurde auch der Einfluss von Räumungen nach einem Windwurf untersucht. Die Validierung von YASSO zeigte, dass gemessene

Bodenkohlenstoffwerte ziemlich genau vorausgesagt werden konnten. Es wurde geschätzt, dass bei heutiger Waldbewirtschaftung mit leicht erhöhter Erntemenge (111% der heutigen Menge) und einer geringen Sturmwahrscheinlichkeit (ca. alle 15 Jahre), die über die nächsten 40 Jahre gemittelte Zunahme des oberirdischen Kohlenstoffs 135 g m^{-2} a^{-1} beträgt. Für die unterirdischen Kohlenstoffmengen wurde die jährliche Zunahme auf 20 g m^{-2} a^{-1} bei Räumung, respektive 27 g m^{-2} a^{-1} ohne Räumung des Sturmholzes nach Windwurf, geschätzt.

In Kapitel IV wurden die Modelle MASSIMO/YASSO und das prozessbasierte, ökophysiologische Modell Biome-BGC (Partner Dissertation von Stéphanie Schmid, in Vorbereitung) verwendet, um den Einfluss verschiedener Waldbewirtschaftungen sowie verschiedener Modelle auf die zukünftige Kohlenstoffspeicherung in ausgewählten Schweizer Waldbeständen abzuschätzen. Die von den beiden Modellen prognostizierten Kohlenstoffflüsse wiesen sehr ähnliche Verläufe auf, was das Vertrauen in die Modellschätzungen stärkt. Aus beiden Modellen resultierte, dass, falls grossflächige Störungen ausbleiben, die Schweizer Kohlenstoffspeicher weiter ansteigen und die Wälder somit als Kohlenstoffsenken genutzt werden können. Die zeitliche Dauer der Senkenwirkung wird auf circa 80-100 Jahre geschätzt. Die unterschiedlichen Resultate bezüglich verschiedener Waldbewirtschaftungen können durch die unterschiedlichen Zeiträume, für welche die Kohlenstoffeinlagerung maximiert werden soll, erklärt werden: Die Kohlenstoffmenge im Wald kann entweder kurz- (30-40 Jahre) oder langfristig (100 Jahre oder mehr) maximiert werden. Obwohl der prognostizierte Verlauf der Kohlenstoffflüsse beider Modelle ähnlich war, unterschieden sich die absoluten Kohlenstoffwerte bedingt durch Modellannahmen wie beispielsweise die unterschiedliche Berücksichtigung der sehr heterogenen Klimabedingungen in der Schweiz.

Diese Dissertation zeigt, dass die Bewirtschaftungsart, mit welcher Kohlenstoffspeicher oder -flüsse maximiert werden können, stark von Standortsfaktoren wie Bodenqualität und Wachstumsbedingungen, sowie vom Ausgangsvorrat abhängt. In den Alpen, wo der stehende Vorrat hoch ist, aber die Wachstumsbedingungen schlecht sind, ist es die beste Strategie, den bestehenden Wald zu schützen. Im Mittelland, wo die Wachstumsbedingungen viel besser sind, kann es sich lohnen, den maximalen Zuwachs abzuschöpfen, um das Holz entweder in langlebigen Produkten einzulagern oder um fossilen Brennstoff zu ersetzen. Um eine Strategie zu finden, welche die Zunahme von atmosphärischem CO_2 verlangsamt, wäre es sehr wichtig, nicht nur die Kohlenstoffeinlagerung in Wäldern zu maximieren, sondern Holzprodukte und insbesondere den Ersatz von fossilen Brennstoffen in die Berechnungen aufzunehmen.

Modelle, welche verwendet werden, um den Einfluss der Waldbewirtschaftung auf die Kohlenstoffspeicher und -flüsse realistisch abzuschätzen, sollten Informationen wie Baumart und Bestandesstruktur enthalten. Das empirische, individuenbasierte Modell MASSIMO enthält solch strukturelle Informationen und eignet sich daher für diese Untersuchungen. Der Nachteil von empirischen Modellen ist aber, dass sie im Gegensatz zu prozessbasierten Modellen oft auf konstanten Parametern beruhen, und nicht auf konstanten Mechanismen. Als Folge können empirische Modelle den Einfluss von veränderten Klimabedingungen wie zum

Beispiel Temperatur, atmosphärischem CO_2 und Stickstoffkonzentrationen meist nicht abschätzen. Veränderungen dieser Faktoren könnten zukünftige Kohlenstoffszenarien aber stark beeinflussen.

Die Grösse der Kohlenstoffsenke/-quelle, welche unter dem Kyoto Protokoll angerechnet werden kann, hängt davon ab, welche Kohlenstoffspeicher angerechnet werden können. Wenn das so genannte "volle Anrechungssystem" angewendet wird, können Veränderungen der Kohlenstoffspeicher seit 1990 von beinahe der gesamten Schweizer Waldfläche angerechnet werden. Extrapoliert man die Resultate aus Kapitel III auf die wirtschaftlich genutzte und gut zugängliche Waldfläche von ungefähr 8'000 km^2, dann können in den nächsten 50-80 Jahren jährlich 1.24 Mt C eingelagert werden. Wird aber das so genannte "partielle Anrechungssystem" angewendet, dann sind die Kohlenstoffflüsse viel kleiner.

Obwohl gezeigt wurde, dass die verwendeten Modelle für die Abschätzung zukünftiger Kohlenstoffszenarien verwendet werden können, bleiben doch gewisse Unsicherheiten. Wie in Kapitel IV erwähnt, hat jede biologische Senke eine Obergrenze, weshalb sie keine nachhaltige Lösung bildet, um den Anstieg an atmosphärischem Kohlenstoff zu reduzieren, sondern höchstens eine Interimstrategie für die folgenden Jahrzehnte darstellt. Es ist jedoch unerlässlich, in dieser Zeit Lösungen zu finden, die das eigentliche Problem, den menschlichen CO_2 Ausstoss, reduzieren und diese Lösungen auch durchzusetzen.

Introduction

1 Overall subject of the thesis

In the global carbon cycle, terrestrial ecosystems are important (Tans et al. 1990). For biomass increment and maintenance, plants sequester atmospheric carbon by photosynthesis. By auto- and heterotrophic respiration, carbon is released to the atmosphere again. If photosynthesis exceeds respiration processes, the amount of biomass increases, and therefore, the terrestrial ecosystem represents a carbon sink. If respiration exceeds photosynthesis the amount of biomass decreases, and the system represents a source of carbon.

Because at least for some time photosynthesis has exceeded respiration, terrestrial ecosystems, and particularly forests, have formed large global carbon pools. Results from Dixon et al. (1994a) show that at the global scale forests store almost twice as much carbon (1146 Gt C, of which 359 are in vegetation and 787 are in soils) as the entire atmosphere (≈750 Gt C). They estimate that the world's forests contain up to 80% of all aboveground and ≈40% of all belowground (soils, litter, and roots) terrestrial carbon.

Up to now, forests have been significant as global carbon sinks. There is general agreement that the terrestrial biosphere is currently absorbing carbon. Estimations about the magnitude of this sink however, vary greatly. Results from Battle et al. (2000) suggested the land biosphere to sequester 1.4±0.8 Gt C year^{-1} (1991 to 1997), and Fan et al. (1998) estimated a global terrestrial carbon uptake of 1.0 - 2.2 Gt C year^{-1}. Mainly the Northern Hemisphere is responsible for the carbon sequestration, and many studies have estimated the magnitude of this carbon sink (Tans et al. 1990, Sedjo 1992, Dixon et al. 1994b, Myneni et al. 2001, Goodale et al. 2002). Their estimates generally range from a carbon sink of 0.5 to 1 Gt per year (Sedjo 1992, Dixon et al. 1994b, Myneni et al. 2001, Goodale et al. 2002), with a few exceptions ranging from 2 to 2.7 Gt per year (Tans et al. 1990). Beside the differing magnitudes, there are various explanations for the reason and the spatial distribution of this carbon sink (Goodale et al. 2002). Results from Nemani et al. (2003) indicate that global changes in climate have promoted an increased plant growth, and findings from Barford et al. (2001) and Kirschbaum & Fischlin (1996) support the view that historical legacies such as large-scale deforestation and overexploitation in the 19th century decreased the carbon stocks and thus made the accumulation of additional carbon possible. However, Schimel et al. (2001) suggest that not until the 1990s the terrestrial biosphere became a carbon sink. They imply that this sink is largely the result of changes in land use over time, e.g. regrowth of forest on abandoned agricultural land or changes in forest management, and of responses to environmental changes.

Carbon stored in forests can be lost due to human activities or natural disturbances. Mainly as a result of burning fossil fuel and land-use change, humans influence the natural carbon fluxes between the atmosphere and the biosphere. Historically (until around 1910), the conversion of forests to other land-uses was the largest anthropogenic source of CO_2 release to the atmosphere (Houghton 1996). At present, deforestation is still the largest source of carbon emissions in many tropical countries, contributing almost 25% of the global emissions (Schimel 1995). At the global scale, however, the burning of fossil fuels is the largest source of anthropogenic carbon emissions today. Natural disturbances can cause the ecosystems to become a carbon source. The larger the amount of carbon stored in forests, the higher is the danger of losing this carbon due to disturbances such as windthrow, pests or fire (Breshears and Allen 2002, Law et al. 2004). If large scale disturbances are not taken into account, the potential sink effect of forests may be overestimated strongly (Körner 2003, Williams et al. 2004).

Over the past two decades, many methods have been developed and applied to quantify past and current terrestrial carbon pools and fluxes and to assess their future development. Each method has its strengths and weaknesses, and the resulting estimates show large variation. Houghton (2003b) emphasizes that the differences often result from different accounting systems. For example, these methods differ with respect to their spatial scale. Global carbon fluxes are often estimated by applying inverse models based on a network of CO_2 measurements in the atmosphere (Gurney et al. 2002). National to regional assessments can be made using biogeochemical models (Churkina et al. 2003) or analysis of land-use change (Houghton 2003a). Moreover, assessments of national carbon pools can also be achieved using direct measurements such as forest inventories or soil sampling, from which carbon fluxes (sources or sinks) can be derived as the differences between stock estimates at different times (Fang et al. 2001, Goodale et al. 2002, Shvidenko and Nilsson 2002). Detailed measurement of gas exchange above the forests, so-called eddy correlation measurements, can be applied to define detailed carbon fluxes at small spatial scales (Baldocchi 2003).

The relevance of forests for atmospheric CO_2 levels has recently received a lot of attention, particularly since countries started negotiations regarding reduction commitments of greenhouse gas emissions in Kyoto in December 1997 (UNFCCC 1997). A good overview of the negotiations is given in Schulze et al. (2002). The Articles 3.3, 3.4, Article 6 and Article 12 of the Kyoto Protocol include the following activities: land use change such as afforestation, reforestation and deforestation (ARD), additional human activities such as forest management (e.g., choice of species, change of rotation length), Joint Implementation Projects (JI), Emission trading and Clean Development Mechanism (CDM). These mechanisms should help industrialized countries to meet their commitments. However, the amount of forestry activities accountable under the Kyoto Protocol is defined by country-specific upper limits, so-called caps. Globally, these caps amount to 0.169 Gt of carbon. This is equivalent to 3.4% of the emission amounts assigned to Annex I Parties, thus effectively reducing their average emission reduction target from 5.2% to a mere 1.8[1]. Under Article 3.4 of the Kyoto Protocol, "additional human-induced" forestry activities of Annex I Parties since

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[1] http://www.una-uk.org/Environment/kyotoprotocol.html

1990 can be included (UNFCCC 1997). For the first commitment period (2008-2012), countries can decide whether they want to credit additional activities listed in Art. 3.4. To do so, the Parties must establish their carbon stocks for the reference year 1990, and must provide estimates of carbon stock changes in subsequent years, for the first time during the First Commitment Period (2008-2012).

To provide a basis for political decisions that were taken on issues related to greenhouse gases and Land-Use, Land-Use Change and Forestry (LULUCF), a special report of the IPCC (Intergovernmental Panel on Climate Change) was commissioned (IPCC 2000). In this report, scientific and methodological questions concerning national inventories of carbon stocks and greenhouse gases were addressed. Among others, this Special report concluded that the global terrestrial uptake of atmospheric CO_2 exceeded the terrestrial emissions in the decade 1991-2000. It also indicated that the forestry sector may hold a considerable potential to mitigate the accumulation of carbon dioxide in the atmosphere, at least for a limited period of 30-50 years. The report estimated the potential global effect of the human-induced activities (Art. 3.4) in Annex I countries in the first commitment period to be up to 0.52 Gt C $year^{-1}$ (only on-site carbon stock changes without accounting for wood products and substitution of fossil fuels). However, the report also concluded that the relative importance of different silvicultural practices under Art. 3.4 responsible for this carbon sink are not entirely clear. In addition, the previous IPCC assessment also pointed out many uncertainties - particularly on the regional to national scales - because " ... scientifically sound and rigorous estimates of forest-related carbon stocks and fluxes challenge our scientific and technical abilities..." (IPCC 2000). In the IPCC Report, several scientific and methodological questions concerning carbon sequestration potential were pointed out that need to be considered, some of which are highlighted below. (1) Over what time scales are different forest management scenarios effective for inducing a carbon sink? (2) What are the accuracy and precision of our capabilities to track carbon pools and fluxes? (3) What are the main spatial and temporal uncertainties? Answers to these questions are important for a reasonable implementation of the Kyoto Protocol. To support the countries in their reporting efforts, the IPCC produced the "Good practice guidance for land use, land-use change and forestry" (IPCC 2003). This report contains guidelines for the calculation of carbon pools and fluxes related to land use, land-use change and forestry.

Increasingly, national policymakers are asking for answers to such questions, based on reliable scientific results. Under the Kyoto Protocol, Switzerland has committed to reduce its CO_2 emissions by 8% relative to 1990. This commitment is lower than the one specified in the Swiss CO_2 law, which has been in force since May 2001[2], demanding a reduction of 10%. As a consequence of the Marrakech negotiations, a new aspect of the Kyoto commitment is the role of CO_2 sinks such as forests, which are not included in the Swiss CO_2 law[3]. Especially the middle and long term (40-100 years) role of forests as carbon sinks is scientifically still

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[2] http://www.buwal.ch/nachh/co2/factssheet_d.pdf

[3] http://www.uvek.admin.ch/umwelt/div/00709/?lang=de

quite contentious. For this reason and as a member of the COP (Conference of the Parties), Switzerland wishes to assess the potential for domestic biotic carbon sinks. Therefore, it is necessary to assess the potential for increasing the pool size as a function of forest management, and to evaluate the uncertainty of such assessments.

2 State of the art

To date, a considerable amount of research activities has focused on estimating the national to global carbon sequestration potential of forests. Carbon pools and fluxes can be assessed by using data, models or a combination. Martin et al. (2001) provide a good summary of methods, constraints and opportunities for carbon sequestration. Assuming a continuation of present management regimes, enhanced or reduced harvesting amounts, many different model approaches have been applied (e.g. Dewar and Cannell 1992, Peng et al. 2002, Seely et al. 2002, Komarov et al. 2003, Kaipainen et al. 2004). Stage (2003) evaluated different models according to their suitability in the forest management decision process. The model outputs differ and lead to a range of answers to the question to which degree and spatial and temporal extent forests may act as carbon sinks (Houghton 2003b). For example, estimates based on forest inventory data usually result in much lower carbon fluxes than estimates based on inverse atmospheric models (Janssens et al. 2003).

2.1 Estimates of global to national C sequestration potential

Many nations, partly in addition to their reporting of Greenhouse Gas Inventories (GHGI) to the United Nations Framework Convention on Climate Change (UNFCCC), provided country-wide estimates of their current carbon fluxes. For example, terrestrial ecosystems were estimated to sequester 0.3-0.58 Gt year^{-1} in the United States (Pacala et al. 2001), 0.098 Gt year^{-1} in China (Zhang and Xu 2003), and 0.08 - 1.6 Gt year^{-1} in North America (Turner et al. 1995, Fan et al. 1998). Also for Europe, there are several studies where the current above- and belowground carbon fluxes were estimated (Liski et al. 2000, Liski et al. 2002, Nabuurs and Schelhaas 2002). Janssens et al. (2003) estimated a carbon sink of 7 to 12% of the 1995 anthropogenic carbon emission. Finally, estimates for the future development of carbon pools and fluxes in Europe were performed. Nabuurs et al. (2003) examined strategies to estimate national forest carbon stocks from inventory data, and the effects of forest management regimes, such as changing rotation lengths, on the carbon budget were investigated by Liski et al. (2001), Jiang et al. (2002), Karjalainen et al. (2003) and Kaipainen et al. (2004).

2.2 Estimates of Swiss C pools and sequestration potential

Fischlin et al. (2003) and Bugmann (2000) gave a summary of the accounting methods, state of reporting and research perspectives relating to the carbon budget in Switzerland. So far, Switzerland has submitted nine Swiss Greenhouse Gas Inventories (GHGI) to the UNFCCC. The latest Swiss GHGI was submitted by the Swiss Agency for the Environment, Forest and Landscape (SAEFL) in 2004, and refers to the state of 2002 (SAEFL 2004). Category 5 of the Report deals with the subject “land-use change and forestry”.

2.2.1 National Forest Inventories

An important source of data is the Swiss National Forest Inventory (NFI). The first NFI was conducted in 1983-1985 (10975 sampling plots), the second NFI in 1993-1995 (6412 sampling plots) (Brassel and Brändli 1999). The first NFI provides information about the state of the forest, particularly variables from which biomass can be assessed. With the help of the second inventory, changes of biomass over time can be analyzed, and estimates for the near future can be made (Kaufmann 2000a, b).

2.2.2 Prognosis and management scenarios derived from the NFI I+II

The NFI contains mainly data on aboveground biomass (e.g., tree diameter at 1.3 m for all trees, upper tree diameter at 7 m and tree height for approximately 12% of the trees). Based on these variables, individual aboveground tree volume and estimates of coarse root volume can be obtained using species-specific allometric equations (Perruchoud et al. 1999b, Kaufmann 2000a). Perruchoud et al. (1999b) provided estimates of tree biomass including foliage, twigs and fine roots.

Based on these two inventories, changes in standing volume as well as increment and mortality in Swiss forests during the period 1995-1995 can be estimated. Probabilities for management practices applied during this period (e.g., "Business-as-Usual", BAU) can also be derived from the observed data. Besides determining the stock changes and the management practices over the last 10 years, it is also of interest to assess possible future developments as a function of different management practices. Kaufmann (1999) provided short-term (20 years) predictions with an empirical individual-based model derived from the data set of the two inventories using mathematical growth functions that were derived from these data as well. He estimated that, assuming the current harvesting amount, the growing stock will increase by 10% in the next 20 years. Apart from this BAU scenario, a set of management strategies with various objectives (e.g., minimizing the harvesting amount causing an increase in growing stock of 45%) were investigated. However, as it may take a long time to survey the reaction of forests to changes in the management regime, simulating longer time periods (up to 100 years) would be a better option. As long-term projections should not be based on one empirically-based model alone, the reliability of the assessment could be enhanced by comparing the simulation results from several modeling approaches.

2.2.3 Other estimates of carbon stocks and sequestration potential in Switzerland

One of the first studies assessing the potential of Swiss forestry to sequester carbon was done by Fischlin & Bugmann (1994). This study revealed the significant potential (5-50% relative to 1988 emissions) of sinks in Swiss forests. However, the study relied on simple models and distinguished only a few forest regions according to their general productivity. Moreover, it did not estimate the Swiss sink potential in a spatially explicit manner. Paulsen (1995) made an area-wide estimation of the amounts of carbon stored in living biomass and soil. As data source he used the digital elevation model RIMINI, land area statistics (GEOSTAT), soil suitability maps, the NFI I and further literature data. To estimate forest litter amounts, he made field studies (Paulsen 1994). Paulsen provided extrapolations of the estimated carbon stocks for the whole of Switzerland, but due to the available data sources (e.g., grid size of RIMINI is 250 m x 250 m), the estimates have a relatively low precision.

Combining NFI data (Kaufmann 2000a) and succession models (Bugmann 1996, Perruchoud 1996, Perruchoud et al. 1999b), Perruchoud et al. (1999a) estimated the potential of forest soils in the Alps to sequester carbon throughout the 20th century. They applied the decomposition model ForClim-D using long-term (1900-1085) litter input scenarios reconstructed from forest inventory data, dendrochronological data and time series of anthropogenic litter removal. Their results indicate that during the last century, soil carbon in European forests was increasing due to an increased litter production induced by changing environmental conditions and altered harvesting practices. They found the soil organic carbon (SOC) to remain the most uncertain part of the carbon stock estimations. An approach to obtain better SOC estimates was conducted by Perruchoud et al. (2000). They used forest soil data with a regular grid size of 8 km. However, geostatistical analyses of these data showed no clear spatial trends for SOC, and regression analyses using the entire data set yielded no strong climatic or topographic signal for forest SOC stocks in these data.

Fischlin et al. (2003) compiled a report on the present carbon pools in Switzerland. To quantify the amount of carbon sequestered in forests and agriculture and to estimate the potential for future sinks, they used data of the NFI I and II, the land use statistics of Switzerland, the Forest Statistics and soil data measured by Lüscher et al. (1994). They estimated the carbon flux accountable under Art. 3.4 of the Kyoto Protocol to be 0.3 Mt C year^{-1}. This is less than the cap of 0.5 Mt C year^{-1} negotiated for Switzerland.

Forest management can significantly influence carbon sequestration in forests, at least for a short time (Harmon and Marks 2002). To estimate the future development of carbon pools and fluxes as a function of forest management, models have to be applied. The literature review shows that in Switzerland the effects of different management scenarios on the carbon sequestration potential of forests were investigated for a short time period of 20 years (Kaufmann 2000b), but not for longer time periods (40-100 years). Models appropriate to investigate such scenarios are either not validated or they are not adapted to the large climatic, spatial, and structural variability prevailing in Switzerland. As forests show a time-lag in reacting to changed management strategies, the model simulations should cover a period which is long enough to mirror the changes in biomass and stand structure. Therefore, it is important to (1) select models suitable for this purpose, (2) to validate the selected models thoroughly, and (3) to apply these models with management scenarios reflecting practicable and realistic forest management over a long time period.

3 Aims and research questions

The overall aim of this project was to assess the range of current and future pools, sources and sinks of carbon in Swiss forests over a period of up to 100 years into the future. To do so, four models were selected. The models were evaluated to assess this applicability and performance for Swiss conditions. Three of the models were applied under a suite of future forest management scenarios to derive estimates of carbon pools and fluxes under different management regimes. Above- and belowground carbon stocks and fluxes were simulated, whereby the main focus was put on the aboveground part.

Specifically, the following questions were addressed in this thesis:

- What is the accuracy and precision of the different models in estimating carbon pools and fluxes in Switzerland?
- What are possible and practicable management strategies for increasing above- and belowground carbon storage in forest ecosystems?
- What are the effects of a range of these management strategies with and without windthrow for carbon sequestration in forests within the next 100 years?
- How large are the differences between different model projections obtained under the same scenarios of forest management, and what is the major cause of these differences?

This thesis was part of the project "Carbon pools and fluxes in the Swiss forests: A quantitative assessment for the present and the 21st century (CPF-CH)". Another part of the project was the thesis of Stéphanie Schmid "Carbon budget of Swiss forests: Evaluation and application of process models for assessing the future impact of management and environmental change". Both theses were performed in the framework of the COST (Intergovernmental Framework for European Co-Operation in the Field of Scientific and Technical Research) Action E21 "Contribution of Forests and Forestry to Mitigate Greenhouse Effects".

4 Models

The first step of this thesis as well as of the thesis by Stéphanie Schmid was to select models that are appropriate for answering the main research questions. In both theses, the models should at least potentially be applicable "as-is" to Swiss conditions, and they should be applicable in all European countries and thus enable a comparison of the carbon budget across Europe. Furthermore, the models should be able to estimate aboveground as well as soil carbon.

In the thesis by Stéphanie Schmid, the focus was on assessing the effect of environmental changes on the forest's carbon budget, whereas in the present thesis, the emphasis was on assessing the effect of forest management scenarios on forest carbon pools and fluxes. As no model was found to fulfil all these demands, we selected different models to investigate the different aspects. Stéphanie Schmid selected the process-based, ecophysiological model Biome-BGC and the distance-dependent, individual-based model SILVA. I selected the empirical, individual forest model MASSIMO, the soil carbon model YASSO and the large-scale model EFISCEN.

MASSIMO (MAnagement Scenario SImulation MOdel) is an individual-based empirical model that was derived from the Swiss NFI I & II (Kaufmann 2000b). It is very data intensive but well adapted to Swiss conditions. The model runs with a time step of 10 years.

YASSO is a simple dynamic soil carbon model (Liski et al. 2004). It requires only few input data and can easily be linked to aboveground forest growth models. YASSO also forms the belowground part of the EFISCEN model. It runs with a time step of 1 year.

EFISCEN (European Forest Information SCENario model) is a large-scale model that has been applied for most of the countries in Europe (Nabuurs et al. 2000). It is a matrix model with age and volume classes. EFISCEN is not very data intensive, thus enabling a "Europe-wide" comparison of forest carbon budgets. The model has a time step of 5 years.

5 Structure of the Ph.D. thesis

The thesis is divided into four chapters, followed by an overall synthesis.

Validation of Massimo (chapter I)

The aim of this chapter was to evaluate the empirical growth model of MASSIMO. This was done by applying the model to an independent data set, and by a partial sensitivity analysis. The following questions were of particular importance for this study: (1) How accurately does the model predict tree growth for an independent data set? (2) What are the reasons for possible deviations? (3) How sensitive is the tree growth prediction to the variations of the independent variables, and to uncertainty in the model parameters?

Validation of EFISCEN (chapter II)

This study aimed at investigating how the EFISCEN model performs on a sub-country and a regional level in forests that may not correspond to Scandinavian conditions for which the model originally had been developed. For this purpose, we took Switzerland as a case study. The main questions were: (1) How accurate is the initialisation of the forest matrices? (2) How well does EFISCEN simulate the development of growing stock, stand-age structure, increment, management and natural mortality? The results showed that the formulation of management in EFISCEN is not flexible enough to implement realistic management practices as applied in Switzerland. Therefore, it was concluded that EFISCEN is not suitable for simulating the effect of different forest management scenarios on carbon sequestration in the present study.

Validation of YASSO and short term (40 years) assessment of management and windthrow (chapter III)

This chapter aimed at assessing the influence of an increased frequency of windthrow on the permanence of forests to act as carbon sinks. The focus was on: (1) adapting and evaluating the applicability of the soil carbon model YASSO for Switzerland; (2) investigating the influence of different management regimes and storm effects on the fluxes and pools of carbon in forests. This led to the following research questions: a) How does increased harvesting of large trees affect the C balance? b) How does "no-clearing" of windthrown wood influence the belowground C budget? c) How does an increasing storm frequency affect the size of above- and belowground C pools?

Effect of forest management on carbon pools and fluxes: long-term (100 years) application and comparison of three different models (chapter IV)

The aim of this study was to apply selected models from my thesis and from the thesis by Stéphanie Schmid for representative forest types and to compare the carbon pools and fluxes simulated by the models as a function of different forest management scenarios. The models MASSIMO/YASSO and Biome-BGC were applied for the next 100 years, assuming various forest management strategies. The following research questions were investigated: (1) How large is the effect of different models on the assessment of carbon source/sink relationships over time? (2) What is the potential range of the influence of different management scenarios on the carbon budget? (3) How do the carbon fluxes differ between the regions?

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Evaluation of the growth function of an empirical forest scenario model

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Abstract

Forests have an important role in the global carbon cycle as carbon pools, sinks and sources, and their quantification has become a relevant task. Empirical models based on national forest inventories are widely used for the assessment of carbon sequestration. However, these models do not treat explicitly all the processes occurring in the ecosystem, as they are mainly based on statistical relations to estimate forest development. Therefore, there is a need for validation of these models to increase confidence in the predictions of future forest development. This study evaluates an empirical single tree model that was developed in Switzerland (MASSIMO). The accuracy and precision of the growth function of the model is evaluated with data from the National Forest Inventory (NFI) of Liechtenstein. MASSIMO was found to predict the basal area per ha of the Liechtenstein data very precisely (underestimation of 0.65%). The main differences between observed and predicted diameter increment occur mostly for larger DBH classes, where the increment is underestimated by the model. However, these differences may be related to the precision of the input variables. For example, the explanatory variable stand age is determined with relatively low precision; therefore it shows a high variability. For future model development, either the variable stand age should be estimated more reliably, or stand age should not be an explanatory variable of the growth function.

Keywords: carbon sequestration; Liechtenstein; NFI; model evaluation; forest growth model; MASSIMO; Switzerland

1 Introduction

Forests play an important role in the global carbon cycle (Cannell 1995, Schimel et al. 2001). They are important as global carbon pools and carbon sinks or sources (Dixon et al. 1994, IPCC 2000). Changes in C fluxes to or from forests can have a considerable impact on atmospheric CO_2 concentrations. There is compelling evidence that the terrestrial biosphere is currently absorbing carbon in the Northern Hemisphere (Tans et al. 1990, Sedjo 1992, Ciais et al. 1995, Brown et al. 1996, Fan et al. 1998, Houghton et al. 1999, Battle et al. 2000, IPCC 2000, Janssens et al. 2003). However, there is still great uncertainty about the magnitude, location and mechanisms of the terrestrial C sinks (Houghton 2003). National forest inventories can be used to provide ground-based estimates of the large-scale C balance that help to identify the location and mechanisms of C sources and sinks (Goodale et al. 2002).

Many forest growth models estimate stemwood using data from forest inventories (Monserud and Sterba 1996, Andreassen and Tomter 2003). Using conversion and expansion factors, these models can also be applied to assess whole tree carbon balance (Körner et al. 1993, Perruchoud et al. 1999, Löwe et al. 2000). Pretzsch et al. (2002) and Peng (2000) give a summary of inventory-based forest growth models. Inventory-based or descriptive models rest upon statistical correlations, not on process-based assumptions. Correlations may be accurate to the calibration region, but application for different regions or predictions under changed environmental conditions can be highly uncertain (Lischke 2001). A further difficulty of inventory-based models is the uncertainty arising from the conversion of inventory measurements (e.g. tree diameter) into C stocks and fluxes for the entire forest ecosystem (conversion of stemwood volume to stemwood biomass via wood density, expansion to whole tree biomass and conversion of biomass to carbon via the carbon content) (Löwe et al. 2000). However, the compilation of a great number of representative measurements makes inventories a powerful resource for quantifying the net C balance across heterogeneous regions and for short term extrapolations, i.e. over a few decades (Goodale et al. 2002). However, due to the uncertainties mentioned above, the evaluation of empirical growth models is very important.

There are many ways to evaluate a model, and there is no such thing as the appropriate procedure; evaluation is problem-dependent. Various authors have discussed the range and importance of model evaluation (Mayer and Butler 1993, Soares et al. 1995, Loehle 1997, Vanclay and Skovsgaard 1997). Main categories are assessments in terms of logic structure, characterization of errors, tests using statistical approaches (Reynolds et al. 1981, Mayer and Butler 1993, Power 1993) and sensitivity analyses (Saltelli et al. 2000).

Validation of a simulation model sensu Popper (1984) requires that the predictions of the model are compared with real-world data that are independent of the data used in the construction of the model (Reynolds et al. 1981). The comparison of model estimates with independent data from permanent plots is important especially when empirical forest models are used for estimating long-term growth trends, with or without anthropogenic influences, as decision-support tools in forest management (Reynolds 1984, Sterba and Monserud 1997, Köhler et al. 2001). Various authors have evaluated inventory-based models with the help of such observations (Sterba and Monserud 1997, Köhler et al. 2001, Pretzsch and Durský 2001, Phillips et al. 2003). For example, Sterba and Monserud (1997) have successfully applied the forest stand growth simulator PROGNAUS for the Austrian part of the Bohemian Massif. In the absence of suitable independent data, another evaluation method is that of comparing the performance of two models (Ek and Monserud 1979, Bugmann 1996, Yaussy 2000, Andreassen and Tomter 2003).

In Switzerland, the empirical single tree model MASSIMO (Management Scenario Simulation Model) has been applied to assess possible forest development up to 40 years into the future (Kaufmann 2000a, b). The model was calibrated with Swiss National Forest Inventory (NFI) data. For two main reasons, this model is suitable for predicting carbon sequestration in Swiss forests under different management practices for the next 40 years: firstly, MASSIMO is based on a large data-base (the Swiss NFI) and secondly, comprehensive and flexible tools have been implemented in this model to estimate the impact of changing management regimes. However, due to the lack of process-based mechanisms, the predictive power of empirical models is always limited and needs to be assessed.

Our aim was to evaluate the growth model of MASSIMO. This was done by applying the model to an independent data set, and by a partial sensitivity analysis. Basal area increment was estimated using the model, converted to diameter increment and compared to the observed diameter increment. Our validation data test the performance of the model under particular, but important conditions: Pre-alpine, mixed stands of Norway spruce (*Picea abies*), European beech (*Fagus silvatica*) and European silver fir (*Abies alba*). The test data come from the forest inventory of Liechtenstein, which were collected in a manner comparable to that of to the Swiss National Forest Inventory (NFI), but the Liechtenstein data had not been used to calibrate the growth model. The following questions are of particular importance for the present research: (1) How accurately does the model predict tree growth for an independent data set? (2) What are the reasons for possible deviations? (3) How sensitive is the tree growth prediction to the variations of the independent variables, and to uncertainty in the model parameters?

2 Material and Methods

2.1 The model MASSIMO

MASSIMO (Kaufmann 2000a, b) is an individual-based, stochastic and dynamic model. It consists of four sub-models: Regeneration, growth, mortality and management scenarios (including harvesting). Fig. 1 gives an overview of the model flow chart. These four processes are simulated based on empirical formulations that were derived from the first and the second Swiss NFI (1985, 1995). The NFI data represent the situation in the entire country at a specific point in time. With MASSIMO, the implications of various management strategies can be investigated. Probabilities for silvicultural interventions in use today, i.e. the so-called "business as usual" scenario of the model, were derived from observed data. The core of MASSIMO is the growth function which is derived from the inventory data and describes the decadal basal area increment between the first two NFIs (Kaufmann 1996). The increment was estimated on an individual tree basis as a function of site conditions and forest structures, which are updated after each projection decade and thus influence growth in the subsequent decade. The time period for projections is limited to ≈ 40 years because the model is based on empirical assumptions. Random errors were specified and include sampling errors, model prediction errors and random variation caused by stochastic processes (Kaufmann 2000a). In this study, we focus on the growth function as a crucial part of the model.

2.1.1 Growth function

One approach to describe individual tree growth is to start from a potential growth function that is multiplied by a modifier function (Quicke et al. 1994). Potential growth represents the

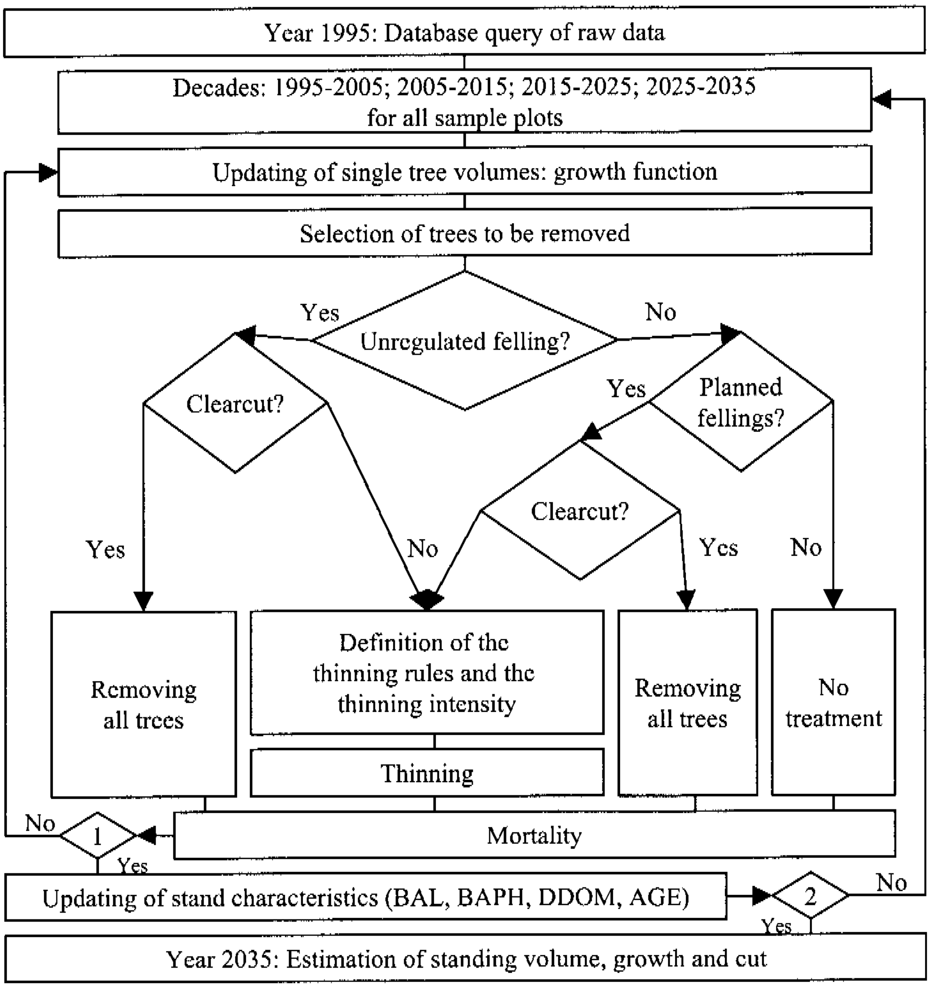


Fig. 1. Flow chart of the scenario model MASSIMO. Questions in diamonds indicated by numbers: (1) All sample plots processed? (2) All decades processed? Definition of the terms: BAL: Basal area (m^2 ha^{-1}) of trees larger in diameter than the subject tree, measure for competition within a stand; BAPH: Basal area per ha (m^2 ha^{-1}); AGE: stand age; DDOM: Average DBH of the hundred trees having the largest DBH per hectare (cm); Modified from Kaufmann (2000a).

maximum growth attainable for a tree, depending mostly on its diameter at breast height (DBH, 1.3 m above the forest floor). The modifier function represents deviations from the potential due to competition and environmental factors, often parameterized by site or stand indices (Quicke et al. 1994). All parameters are estimated simultaneously to minimize model errors and provide a variance-covariance matrix for the model as a whole (Vanclay and Skovsgaard 1997).

The equation for growth modelling used in MASSIMO has a form similar to the one developed by Quicke et al. (1994) and Teck and Hilt (Teck and Hilt 1991) and applied in PROGNAUS (Monserud and Sterba 1996). The model is a single, nonlinear regression function for basal area increment (BAI) as the dependent variable (cf. Kaufmann 1996). The function used here is a further development based on Kaufmann (2000a), where the effect of the "growth boost" (release effect after thinning) is newly implemented. The function has the form:

$$BAI = \underbrace{\exp[b_0] \cdot \prod_{i=1}^{6} \exp[b_i \cdot B_i]}_{A} \cdot \underbrace{\exp[b_7 \cdot \{1 - \exp(b_8 \cdot DBH)\}]}_{B} + \underbrace{\varepsilon_i}_{C} \qquad (1)$$

where the term B represents potential growth, A the modifier and C the residual variance. The explanatory variables are: B_1, basal area per ha (BAPH); B_2, basal area (m^2 ha^{-1}) of trees larger in diameter than the subject tree (BAL); B_3, soil quality ("Gesamtwuchsleistung"); B_4, altitude; B_5; stand age; B_6, growth boost (dummy variable yes/no); $b_0 - b_8$, model coefficients.

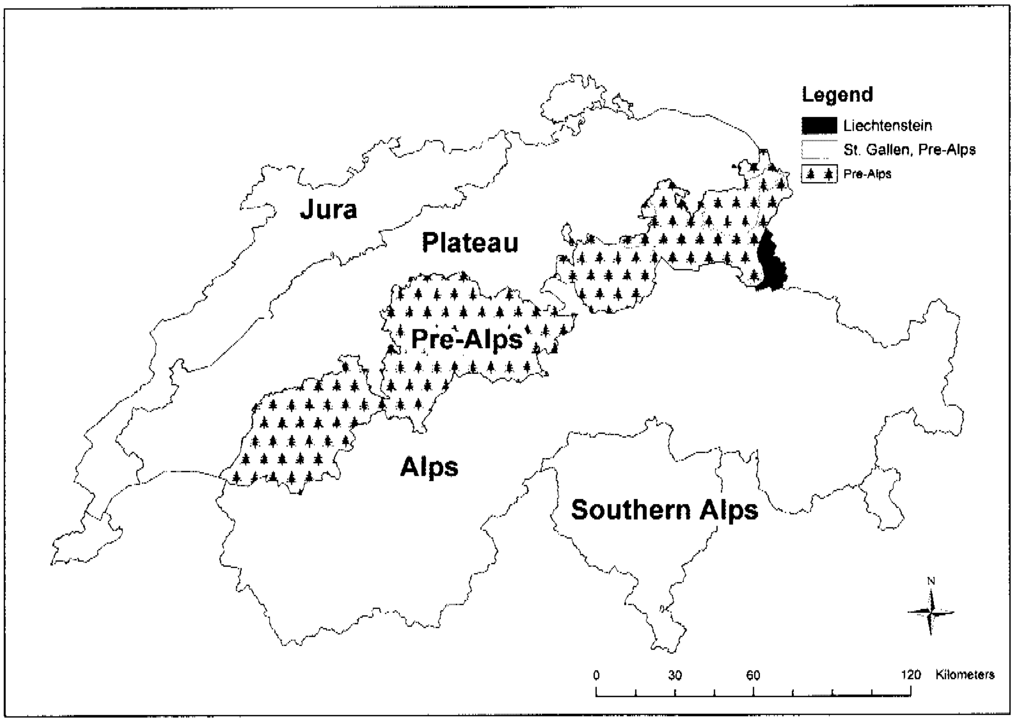


Fig. 2. The five Swiss production regions and Liechtenstein. The pre-alpine part of canton St. Gallen, which was used for the model verification, is marked.

To estimate the model parameter, the NFI data were stratified according to five production regions (Fig. 2) and 11 tree species. As an example, Fig. 3 shows the course of modelled growth for three dominant tree species in a uniform high forest stand and elucidates the magnitude of the influence of different explanatory variables, which were kept at a constant level that is representative for the test data region (Liechtenstein). The solid line represents potential basal area increment (B). The variables BAPH and stand age reduce the growth curve with time. The older and denser a stand is, the more growth is reduced. After thinning events, growth is enhanced because the dominant trees often profit from increased growing space.

Parts A and B of Equation (1) describe the deterministic effects of BAI. Part C takes into account the stochastic effect ε_i, which is a random variable. This random variable is assumed to be distributed normally $\sim(0, \sigma^2)$. To account for this stochastic effect, ε_i is added to the simulated variable BAI. The variance σ^2 is estimated from the residual distribution. Thus, for stochastic simulators such as MASSIMO, predictions are usually based on the average of several simulations runs (Reynolds 1984).

2.1.2 Model calibration for Switzerland

For model calibration, data from the first and the second NFI of Switzerland were used (EAFV 1988, Brassel and Brändli 1999). The NFI I was undertaken in 1983-1985 with the NFI II following in 1993-1995. In the NFI II, about 6,000 forest sample plots were included on a 1.4 km grid. In each plot, trees were measured within two concentric circles. Trees with a DBH between 12 and 36 cm were measured in a small circle (200 m^2), trees with a DBH > 36 cm were measured in a larger circle (500 m^2). Only trees measured in both inventories were considered for model calibration.

The trees were stratified according to region, tree species and forest structure. As a modification to Kaufmann (2000a), dominant and subdominant trees were distinguished for uniform high forests, because only the dominant trees profit from a thinning event. This stratification resulted in a differentiation of 90 tree categories for Switzerland. Regression parameters were estimated for each of the strata. The resulting equations contain only the statistically significant parameters at the 95% level of significance. As an example, Table 1 shows the fitted parameters for uniform high forests. Note that the annual increment was assumed to be constant over the measurement period (1985-1995).

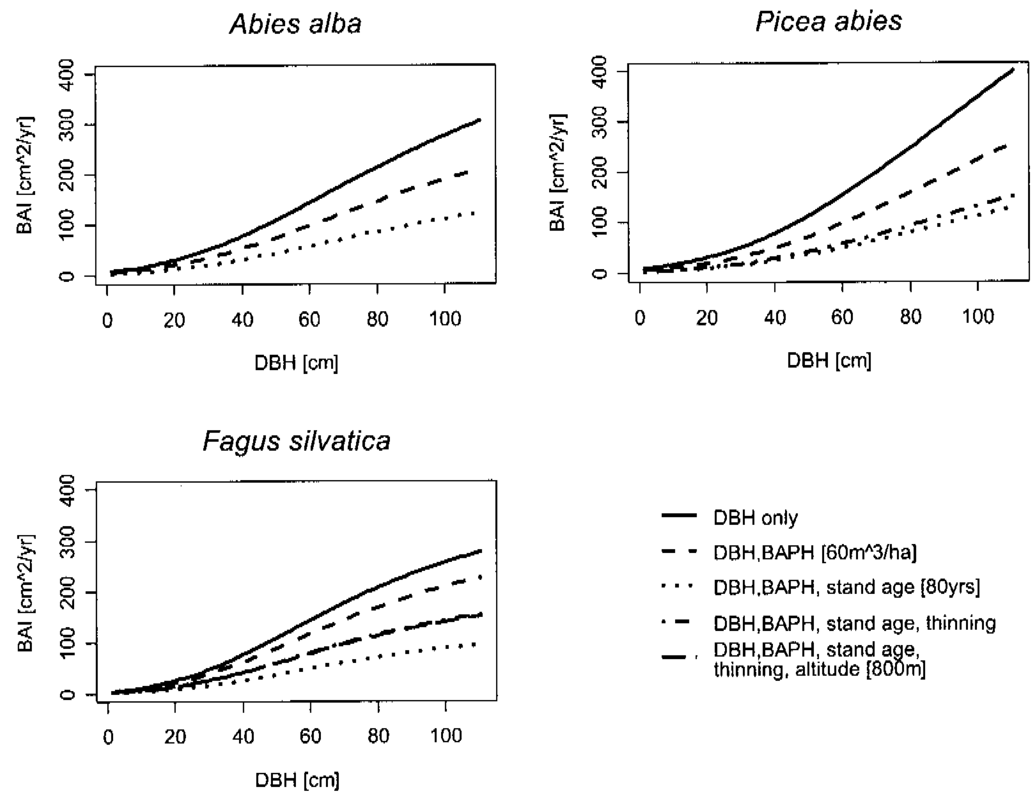


Fig. 3. Application of the growth function for dominant trees in a uniform high forest: influence of various explanatory variables on BAI concerning different tree species. The solid line represents basal area increment (BAI) as a function of DBH only (Part B of Eq. (1)), the other lines show BAI with various modifiers added (Part A), such as basal area per hectare (BAPH), stand age, a thinning effect, and altitude. Forest structure variables such as BAPH and stand age are mean values for Liechtenstein. Only significant parameters according to Table 1 are considered.

The residuals of the model show heteroscedasticity, thus invalidating the statistical assumption of a constant variance of the error. There are at least three possibilities to handle this problem: (a) The dependent variable (BAI) can be log-transformed, as applied e.g. by Monserud and Sterba (1996). As a consequence of this nonlinear transformation, the estimators are minimized according to the geometric mean instead of the arithmetic mean, and a bias correction in BAI units is necessary (Bradu and Mundlak 1970). (b) The heteroscedasticity can be considered by using weighted residuals, where the weights are inversely proportional to the residuals, which increase with increasing DBH. (c) The heteroscedasticity can be "tolerated"; as a consequence trees with a large basal area (i.e. trees with larger squared deviations and a larger BAI) obtain a higher weight in the model fit. Often, this is not a problem, but it may even be required to obtain a better fit, especially for larger trees. The model in the present study was fitted using the third approach.

Table 1. Parameter estimates based on the nonlinear regression analysis for different production regions (Fig. 2) and tree species, respectively. For every stratum, significant parameters were estimated separately using stepwise reduction, resulting in a different number of explanatory variables. Parameters are for uniform forest sites and dominant tree species only.

	Pre-Alps			**Plateau**	**Alps**
Explanatory Variables	*Picea abies*	*Fagus silv.*	*Abies alba*	*Picea abies*	*Picea abies*
B_0: Intercept	-4.6670	-5.3721	-4.8120	-5.0510	-5.0011
B_1: Basal area / ha (BAPH)	-0.0074	-0.0034	-0.0063	-	-0.0065
B_2: Basal area index (BAL)	-	-	-	-0.0163	0.0012
B_3: Soil quality (GWL)	-	-	-	0.0001	-
B_4: Altitude	-	-0.0005	-	-	-0.0004
B_5: Stand age	-0.0085	-0.0058	-0.0066	-0.0040	-
B_6: Thinning history	0.1544	0.0820	-	0.1134	-
B_7: DBH	4.4743	4.3174	4.0183	2.4276	3.0186
B_8: DBH	-0.0166	-0.0268	-0.0212	-0.0277	-0.0237

2.2 Test data

As mentioned above, permanent plot data from a different region (Liechtenstein) were available for model validation. Due to its vicinity (see Fig. 2), climate and geology as well as the similar forest management practices, the Liechtenstein data are well comparable to Swiss pre-alpine conditions. To date, Liechtenstein has conducted two national forest inventories (1986, 1998). The grid size was 354 m x 354 m (488 sampling plots). The procedure and the surveyed features were comparable to those used in the Swiss NFI. Tree species in Liechtenstein are mainly Norway spruce, European silver fir and European beech. They account for 75% of the trees and 77.5% of the standing stock (including standing dead wood) (AWNL 1998). For these reasons, Liechtenstein provides an excellent data base for the evaluation of the Swiss basal area increment function.

2.3 Statistical analysis of model behavior

Basal area increment for the twelve years between the first and the second forest inventory (1986-1998) was simulated for all living trees measured in Liechtenstein at both inventories (1986, 1998), which amounted to 3411 trees. The growth function of equation (1) was applied with the explanatory variables and parameters calibrated in the Swiss Pre-Alps (Table 1). Because equation (1) had been calibrated to estimate the ten-year increment of the two Swiss NFIs, a linear extrapolation to twelve years was made for Liechtenstein.

2.3.1 Model verification

To test the accuracy of the fitted growth function (does the model properly represent what it is intended to?), the regression parameter set calibrated for the Swiss Pre-Alps was applied to a systematic sub-sample, namely the pre-alpine part of the canton St. Gallen (Fig. 2). This sub-sample exhibits similar biotic and abiotic conditions as the independent test data; therefore it is suitable for verification. A total of 137 random sample plots were included in this analysis, resulting in 1520 sample trees. Due to the stochastic model part (C), the mean increments vary. The distribution of these mean diameter increments was tested against the mean observed increments. Because the data are not normally distributed, the non-parametric Wilcoxon signed rank test was used to test for significant differences between the prediction and the observation.

2.3.2 Analysis of model accuracy, precision and excess error

An important validation step is the quantitative comparison between predicted and observed growth. Relevant measures for this are accuracy, precision and excess error, as outlined below. To calculate the average residuals of model accuracy $\bar{e}$, the difference between predicted diameter increment x_i and observed diameter increment X_i is determined over all trees $i = 1 \dots n$:

$$\bar{e} = \sum (x_i - X_i) / n \tag{2a}$$

Systematic deviation from the observed value can be expressed in relation to the mean observation value m:

$$\text{accuracy } (\%) = (\bar{e} \cdot 100) / m \tag{2b}$$

In the present paper, the percent specification of accuracy always refers to the mean observed diameter increment of the tree species or tree group (size class) considered.

A measure of the model variation is the precision (= variation of the prediction) s_e, calculated as the standard deviation of the differences between predicted diameter increment x_i and observed increment X_i (Byrne and Reed 1986, Pretzsch and Durský 2001).

The excess error expresses the increase of the residual variance when a model is applied to independent data which were not used for model calibration (Efron 1982). It can be estimated theoretically or empirically. The empirical excess error is:

$$\hat{E}_{emp}[\%] = (1 - s_{ec} / s_{ei}) * 100 \tag{3}$$

where $\hat{E}_{emp}$ is the empirical excess error, s_{ec} is the precision of the calibration data and s_{ei} is the precision of the independent data. The theoretical excess error is estimated by cross validation where the model is calibrated repeatedly with the same data set. At every iteration, one randomly chosen tree group is excluded from the model calibration, and is used to validate the model:

$$\hat{E}_{cross} = \frac{1}{n}\left[\sum_{i=1}^{n}(x_i - \hat{y}_{-i})^2 - \sum_{i-1}^{n}(x_i - \hat{y}_i)^2\right] \tag{4}$$

where $\hat{E}_{cross}$ is the theoretical excess error, estimated by cross validation; x_i is the measured increment; $\hat{y}_{-i}$ is the increment estimated using the growth function, with tree-group i excluded for model calibration; $\hat{y}_i$ is the increment estimated using the growth function, with tree-group i included for model calibration. The empirical excess error should not exceed the theoretical one.

2.3.3 Analysis of mean residual variance

The residual variance ε_i can be estimated either empirically with a regression model (Part A and B of Equation (1)) plus a normally distributed random number generator (Part C), as done originally in the model MASSIMO (Kaufmann 2000a), or by using model coefficients of Part A and B that are varied within their confidence interval considering the covariances between the parameters. In this study, the latter approach was applied to test the model's intrinsic residual variation coefficient ε_i. Therefore, random variables of the model coefficients were generated using a multivariate normally distributed random number generator based on the variance-covariance matrix of the coefficients (Gardner et al. 1980, Ripley 1987, Saltelli et al. 2000). The simulation results of 400 runs represent the distribution of the mean according to the residual variance. This distribution was compared to the distribution generated with the model intrinsic stochastic term.

2.3.4 Stratification of single tree diameter increment

To assess the modeled diameter increment according to the main tree species and DBH groups in addition to validating the aggregated estimation of tree growth, trees were stratified for (a) the main tree species (Norway spruce, European beech, European silver fir); (b) trees smaller and larger than 36 cm DBH respectively (due to the two concentric NFI sample plots); and (c) DBH groups (10 cm DBH classes).

2.3.5 Sensitivity analysis

We also wanted to assess the effects of the coefficients of the regression function calibrated in regions differing from the Pre-Alps (Plateau, Alps) on the growth estimation in Liechtenstein. Therefore, diameter increment was simulated by applying the regression coefficients calibrated for the Plateau and the Swiss Alps and compared to the model results obtained using the pre-alpine model coefficients. All simulation results were compared with the observations.

Some of the explanatory variables, such as diameter at breast height (DBH), basal area per hectare (BAPH), basal area of trees larger in diameter than the subject tree (BAL) and altitude, can be measured directly or can be derived easily from measured variables. However, the derivation of other variables, such as soil quality or stand age, rest upon models. These modeled variables exhibit a much larger uncertainty than the measured ones. Stand age is the only modeled (not measured) variable that turned out to be significant for MASSIMO in the Swiss Pre-Alps (Table 1). The standard error of the calibrated model reflects the variability of this parameter (±30 years). To assess the influence of this variation on the simulation results, a small parameter sensitivity analysis of the model was conducted. The input variable "stand age" was varied systematically within the error bounds, resulting in three different model runs: “normal” stand age, +30 years, -30 years. The resulting model outputs were compared graphically.

3 Results

3.1 Model verification

Figure 4a shows a histogram of the predicted diameter increment of 100 simulations (solid line: mean increment=3.36 cm). The dashed lines represent the mean observed increment (3.35 cm) and the standard error of the mean. For St. Gallen, the simulated means are situated clearly within the error bounds of the observations. The accuracy is –0.01 cm or –0.3% of the mean observed increment. The precision of the model is 3.32 cm. The theoretical excess error estimated with cross-correlation ($\hat{E}_{cross}$, Eq. (4)) is 18%. This demonstrates that the growth function of the model is well calibrated for the Pre-Alps.

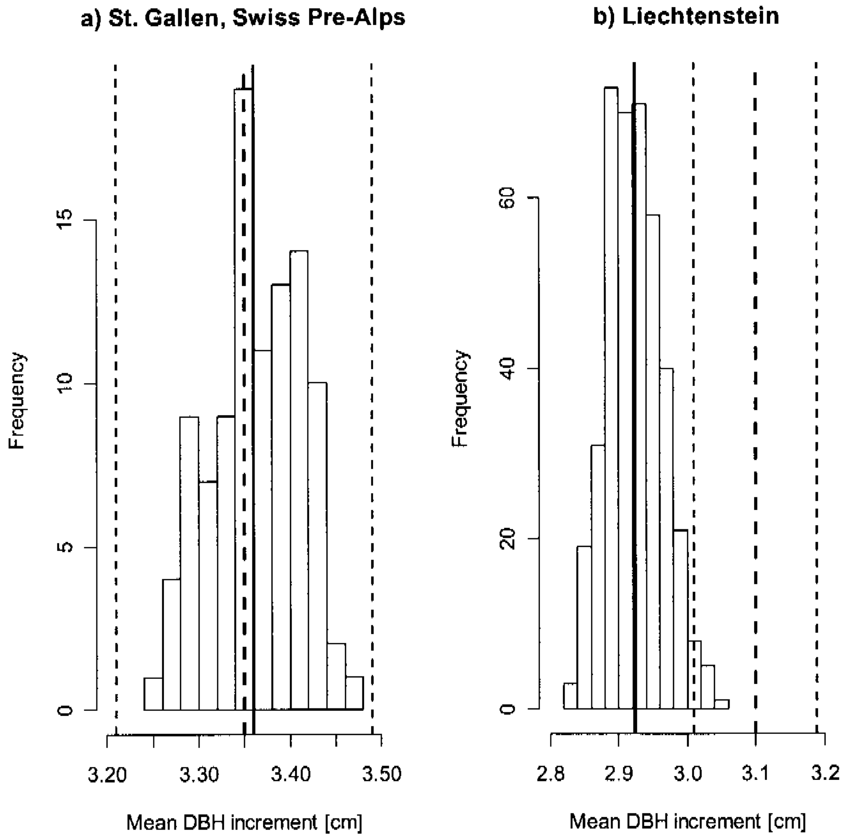
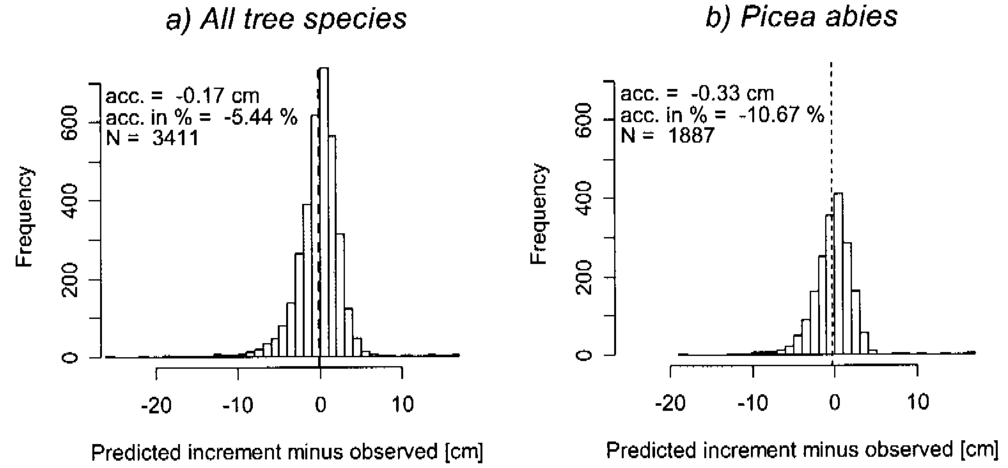


Fig. 4. Distribution of the mean predicted DBH increment. Dashed lines: mean observed increment and error of the mean; solid line: mean estimated DBH increment; a) Data from St. Gallen, Swiss Pre-Alps, 137 sample plots, 1520 single trees, N=100 simulations; b) Data from Liechtenstein, 304 sample plots, 3411 single trees, N=400 simulations

3.2 Test with independent data

3.2.1 Analysis of overall model accuracy, precision and excess error

A comparison of the predicted versus the observed diameter increment shows an accurate agreement (Fig. 4b). The mean observed increment is 3.10 cm, the simulated mean is 2.93 cm. The model accuracy is -0.17 cm or -5.44% compared to the observed increment. The precision is 3.42 cm. The Wilcoxon signed rank test of the variation of the single trees (Fig. 5a) shows no significance (P-value = 0.83) to reject the hypothesis that the true mean of the residuals is equal to zero. Therefore, considering the large variation of the growth prediction of the single trees, the overall mean single tree increment of diameter is estimated accurately by the model. The empirical excess error was estimated with Eq. (3) and amounts to 2.92%, which is much smaller than the theoretical excess error (18%). Therefore, the variation of the residuals in Liechtenstein is smaller than the theoretically expected variation.



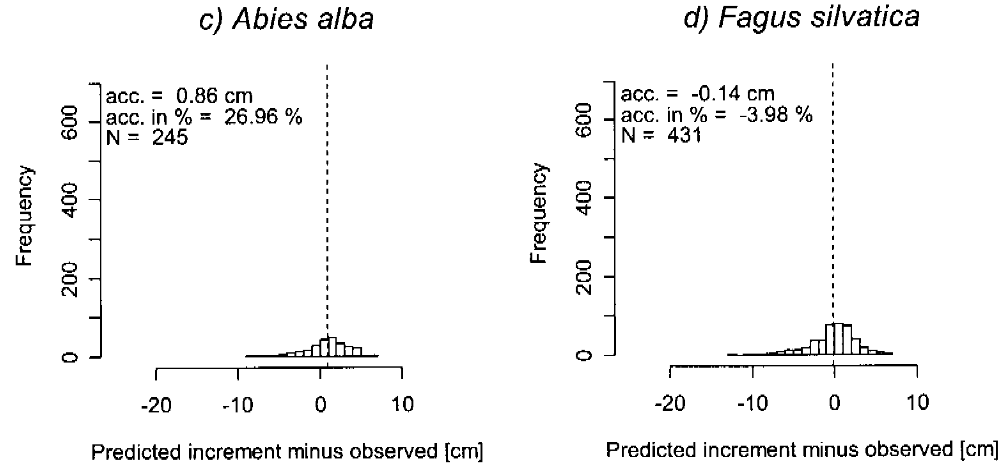


Fig. 5. Comparison between predicted and observed single tree increment: a) All tree species, b)-d) stratification according to the dominant species in Liechtenstein. Accuracy and accuracy in % of the mean observed DBH increment. The coefficients for the growth function are from the Swiss Pre-Alps. The percent specification of the accuracy refers to the mean observed increment of the stratified group.

3.2.2 Analysis of mean residual variance

To investigate the reliability of the error term ε_i the means of Monte Carlo simulations with varying parameter values were compared with the distribution of the simulated means based on the stochastic model term ε_i (Fig. 6). The distribution of the mean diameter increment from Liechtenstein generated with the stochastic model term (dashed line, corresponding to the histogram in Fig. 4b) is compared to the predicted means generated with varied parameter values (solid line). The simulations with parameter variation show a similar distribution as the simulations with the stochastic model term. This visual inspection suggests that the residual variance can be reproduced adequately by the stochastic model term. To analyze the predictions of single tree growth, the stochastic model term was omitted.

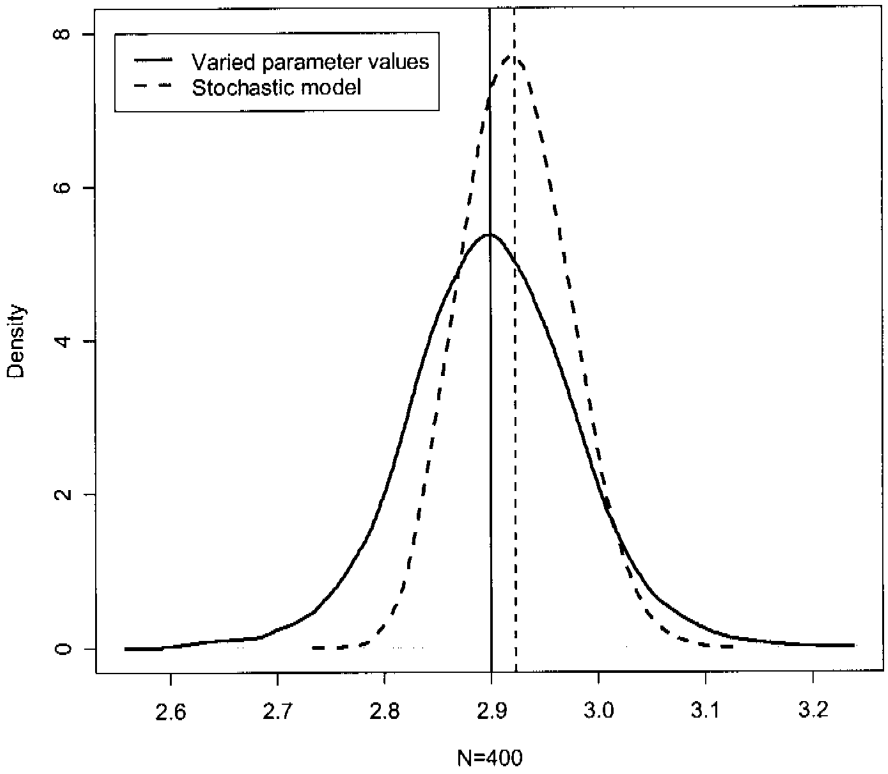


Fig. 6. Mean DBH increment. Comparison of Monte Carlo simulations with multivariate normal-distributed regression parameters and stochastic model simulations, N=400 simulations.

3.2.3 Stratification of single tree increment

To evaluate whether the difference between predicted and observed increment is similar across tree species or DBH classes, stratified single tree increment was analyzed (Fig. 5b-d). Considering the three main tree species separately, significant deviations can be found. While beech shows no significant difference (P-value = 0.75), spruce shows 10% higher growth than predicted by the model (P-value <0.0001) whereas fir shows 26% lower growth (P-value <0.0001).

Are the significant differences of the species-specific mean increments the same for different DBH classes? Growth of trees smaller than 36 cm DBH was underestimated by the model by 2.1%, whereas growth of trees larger than 36 cm was underestimated more strongly, i.e. by 9.5%. In Table 2, accuracy, accuracy in % and the P-value of the Wilcoxon signed rank test are given. The data are classified for trees with DBH smaller than 36 cm and trees with DBH equal to or larger than 36 cm. Due to the two concentric NFI sample plots, the selection probability of small trees is lower than that of larger trees. When trees are weighted according to the selection probabilities, the overall relative accuracy of the prediction is about -4.6%, whereas the unweighted relative accuracy is -5.44%. Furthermore, single trees were categorized into 10 cm-DBH classes (Table 3). For beech, all diameter classes are well estimated ($P_w>0.22$). For spruce, diameter increment of small trees (DBH < 30 cm, $P_w>0.57$) is estimated more accurately than that of large trees (DBH >30 cm, $P_w<0.005$).

Table 2. Predicted minus observed increment for all tree species. Comparison of trees and classified in two DBH classes. The percentages refer to the mean observed increment of the stratified group. P_w: P-value of the Wilcoxon signed rank test.

	DBH < 36 cm				DBH > 36 cm			
	Accuracy [cm]	Accuracy in %	P_w	N	Accuracy [cm]	Accuracy in %	P_w	N
All tree species	-0.06	-2.14%	0.03	2102	-0.34	-9.47%	0.003	1309
Norway spruce	-0.18	-6.62%	0.46	1141	-0.56	-15.27%	<0.0001	746
Europ. silver fir	1.17	45.29%	<0.0001	92	0.68	18.95%	<0.0001	153
Europ. beech	-0.03	-0.9%	0.24	285	-0.37	-8.27%	0.12	146

Table 3. Predicted minus observed increment for Norway spruce, European beech and European silver fir. Comparison of all trees and stratification according to different DBH classes. Percentages refer to the mean observed increment of the stratified group. P_w: P-value of the Wilcoxon signed rank test.

	11-20 cm	20-30 cm	30-40 cm	40-50 cm	50-100 cm	All classes
All tree species						
Accuracy	-0.04 cm	0.02 cm	-0.31 cm	-0.3 cm	-0.51 cm	-0.17 cm
Accuracy in %	-1.57 %	0.68 %	-9.16 %	-8.19 %	-12.99 %	-5.44 %
P_w	0.02	0.08	0.11	0.05	0.02	0.83
N	1095	744	713	542	317	3411
Norway spruce						
Accuracy	-0.12 cm	-0.10 cm	-0.40 cm	-0.60 cm	-0.93 cm	-0.33 cm
Accuracy in %	-4.65 %	-3.73 %	-12.08 %	-16.04 %	-22.39 %	-10.67 %
P_w	0.57	0.92	0.005	<0.0001	<0.0001	<0.0001
N	579	411	409	306	182	1887
European beech						
Accuracy	0 cm	-0.02 cm	-0.43 cm	-0.35 cm	-0.25 cm	-0.14 cm
Accuracy in %	-0.01 %	-0.65 %	-10.15 %	-7.45 %	-5.35 %	-3.98 %
P_w	0.44	0.36	0.30	0.22	0.67	0.75
N	172	91	73	58	37	431
European silver fir						
Accuracy	1.14 cm	1.55 cm	0.34 cm	0.7 cm	1.14 cm	0.86 cm
Accuracy in %	61.75 %	61.84 %	8.77 %	19.45 %	36.44 %	26.96 %
P_w	0.006	0.001	0.08	0.005	0.003	<0.0001
N	32	36	67	66	44	245

3.3 Sensitivity analysis

3.3.1 Sensitivity of model coefficients

There are differences between predictions and observations which imply that the model does not make statistically exact predictions for Liechtenstein (Fig. 4b); a reason for this may be that growth conditions in Liechtenstein are somewhat different from those of the Pre-Alps. To assess the sensitivity of the predicted increment according to various parameter coefficients, diameter increment for Liechtenstein was predicted using parameter sets from the Plateau and the Alps. The following analyses are illustrated for spruce, which is the most abundant species in Liechtenstein.

The simulations with different model coefficients (Fig. 7) indicate that the growth of small trees in Liechtenstein (<30 cm DBH) is estimated precisely by the pre-alpine coefficients. However, the growth of the larger trees (>40 cm DBH) is estimated more accurately by the Plateau coefficients. These results suggest that growth conditions in Liechtenstein are more variable than in the Pre-Alps.

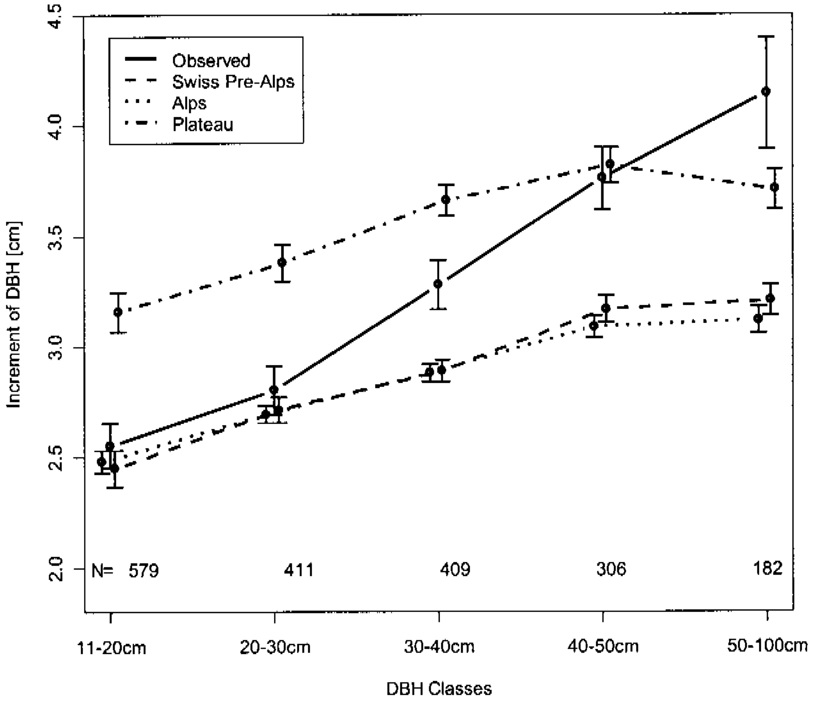


Fig. 7. Predicted and observed DBH increment of spruce per DBH class in Liechtenstein: means and errors of the means. Visual comparison of the simulation results using regression parameters from different calibration data.

3.3.2 Sensitivity analysis of the explanatory variable stand age

Fig. 8 shows the influence of the explanatory variable stand age, which was varied within the standard deviation of the calibrated model for spruce. A systematic increase of stand age by 30 years causes an underestimation of the diameter increment of -17% to -19%. A corresponding systematic decrease of the stand age causes an overestimation of the diameter increment of +21% to +24%. Therefore, stand age has a strong influence on model output.

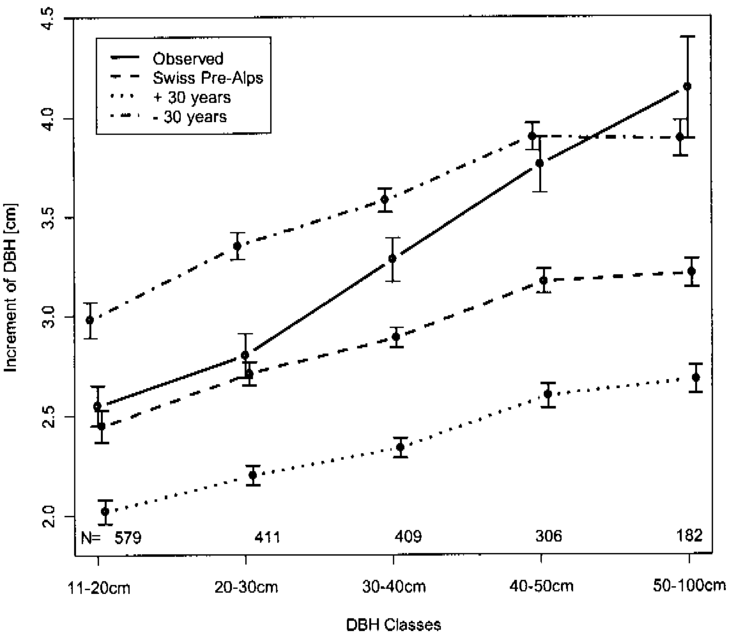


Fig. 8. Sensitivity analysis of the explanatory variable stand age (stand age ± 30 years): means and errors of the means. Predicted and observed increment for Norway spruce in Liechtenstein using parameters from the Swiss Pre-Alps.

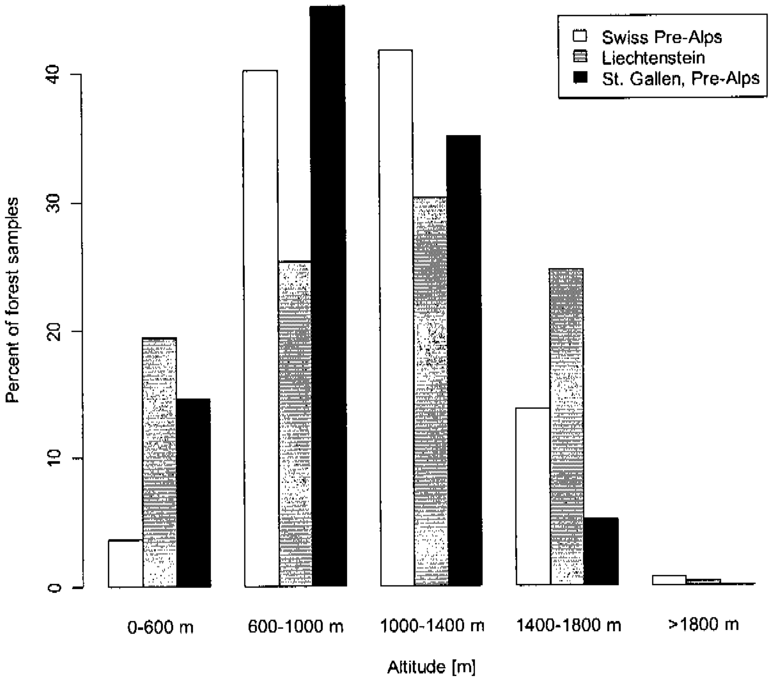


Fig. 9. Distribution of forest samples over altitude classes. Comparison between Liechtenstein, the pre-alpine part of St. Gallen and the Swiss Pre-Alps.

4 Discussion

To validate the BAI model of MASSIMO we compared predicted diameter increment with independent observations and analyzed the differences with a focus on accuracy, precision and sensitivity. Overall, the results indicate that the model accurately predicts diameter increment in pre-alpine regions with similar environmental conditions.

The overall model accuracy was found to be good, as the modelled diameter increment underestimates the observed increment by 5.44%. Regarding the prediction of diameter, the accuracy is even better because of the differing relation (the diameter increment amounts to 12% of the initial diameter: 0.12 x 5.44% = 0.65%). Thus, the underestimation of the predicted diameter is only 0.65%.

The accuracy of the increment predictions varies across the different tree species, ranging from 11% underestimation (spruce) to 27% overestimation (fir), whereas the increment of small spruces is estimated better than large spruces. This can have two reasons. First, the changes of the bole taper of small spruces are less variable than with large trees and therefore the increment can be predicted more precisely. Second, the uncertainty of the explanatory variable stand age is large and increases with increasing DBH. The growth model reacts in a very sensitive manner to stand age; consequently, relatively small systematic under- or overestimations of stand age may result in large over- or under-estimation of the predicted increment. An improvement could be a more exact estimation of stand age, e.g. by dendrochronological methods. Alternatively, forest growth could be estimated without the variable stand age (Monserud and Sterba 1996, Phillips et al. 2003), but this normally causes a lower model precision.

A further reason for the discrepancies between prediction and measurement could be the different distribution of forest area by elevation in Liechtenstein versus St. Gallen or the Swiss Pre-Alps in general (Fig. 9). The forest area of Liechtenstein is distributed quite evenly over the altitudinal zones, whereas more than 80% of the forest area in the Swiss Pre-Alps and the canton of St. Gallen are located between 600 and 1400 m. Therefore, the model fitted in the Swiss Pre-Alps was applied partly outside the range of calibration in Liechtenstein. For the same reason, the model estimates of stand age may be prone to a systematic bias, since this model was calibrated in the Pre-Alps as well, and since DBH is its most important predictor variable. Generally, trees with equal DBH are younger if they grow at a lower elevation, and hence tree growth on lower sites (<600 m) in Liechtenstein may have been overestimated systematically. Thus, we believe that the systematic underestimation of the increment can be explained at least partly.

Empirically based models contain only few assumptions about biological processes or theoretical relations. Instead, they statistically relate measured environmental conditions to the observed tree growth. Therefore, a crucial question is: how accurately can the future forest stock be predicted under different environmental conditions? Yaussy (2000) compared the behaviour of an empirically based single-tree model (Teck and Hilt 1991) with a forest gap model on a short time scale (30 years) against measured data and found that the growth prediction of the empirical model was superior to that of the gap model within the time frame. In the present study, the test data were not situated within the area used for calibration, as in Sterba and Monserud (1997), but they were derived from a different region, and - as pointed out above - the growth conditions were not exactly the same as in the calibration area. The model nicely predicted the diameter increment of the remaining trees, which supports the plausibility of the empirically-based model for predicting the development of the stock for the near future.

Although a model can never be validated conclusively (Popper 1984) confidence in the model's adequacy for a given purpose can be increased if it adequately predicts independent data. There are many ways of model validation. A verification or cross-validation can be done by randomly dividing the calibration data set in two parts, using one part for calibration and the other part for model verification. In our case, such a validation on the basis of the Swiss NFI data would at best confirm the sampling theory, since this data set is systematically randomized. Therefore, in our study we used an arbitrarily selected part of the calibration data to verify model behaviour. A much stronger test for the model is the comparison of its predictions with independent data. The environmental factors in Liechtenstein are comparable to those of the Swiss Pre-Alps, but differences exist in terms of the variation in the distribution of forests over altitudinal levels. The strongest model test of an empirically-based model would have to be performed with a totally different data set. For example, such a test could be done by predicting tree growth for Austria. Furthermore, the results could be compared to the Austrian forest stand growth simulator PROGNAUS (Monserud and Sterba 1996). However, models can only be evaluated in relative terms, and their predictive value is always open to question (Soares et al. 1995). Furthermore, the acceptance or rejection of a null hypothesis (the model adequately represents observations) is not the answer to the evaluation of a model. If the null hypothesis is rejected, the question is where and why the model failed and what can be done to improve it (Soares et al. 1995), while acceptance still leaves some uncertainties.

However, the results of this study suggest that the growth function implemented in the scenario model MASSIMO is a reliable tool to predict forest growth in Switzerland for the next few decades. Hence, MASSIMO seems to be a suitable basis to calculate carbon sequestration scenarios.

5 Conclusion

Empirically-based models need to be validated to increase our confidence in their predictions. As long as the model produces reasonable results, the strength of the validation increases with increasing differences between the calibration and the validation data set. MASSIMO predicted growth of the independent data in Liechtenstein satisfactorily, which raises confidence in the accuracy of the model for predicting the development of the forest stock over the next few decades. The growth model implemented in MASSIMO performed best with European beech and Norway spruce, the major forest species in Liechtenstein, which dominate also in Switzerland. Main differences between observed and predicted basal area increment occurred mostly for larger DBH classes, where the increment was underestimated by the model. The increment of silver fir, on the other hand, was overestimated significantly by the model. However, these differences may be related to the precision of input variables such as stand age. For future model development, either the variable stand age should be estimated more reliably or the growth function should be constructed without the use of stand age.

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Evaluation of a large-scale forest scenario model in heterogeneous forests: A case study for Switzerland

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Abstract

Large-scale forest scenario models are widely used to simulate the development of forests and to compare the carbon balance estimates of different countries. However, as site variability in the application area often exceeds the variability in the calibration area, model validation is important. The aim of this study was to validate the European Forest Information Scenario model (EFISCEN) outside the conditions for which it was developed. As Switzerland exhibits high spatial and climatic diversity, it was taken as a case study. The model output was compared to measured data in terms of initialization, estimation of growing stock, stand-age, increment, management and natural mortality. Comparisons were done not only at the country level, but also for regions and site classes. The results showed that the initialisation procedure of EFISCEN works well for Switzerland. Moreover, EFISCEN accurately estimated the observed growing stock at the country level. On a regional level, however, major differences occurred. Especially the distribution of the harvesting amounts to different forest types, the mortality and the age class distribution deviated considerably from the empirical values. For future model applications, we therefore propose to define the harvesting amounts not only per country, but also for smaller regions. Moreover, we recommend that the EFISCEN simulations should be improved by refining the mortality function and by incorporating more flexibility in forest management practices.

Keywords: Model evaluation, forest carbon, Switzerland, Picea abies, EFISCEN

1 Introduction

There is compelling evidence that nowadays forests in the northern hemisphere are absorbing atmospheric carbon (Goodale et al. 2002). Assessing these carbon pools in forests and the carbon fluxes between forests and the atmosphere has become scientifically and politically significant (IPCC 2000, Wofsy 2001). Various methods have been developed to estimate these pools and fluxes, including (1) inverse modelling based on a network of CO_2 measurements in the atmosphere (Gurney et al. 2002), (2) detailed measurements of gas-exchange above the forest by eddy correlation techniques (Baldocchi 2003), (3) the use of biogeochemical models (Churkina et al. 2003), (4) the analysis of land-use change (Houghton 2003), (5) the use of forest inventory data (Fang et al. 2001, Goodale et al. 2002, Shvidenko and Nilsson 2002), or a combination of these methods (Pacala et al. 2001). In Europe, many countries have developed prognosis models based on their national forest inventories that are used to project forest development under different scenarios (Soares et al. 1995, Sterba and Monserud 1997, Karjalainen et al. 2003). Although in most cases these models were not designed especially for quantifying carbon pools and fluxes, they can still be applied to estimate carbon by using conversion functions or factors (Lehtonen et al. 2003, Zianis and Mencuccini 2004). The simulation results of these models are, however, usually not directly comparable, since the models tend to differ in approach, level of detail and processes taken into account. Moreover, not every country in Europe has such a tool available, which makes it difficult to compile a European overview.

One model that can be used at the European scale is the EFISCEN model (Nabuurs et al. 2000). It is a widely-used matrix model for assessing the development of forest resources under different scenarios. It is especially suitable for large-scale assessments (>10,000 ha) over medium to long periods (20-50 years). The main advantage of EFISCEN is that it is not very data intensive, thus enabling European-wide applications. EFISCEN was originally developed in Sweden (Sallnäs 1990) and aimed at the typical Scandinavian situation of rather homogeneous, even-aged forests, managed in a traditional manner with a clear distinction between thinning and clearcut (Nabuurs et al. 2000). The model has since been applied to all countries in Europe in various studies (Nabuurs et al. 2003, Schelhaas et al., in prep.[1]).

The EFISCEN model comprises many complex, partly implicit assumptions which are valid for the original calibration conditions in Scandinavia (Nabuurs et al. 2000). However, not all forests in Europe correspond to the Scandinavian conditions. Some are more heterogeneous with small-scale variability in tree species, size, age and harvesting amount. The proportion of uneven-aged forests where no clearcut takes place is large, and also in the even-aged forests, the final felling areas are small. This results in deviations from the classical even-aged forest template. Therefore, it is important that the model EFISCEN is validated not only at the country level, but also at a more detailed level, such as for regions and site classes. Moreover,

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[1] Schelhaas M.J. Van Brusselen, J., Pussinen, A., Pesonen, E., Schuck, A., Nabuurs, G.J. and Sasse, V., 2005. Outlook for the development of European forest resources, Geneva timber and forest discussion paper [online]. Available from http://www.unece.org/trade/timber/docs/efsos/03-sept/dp-e.pdf [cited 14 January 2005].

it is important to evaluate not just the aggregated summary output, but also the various model components and assumptions, as suggested by Soares et al. (1995) and Yang et al. (2004). This is a good way for gaining insights into the potential problems of a model (Vanclay and Skovsgaard 1997).

In this study, we investigate how the EFISCEN model performs under conditions different from those for which it was developed. For this purpose, we took Switzerland as a case study. Switzerland is spatially and climatically highly diverse. This diversity is captured to a large extent in the Swiss National Forest Inventory (NFI). Furthermore, we test whether EFISCEN, which works well at the national level, also functions well at the regional and sub-regional level. Specifically, we are interested to evaluate whether deviations at these finer scales are averaged out at the national level. Therefore, a canton in Switzerland was chosen having highly variable sub-regions, both varying in climate, but also in management. As forests in the Plateau and the Pre-Alps are more accessible than Alpine forests, a gradient in management regimes exists, with fewer management interventions in forests in the Alps. A further advantage of using Switzerland as a case study is the availability of repeated measurements from independent permanent plots in some cantons since around 1970.

The main research questions are: (1) How accurate does EFISCEN initialise forest stands? (2) How well does EFISCEN simulate the development of growing stock, stand age structure, increment, management and natural mortality on a regional and sub-regional level? (3) Which model assumptions might be responsible for deviations of the simulation results from the measured data?

2 Concept of the EFISCEN model

The following description of the EFISCEN model was largely taken from Nabuurs et al. (2000) and Schelhaas et al. (in prep.). A detailed description of the model can be found in Pussinen et al. (2001). EFISCEN is an area-based matrix model (Fig. 1), where the cells represent age- and volume-classes. EFISCEN is especially suitable for analyses of large areas, e.g. for a region or a country. The forest area of interest can be classified into different forest types defined by region, owner, site class and/or tree species. This classification depends on the level of detail of the initialization data, the observed variability and the size of each of the resulting forest types. The minimum area that can be traced within the model is 1 ha, but in order to reduce the effect of rounding errors, individual forest types should preferably be at least several thousand hectares. The initialization data needed per forest type have to be stratified by age classes. For each age class, the forest area, the mean standing volume, and the current annual increment have to be given. For each forest type, a separate matrix is set up consisting of an area distribution over 60 5-year age classes and 10 volume classes (Fig. 1).

2.1 Matrix initialization

To keep the required initialization data to a minimum, only the total area and the mean volume is required. Therefore, the volume distribution per age class (matrix columns) is not taken from the initialization data, but generated by an empirically based function. For this purpose, EFISCEN uses a modified normal distribution with the following form (Sergey

Zudin, personal communication):

$$f\langle x\rangle = \mathrm{N}\langle \mu_i, s_i^2\rangle * f_{corr} \tag{1}$$

with μ_i denoting the mean volume in age class i (from the inventory data), s_i^2 the assumed variance in age class i, and f_{corr} is given according to:

$$f_{corr}\langle x\rangle = 1 + \alpha_1\left[-\frac{1}{6}(3x - x^3) + \frac{10}{720}\alpha_1(x^6 - 15x^4 + 45x^2 - 15)\right] + \alpha_2\frac{1}{24}(x^4 - 6x^2 + 3) \tag{2}$$

where α_1 and α_2 are parameters to adjust the shape of the distribution. By default, their values are α_1=1 and α_2=2, but they may be changed to adjust for irregular distributions. If f_{corr} is negative, it is set to zero.

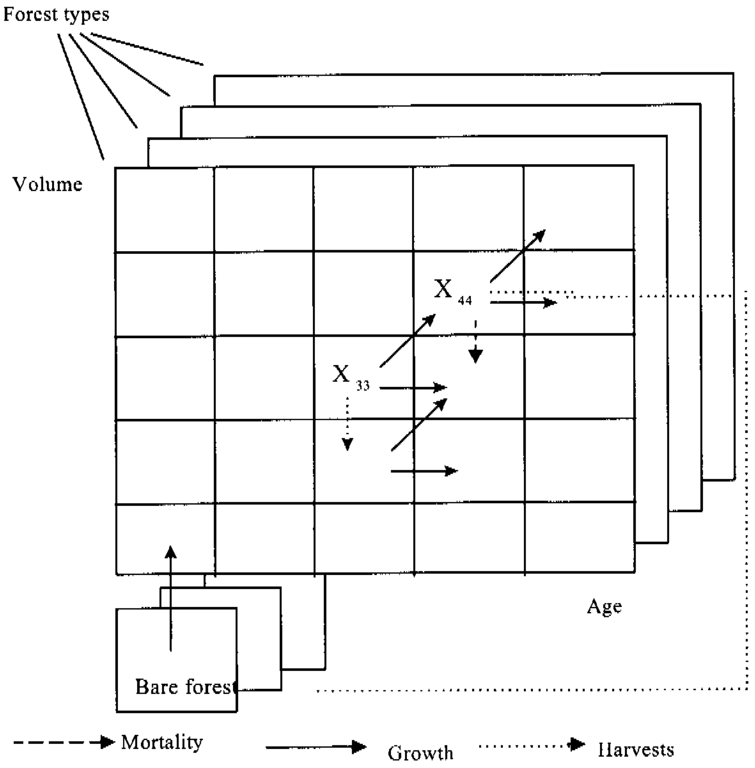

Fig. 1. The area matrix approach of the EFISCEN model (Pussinen et al. 2001).

The variance s_i^2 of age class i is calculated as

$$s_i^2 = kT_i \tag{3}$$

where T_i is the mid point of age class i. k is calculated according to:

$$k = \frac{(1-cr^2)(\overline{V} * cv)^2}{\overline{T}} \tag{4}$$

where $\overline{V}$ is the average volume for the forest type, $\overline{T}$ its average age, cv is the coefficient of variation in volume per hectare, and cr the correlation between volume per hectare and age. The parameter cv is usually set to 0.65 for all forest types, whereas cr ranges from 0.45 to 0.7, depending on the tree species, whether site classes are distinguished or not, and whether the forests are well stocked (see Pussinen et al. 2001). The larger the correlation between volume and age, the smaller is the variance.

This distribution function is used to distribute the total area per age class over the volume classes. The lower and upper limits of the volume classes are not constant but can differ between the matrices. The upper limit of the largest volume class, denoting the highest volume class per matrix, is calculated in the following way. Three times the largest standard deviation calculated by Equation 3 is added to the largest volume per hectare from the initialization data. The range between zero and this upper limit is then divided into a sequence of 10 volume classes of equal width.

2.2 Growth function

In the EFISCEN model, growth dynamics are simulated by shifting proportions of the area numbers (X) in the matrix from one cell to other cells (Fig. 1). At each five-year time step, the area in each cell will move up one age class. Part of the area of a cell will also move to a higher volume class, thus simulating volume increment. Areas in the top volume class cannot grow to a higher volume class. These growth dynamics are influenced by three factors: the growth function, the so-called "young forest coefficient", and a "growth boost" after thinning. The "young forest coefficient" defines the percentage of the temporary non-forested land, so-called bare forest that is moved to the lowest age-volume cell of the matrix per time step. The growth function is incorporated as relative growth of the following form:

$$I_{vf} = a_0 + \frac{a_1}{T} + \frac{a_2}{T^2} \tag{5}$$

where I_{vf} is the five-year volume increment in percent of the standing volume, T is stand age in years, and a_0, a_1, a_2 are coefficients. These coefficients are usually obtained by a regression on the initialization data series, or alternatively from yield tables.

2.3 Management

Management is taken into account at two levels in the model. On the first, more detailed level, a basic management for each forest type is defined in the form of thinning and final felling regimes. These regimes can be regarded as constraints on the total cutting level. Thinning regimes are defined by the range of age classes for which thinning can be carried out. Final felling is controlled by assigning a percentage value to each matrix cell. This percentage value defines the maximum area allowed to be felled. On the second, coarser level, the total final felling amount as well as the amount of thinning is specified for the whole country and for each time step. Taking into account the restrictions of the specific management regime as outlined above, the model harvests the required amounts. Thinning is done in the matrix of each forest type by preventing part of the area in a cell from moving to a higher volume class. The thinned volume then results from the prevented transition. In the following time steps, each of the thinned areas has a slightly increased probability of growing into the next higher volume class, indicating a small growth boost (Pussinen et al. 2001). Not until having received this growth boost, thinned areas can be thinned again. A final felling is done by removing part of the area from a certain age-volume cell. The average volume of that cell is then the harvested amount of wood. This area is transferred to the bare forest land (Fig. 1).

2.4 Natural mortality

In the version of EFISCEN that has been applied in most European scale studies, natural mortality only takes into account a basic level of mortality, disregarding large-scale disturbances. To simulate the death of a few trees, a mortality percentage of the area can be specified for each matrix cell. At each time step, the defined area percentage in the matrix cell is moved into the next lower volume class. This percentage can vary according to forest type, volume and age.

3 Data

The validation of the matrix initialization in EFISCEN was done using the plot data of the Swiss National Forest Inventories (NFI) I and II (Brassel and Brändli 1999). These data were chosen because a large amount of sample plots were required to be able to stratify and test the volume distribution of the plots not only for age classes, but also for volume classes. The Swiss forest area is commonly divided into five production regions: Jura, Plateau, Pre-Alps,

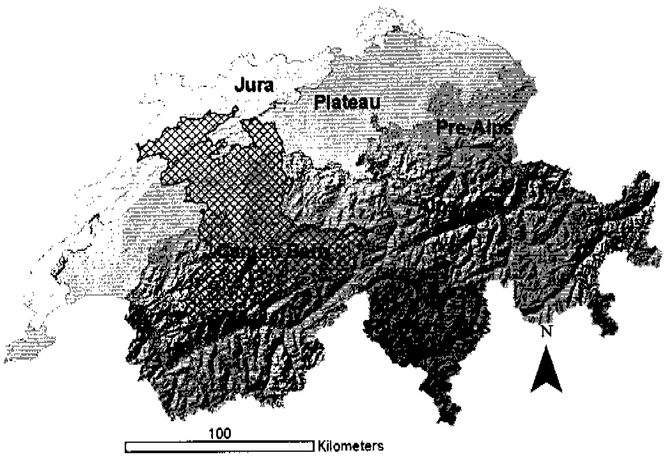

Fig. 2. The five Swiss forest production regions and the Canton Bern.

Alps and Southern Alps (Fig. 2). These regions differ not only in elevation, climate and geology (limestone versus granite), but also in the growing stock of the forests, the management regime and the main forest functions.
Model simulations were validated with the help of inventory data of the Canton Bern because repeated inventories spanning up to 30 years were available. Around 1965, the Canton Bern started to establish permanent plots for forest management planning. These plots have been re-measured between one and three times and cover four different production regions: the Plateau, the Pre-Alps, the Alps and the Jura (see Fig. 2). The sampling method applied was described by Schmid-Haas et al. (1993). Circles with a fixed area (300 or 400 m^2) were distributed systematically. Two different inventory designs were used: rectangular grids with a cell size of 80x150 m (1 plot per 1.2 ha) in the Jura, the Plateau and the Pre-Alps, and triangular grids with a side length of 150 m (1 plot per 2 ha) in the Alps. Within these circles, all trees with a DBH equal to or larger than 8 cm were measured. As there were not enough plots situated in the Jura for our purposes, we considered only the other three regions.

To evaluate EFISCEN with the independent data from Canton Bern, the calibration of the growth function as well as the parameterisation of the other model components was inherited from the most recent application of EFISCEN in Switzerland, the European forest sector outlook study, EFSOS (Schelhaas et al., in prep.).

4 Validation methods

4.1 Matrix initialization

The matrix initialisation was done by distributing the total area of the initialization data over the volume classes of the EFISCEN matrices using the distribution function described in Equations 1 and 2. The mean of this function is defined by the initialization data; its variance, however, is usually parameterized by model-endogenous parameters. With the availability of the NFI plot data, we were able to check the accuracy of this theoretical distribution. To do so, we derived the required initialization for the model (mean standing volume and total area per age class) from the NFI data, and initialized forest matrices based on the same parameters as in the EFSOS study (Schelhaas et al., in prep.). We then compared the generated distribution in the matrices with the NFI plot data. For this test, we selected all NFI plots dominated by conifers (defined in the NFI as a share in the basal area of more than 90%, Brassel and Brändli 1999) located in the Plateau, the Pre-Alps or the Alps. From this set, we used only those plots for which a stand age had been assessed in the field, i.e. 84% of the plots. In the resulting data-set, we distinguished for each production region two site classes. Based on the assessment of soil quality in kg dry wood (production) ha^{-1} yr^{-1} (Lischke and Brassel 2000), we decided to distinguish between poor sites (<3000 kg dry wood ha^{-1} yr^{-1}) and rich sites (>=3000 kg dry wood ha^{-1} yr^{-1}). This is a deviation from previous studies for Switzerland (Schelhaas et al. 2002, Nabuurs et al. 2003) where normally six site classes were distinguished. Our approach was chosen to ensure that the number of NFI plots per age class was large enough for the statistical test to have reasonable explanatory power and accuracy (see below).

To assess how accurately EFISCEN initialized the matrices, we visually compared the model-generated volume distribution per age class with the empirical distribution derived directly from the NFI II plot data. Furthermore, we applied the Kolmogorov goodness-of-fit test (Conover 1999) to compare the empirical distribution with the theoretical distribution function (Equations 1 and 2). We also investigated if small volume classes are fitted better by the theoretical distribution function than large volume classes or vice versa. For this purpose, the age classes were stratified into three volume classes, small (<300 m^3/ha), medium (300-600 m^3/ha) and large (>600 m^3/ha). The Kolmogorov goodness-of-fit test was applied to all these sub-classes.

4.2 EFISCEN simulations in the Canton Bern

To validate how accurately the EFISCEN model simulations are, we applied the model to the period where repeated inventories were available for the Canton Bern. For this purpose, we selected all the plots dominated by conifers (in Bern defined as a share in the volume of more than 80%) that had been re-measured at least twice, excluding the ones in the Jura production region. It can be assumed that each sample plot is representative for 200 ha. As a forest type is made up of at least 35 sample plots, the EFISCEN criterion of minimum forest area is met. Based on soil quality data, we distinguished 4 different site classes: poor sites (1500 kg dry wood ha^{-1} yr^{-1}), moderate sites (1500-3000 kg dry wood ha^{-1} yr^{-1}), rich sites (3000-4500 kg dry wood ha^{-1} yr^{-1}), and very rich sites (>4500 kg dry wood ha^{-1} yr^{-1}). Many plots had been re-measured only twice, and only some plots spanned a times series of 30 years (see Table 1). To use as much of the data as possible, we decided to perform two different simulations, one over 20 and the other over 30 years. Both simulations were initialized with the available measuring data as listed in Table 1.

Table 1. Overview of the data from Canton Bern. Number of sample plots of coniferous stands (>80% of volume) according to production region.

	20 years (3 measurement)	30 years (4 measurements)
Date of first inventory	1970-1980	1967
Plateau	1171 plots	-
Pre-Alps	2648 plots	-
Alps	140 plots	140 plots

To compile the required initialization data for EFISCEN, stand age had to be assigned to each plot, since this was not surveyed in the field. Stand age was estimated using the regression function derived from the NFI I & II (Kaufmann 2000):

$$age = \exp(b_0 + b_1 \bullet DDOM / \ln(GWL) + b_2 \bullet ALT + b_3 \bullet INC / MBAL) \qquad (5)$$

where *age* is the estimated stand age, *DDOM* is the mean diameter of the 100 thickest trees per ha, *GWL* is soil quality, *ALT* is altitude, *INC* is the increment of the survivor trees, and *MBAL* is the mean basal area diameter. This function was calibrated based on tree-ring counts on the stumps of freshly cut stems on the sample plots (Kaufmann 2000). As we had no information about stand structure, the stand age function was applied to all the plots. Plots with a growing stock smaller than 50 m^3/ha were assumed to have undergone a clearcut and were assigned a stand age of 5 years. To estimate the age class distribution of the initialization data at the time point of the third measurement (after 20 years), all forest plots were simply assumed to be 20 years older. Again, plots with a growing stock smaller than 50 m^3/ha were set to a stand age of 5 years. This simple procedure was preferred to applying Equation 5 to the re-measured plots, because the uncertainty of equation 5 is large. Thus, the estimation of stand age for the re-measurements after 20 years is only a proxy for real stand age.

For the initialisation and parameterisation of the model, the same procedures and parameters were used as in the EFSOS study (Schelhaas et al., in prep.). For management, this implies that thinning is possible from a stand age of 20 years up to 110 years, and final harvest starts at year 80, with increasing probabilities in higher age and volume classes. For the lowest site classes (<3000 kg dry wood ha^{-1} yr^{-1}), these values are increased by 20 years. These limits are based on information from the country correspondents within the EFSOS study, yield tables and the expertise of the model operators. Mortality is a constant percentage of 2% of the area in the matrix cell which is moved into the lower volume class as outlined above. In the age classes older than 100 years, this percentage is increased by 0.25% with every 5 year age class. For the highest volume class, this percentage is multiplied by 3. The parameterization of the growth function stratified by region was based on NFI I data and on expert knowledge. The total harvesting amount was derived from the plot data from Canton Bern. At each re-measurement, the total amount of cut and mortality on the plot was assessed. Since no distinction was made between natural mortality and harvest, we had to correct the total amount for natural mortality. Total mortality for all plots was estimated from the growing stock, using a constant percentage per region derived from the NFI I & II (Brassel and Brändli 1999). As in the EFSOS project, 40% of the harvesting volume was assumed to originate from thinning, and 60% was assumed to originate from clearcutting. To evaluate growing stock, increment, age-class distributions, harvest and mortality, we compared the simulated values visually with the values derived from the subsequent inventories.

4.3 Growth function

The EFISCEN growth function used in this study was parameterized for the EFSOS study based on NFI data and on expert knowledge. The relative importance of this function for the simulations results in the Canton Bern was therefore investigated. The growth function (Equation 5) was applied to project forest growth, starting from the initialization data of Canton Bern. In the initialization data of the 20-year and 30-years, mean standing volume and forest area are given per age class. For each age class, growth was calculated by multiplying the mean standing volume taken from the initialization data with the relative growth derived from the growth function. The average growth per region was then derived as the mean growth over all age classes, weighted by the forest area per age class. We compared this average growth per region with the empirical increment from the data and the increment simulated by the EFISCEN model.

4.4 Natural mortality

The natural mortality simulated by EFISCEN was compared to empirical data, stratified for age classes. As the data from Canton Bern contained no information about natural mortality, NFI I and II data were used to evaluate the natural mortality simulated by EFISCEN. To calculate the amount of natural mortality resulting from the mortality fractions as implemented in EFISCEN, we applied the specific mortality rates to the matrices initialized with the initialization data from Bern, as follows. To derive the area affected by natural mortality, the area in each matrix cell was multiplied by the specific mortality fraction derived from the mortality function. This area percentage was not transferred to the bare forest, but reduced in volume, since only single trees are affected by this mortality. Consequently, the amount of natural mortality was then calculated as the difference between the actual volume class and the next lower volume class, multiplied by the area. These amounts of natural mortality per matrix cell were then summed up over the age classes. To compare these simulated amounts of natural mortality in the Canton Bern to the empirical amounts derived from the NFI I and II, they were expressed as the relative percentage of the growing stock.

5 Results

5.1 Matrix initialization

We tested the age class distribution generated by EFISCEN against the measured growing stock distribution from the NFI plots (Table 2). Figure 3 visualises the two distributions for two subgroups with a high and a low p-value. When we look at the results over all plots (Table 2), the only significant differences between the two distributions were for poor soils in the Alps. The results for the volume subgroups, however, yielded more significant differences, especially in the subgroup with the lowest volume. Overall, however, there were not many significant differences, except for poor soils in the Alps. They clearly have the worst score, with five out of 12 age classes showing a significant difference in the lowest subgroup.

Table 2. Results of the Kolmogorov goodness-of-fit test for the differences between the empirical distribution of the mean growing stock within an age classes (based on NFI plot data) and the distribution generated by EFISCEN (p values). Empirical values were additionally stratified for volume groups.

a) Plateau, rich soils

Age class	All plots P value (N)	Small <300 m^3/ha (N)	Medium 300-600 m^3/ha (N)	Large >600 m^3/ha (N)
21-40	0.14 (70)	**0.02 (33)**	0.07 (32)	0.49 (5)
41-60	0.36 (18)	0.70 (2)	0.25 (11)	0.76 (5)
61-80	0.34 (35)	- (1)	0.70 (17)	0.55 (17)
81-100	0.66 (74)	- (1)	0.90 (28)	0.71 (45)
101-120	0.25 (59)	0.13 (5)	0.17 (25)	0.32 (29)
121-140	0.52 (33)	- (1)	0.58 (16)	0.41 (16)
141-160	0.43 (5)	-	0.33 (4)	- (1)
161-180	-	-	-	-
> 180	-	-	-	-

b) Pre-Alps, poor soils

Age class	All plots P value (N)	Small <300 m^3/ha (N)	Medium 300-600 m^3/ha (N)	Large >600 m^3/ha (N)
21-40	0.86 (12)	0.75 (8)	0.90 (2)	0.90 (2)
41-60	0.86 (10)	0.95 (6)	0.17 (4)	-
61-80	0.86 (20)	0.66 (6)	0.72 (7)	0.77 (7)
81-100	0.78 (27)	0.29 (10)	0.96 (8)	0.96 (9)
101-120	0.81 (22)	0.85 (4)	0.23 (13)	0.52 (5)
121-140	0.40 (23)	0.88 (2)	0.15 (8)	0.24 (13)
141-160	0.90 (26)	0.83 (7)	0.72 (9)	0.63 (10)
161-180	0.33 (8)	-	0.82 (8)	-
> 180	-	-	-	-

c) Pre-Alps, rich soils

Age class	All plots P value (N)	Small <300 m^3/ha (N)	Medium 300-600 m^3/ha (N)	Large >600 m^3/ha (N)
21-40	0.60 (22)	0.92 (13)	0.62 (9)	-
41-60	0.18 (14)	-	0.53 (12)	0.53 (2)
61-80	0.40 (26)	**0.02 (4)**	**0.04 (12)**	0.08 (10)
81-100	0.87 (52)	0.37 (8)	0.77 (26)	0.70 (18)
101-120	0.59 (55)	0.25 (5)	0.59 (21)	0.24 (29)
121-140	0.58 (35)	0.12 (2)	0.30 (13)	0.48 (20)
141-160	0.38 (17)	0.21 (3)	0.89 (3)	0.55 (11)
161-180	0.98 (8)	- (1)	0.94 (4)	0.76 (3)
> 180	0.11 (14)	-	0.21 (6)	0.57 (8)

d) Alps, poor soils

Age class	All plots P value (N)	Small <300 m^3/ha (N)	Medium 300-600 m^3/ha (N)	Large >600 m^3/ha (N)
21-40	**<0.001 (46)**	**<0.001 (40)**	0.09 (6)	-
41-60	0.80 (26)	0.75 (23)	-	-
61-80	0.51 (50)	0.77 (37)	0.79 (8)	0.44 (5)
81-100	0.22 (62)	**0.02 (32)**	0.85 (24)	0.54 (6)
101-120	**0.01 (66)**	**<0.001 (23)**	0.38 (33)	0.05 (10)
121-140	0.36 (71)	**0.03 (27)**	0.18 (35)	0.07 (9)
141-160	0.20 (120)	**0.04 (50)**	0.12 (54)	0.89 (16)
161-180	0.66 (92)	0.39 (33)	0.17 (42)	0.70 (17)
181-200	0.55 (78)	0.27 (36)	0.17 (31)	0.96 (11)
201-220	0.45 (43)	0.29 (19)	0.49 (14)	0.85 (10)
221-240	0.99 (13)	0.94 (6)	0.88 (5)	0.63 (2)
> 240	0.23 (75)	0.08 (35)	0.49 (27)	0.62 (13)

e) Alps, rich soils

Age class	All plots P value (N)	Small <300 m^3/ha (N)	Medium 300-600 m^3/ha (N)	Large >600 m^3/ha (N)
21-40	0.95 (6)	0.77 (4)	0.69 (2)	-
41-60	0.73 (7)	0.78 (4)	- (1)	0.99 (2)
61-80	0.95 (6)	0.65 (4)	0.24 (2)	-
81-100	0.91 (10)	- (1)	0.23(5)	0.96 (4)
101-120	0.45 (16)	- (1)	0.18 (5)	0.58 (10)
121-140	0.98 (8)	-	0.87 (6)	0.50 (2)
141-160	0.75 (20)	0.81 (6)	0.55 (12)	0.79 (2)
161-180	0.59 (13)	0.99 (4)	0.20 (8)	- (1)
181-200	0.92 (4)	- (1)	-	0.65 (3)
201-220	0.67 (6)	-	0.75 (4)	0.27 (2)
221-240	- (1)	-	- (1)	-
> 240	0.85 (4)	- (1)	- (1)	0.52 (2)

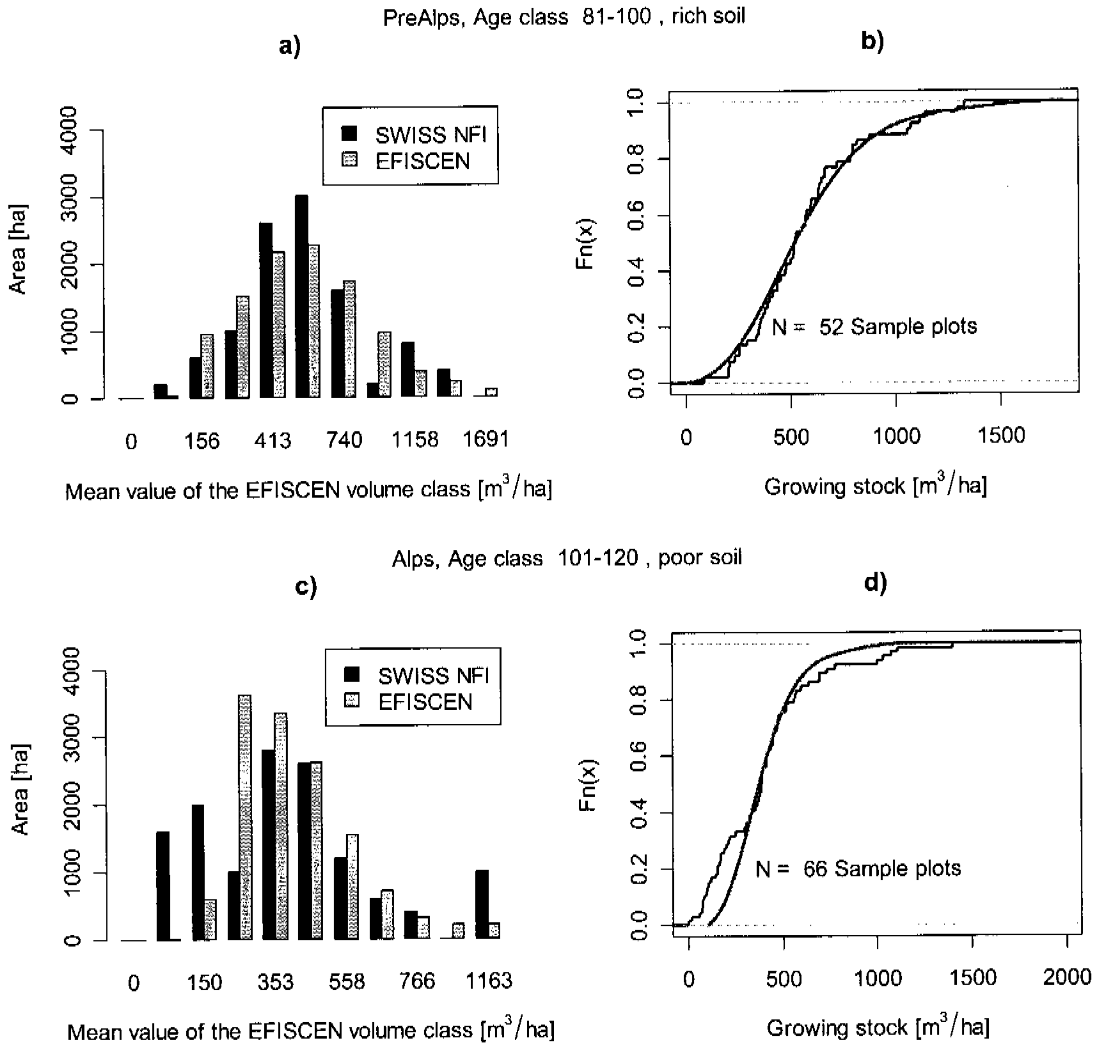

Fig. 3. Comparison of the results from the EFISCEN matrix initialization with NFI plot data for Norway spruce-dominated stands (>90%) in the Pre-Alps (a and b) and the Alps (c and d). a) and c): histogram with increasing class widths. b) and d): empirical cumulative distribution functions of the NFI sample plots (■ black lines) and the function of EFISCEN (■ grey lines). P-values of the Kolmogorov goodness-of-fit test for all data are displayed in Table 2.

5.2 EFISCEN simulations in the Canton Bern

For the whole of Canton Bern, the average growing stock development for the 20 year simulation was acceptable (Figure 4). After 20 years, the model overestimated the average growing stock by 29 m^3 ha^{-1}. At the regional level, however, the results looked different. In the Plateau, the growing stock was overestimated considerably, and in the Alps, it was underestimated considerably. According to the inventory data the growing stock in the Alps increased by 35 m^3 ha^{-1}. However, in the model it decreased by 80 m^3 ha^{-1}. For the Pre-Alps, the model agreed very well with the observed development.

For the 30 year simulation, only plot data for the Alps were available. Here, the simulated development of growing stock agreed very well with the observed pattern, resulting in an underestimation of only 8 m^3 ha^{-1} after 30 years.

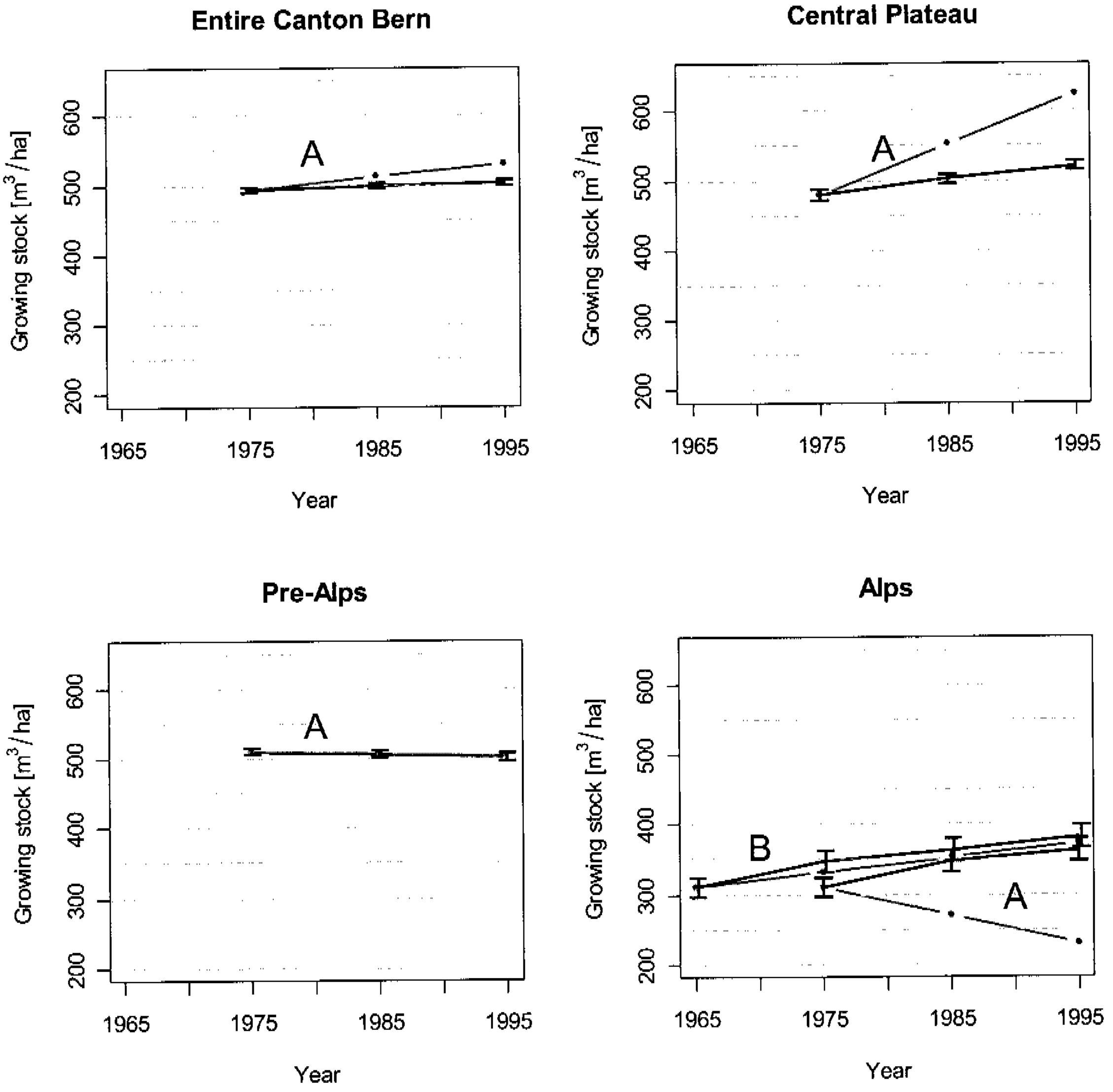

Fig. 4. Development of growing stock in the simulations for the whole of Canton Bern and for the different regions. A) 20-year simulation, B) 30-year simulation. Grey line: mean simulated growing stock. Black line: mean observed growing stock and standard error.

For the entire of Canton Bern, the small overestimation of the growing stock can be attributed to an overestimation of the increment and a large underestimation of the mortality (26%, Table 3). However, the deviation of the increment was not too high (10%), and since the increment was an order of magnitude lower than the growing stock, the deviation relative to the growing stock was still quite small. The influence of the mortality was even smaller, since it was again about a factor 10 smaller than the increment.

The large overestimation of the growing stock in the Plateau arose from a considerable overestimation of the increment combined with a significant underestimation of the harvest. Since the deviations were larger (19%) than for the entire Canton Bern, and the harvest as well as the increment were of about the same magnitude, their combined effect was a substantial overestimation of the growing stock. For the Pre-Alps, most simulations were quite close to the measured data. The small overestimation of the harvest was compensated for by a small overestimation of the increment and an underestimation of the mortality. In the Alps, the large decrease in growing stock in the 20 year simulation was due to a very large overestimation of the harvest. The underestimation of the mortality compensated only for a small amount of this. The harvesting amount was close to reality only with the 30 year simulation for the Alps. The underestimation of the increment was partly compensated for by an underestimation of the mortality, leading to a rather good simulation of the growing stock.

Table 3. Increment, harvest and mortality (in m^3 ha^{-1} yr^{-1}) as simulated by the model (averaged over the entire simulation period, "Mod.") and as estimated from the permanent plots ("Obs."). a) Absolute values for whole of Canton Bern and for the three sub-regions. b) Deviation (in %) of the modelled values from the observed data.

a) Absolute deviations

		Canton Bern		**Plateau**		**Pre-Alps**		**Alps**	
simulation		Obs.	Mod.	Obs.	Mod.	Obs.	Mod.	Obs.	Mod.
20 years	increment	11.15	12.28	14.25	17.29	10.10	10.44	5.22	5.19
	harvest	9.60	9.60	11.48	9.32	9.17	9.80	2.01	8.15
	mortality	1.21	0.90	0.79	0.79	1.38	0.94	1.50	1.04
30 years	increment	-	-	-	-	-	-	5.45	4.55
	harvest	-	-	-	-	-	-	1.59	1.53
	mortality	-	-	-	-	-	-	1.43	0.94

b) Deviations of simulation results relative to the observations

		Canton Bern	Plateau	Pre-Alps	Alps
20 years	increment	10%	21%	3%	0%
	harvest	0%	-19%	7%	305%
	mortality	-26%	0%	-32%	-31%
30 years	increment	-	-	-	-16%
	harvest	-	-	-	-4%
	mortality	-	-	-	-34%

Figure 5 shows the initial age class distribution and the simulated distribution after 20 years. In the Plateau, the stand age class distribution simulated by EFISCEN after 20 years looked quite similar to the distribution calculated with Equation 5 based on NFI data. The most important difference was a slight overestimation in the first age class, partly at the expense of the older age classes. For the Pre-Alps and the Alps, the same pattern is evident, but it is much more pronounced. In the Alps, about half of the area was simulated to be in the first age class after 20 years.

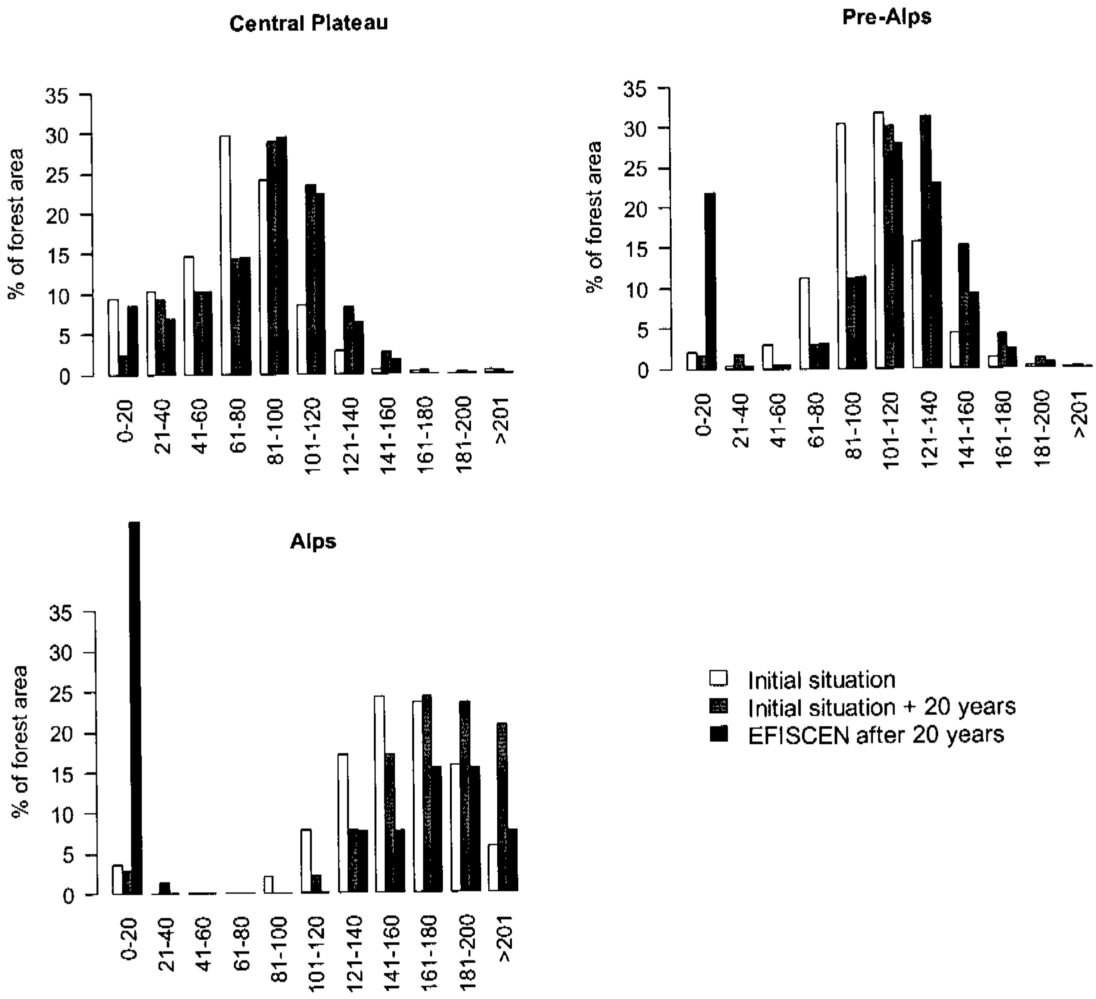

Fig 5. Distribution of age classes. □ Initial stand-age class distribution as estimated by the NFI model for stand age. ▨ Expected situation after 20 years (all stands are twenty years older, and plots with less than 50 m^3 ha^{-1} were assumed to have undergone a clearcut). ■ Simulated stand-age class distribution as simulated by EFISCEN after 20 years.

5.3 Role of the growth function

The application of the growth function alone to the 20-year initialization data from Canton Bern revealed that the growth function used in EFISCEN overestimated actual increments by 23% for the Plateau, by 8% for the Pre-Alps and by 8% for the Alps. If we compare these percentages with the corresponding numbers in Table 3b, the effect of the parameterization of the growth function on the model simulations can be assessed. The overestimation of increment in the Plateau (21%) can be explained by the parameterization of the growth function. In the Alpine region, the EFISCEN simulations of increment over 20 years agreed quite well with the observations. However, according to the growth function analysis, the model should overestimate the increment by 8%. These results indicate that model components other than the growth function itself underestimate net increment in the Alpine region (e.g., the growth boost).

Applying the growth function to the initialization data of the 30-year measurements, we found no difference between the measured and the calculated increments. This implies that for the plots in the Alps, the growth function parameterized with the NFI data and expert knowledge fits the validation data from Canton Bern. However, from the 30-years simulation (Table 3b), we saw that the EFISCEN model underestimates growth by 16%. Therefore, this underestimation confirms the hypothesis that EFISCEN underestimates increment in the Alpine region.

5.4 Natural mortality

From Figure 6 it is evident that natural mortality for forests in the Plateau simulated with EFISCEN was close to that in the NFI. For the Pre-Alps, simulated mortality seemed to be reasonable in the youngest age classes, but according to the NFI data, the mortality increased much faster than projected by EFISCEN. For the Alps, the deviations were much larger and the mortality function assumed in EFISCEN approximated the level derived from the NFI data only for the very high ages.

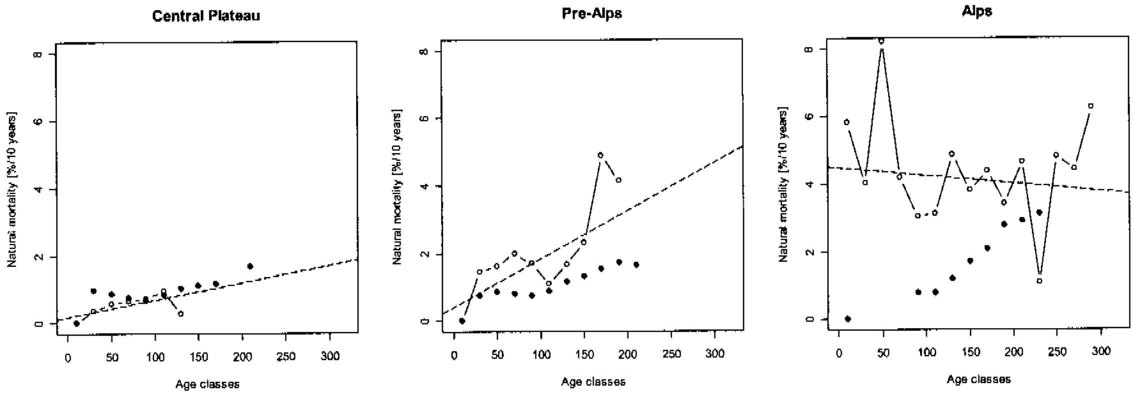

Fig. 6. Empirical and simulated natural mortality per 10 years as a percentage of the growing stock. o Natural mortality estimated with the help of NFI data (Brassel and Brändli 1999); • Natural mortality simulated by EFISCEN. Plots are stratified according to 20-year age classes. The dashed line is a linear regression analysis of the NFI data weighted with the number of NFI plots per age class.

6 Discussion

6.1 Matrix initialization

For the Plateau and the Pre-Alps, we found that the frequency distribution over the volume classes as simulated by the EFISCEN model was very similar to the empirical distribution. However, on poor sites in the Alps, five of the small and one of the large volume subgroups differed significantly from the empirical distribution. The deviation in the small volume subgroups was caused by a large number of observed forest plots with a low growing stock, also in the higher age classes. These plots result from the fact that in reality, Alpine forests often fulfil a protection function against avalanches, erosion and rockfall. Therefore, clearcutting is kept to a minimum and mainly applied as a consequence of natural hazards such as windthrow or bark beetle attacks. In most of the forest stands, nearly all harvesting is done by thinning, and thereby only the growing stock is reduced, but not the stand age. This is illustrated by the fact that 51% of the harvested area between NFI I and II was the result of sanitary felling, and only 28% of thinning (Brassel and Brändli 1999).

6.2 EFISCEN simulations in the Canton Bern

The accuracy of the simulated growing stock varied strongly across the regions. For the simulation of growing stock, different processes play a role, which is discussed below.

6.2.1 Management

The most striking deviation of the model predictions from reality was in how harvesting is distributed over the regions. The model showed a high preference for harvesting in the Alps, leading to a gross overestimation of harvest. At the same time, harvesting in the Plateau was underestimated. In the model, the distribution of harvesting over the regions is regulated by the definition of the management regime, which influences the probability that a forest stand with certain characteristics (i.e. age, volume, site class, and region) will be thinned or felled. The theoretical management regimes used in EFISCEN were the same for all regions, with felling probabilities increasing with age. Since stands in the Alps are generally older than the ones in the Plateau, the model predicts that they are harvested first. However, these theoretical regimes do not take into account information about harvesting costs, accessibility or additional forest functions. Harvesting is less intense because in the Alps, the forests are less accessible than in the Plateau and the Pre-Alps and have a protection function against avalanches and rockfall.

Another important consideration is that the implementation of harvesting in EFISCEN is restricted to either thinning or clearcutting. However, because of the following reasons, this may lead to difficulties in countries such as Switzerland. (1) In EFISCEN, thinning can not be set much higher than 40% of the harvesting amount. As explained in the methods section, not until having received the growth boost, thinned areas can be subjected to thinning again. Thinned areas are therefore locked for a certain time. Moreover, the maximal possible thinning amount is the increment from the last 5 simulation years. (2) In Switzerland, it is often difficult to assign actual silvicultural interventions to either clearcutting or thinning. The typical regeneration technique, for example, is often not a clearcut carried out within one year, but it spans 20-30 years to enhance natural regeneration. (3) The spatial extent of clearcuts is usually small, particularly in the Alps. The number of edge trees that can profit from reduced competition and react with enhanced growth is therefore quite large at the landscape scale. This may cause part of the underestimation of the increment in the Alps. Taken together, we conclude that the current version of the EFISCEN model has an insufficient flexibility with respect to adjusting particular cases of forest management.

6.2.2 Age class distribution

Especially in the longer term, deviations of the simulated stand age class distribution from the actual one affect the simulated increment in EFISCEN (Nabuurs et al. 2000). We therefore compared the distribution of the age classes simulated with EFISCEN after 20 years with the age class distribution generated with Equation 5 (Figure 5). The high harvesting amount in the Alps was the reason for the extreme shift to the youngest age class in this region. The same pattern was also evident in the Pre-Alps, even though the harvest was close to the observed amount. Even in the Plateau, where the harvest was underestimated, the simulated amount of young forest was already higher than the amount calculated with Equation 5. Although this method of calculating and updating the age class distribution was quite coarse, the large deviation between the EFISCEN generated age class distribution and this updated distribution indicate that the EFSCEN generates too much young forest. The large amount of young forests results from the large percentage of clearcut of 60% of the total harvesting amount defined in the methods section. Therefore, a marked contrast exists between the modelled clearcut amount of 60% of the harvesting amount and the reality. Since thinning and clearcut sum up to 100% of the total harvesting amount, and as outline above, thinning can at maximum be 40%, the clearcut amount can not be set lower than 60%.

6.3 Growth function

To determine the effect of only the growth function on the one hand and the effect of the rest of the growth components (young forest coefficient, growth boost) on the other hand, the growth function alone was applied to the initialization data from Canton Bern. In the Alps, this application resulted in an exact estimation of the increment in the 30-year simulation (0% deviation from the reality) and an overestimation of 8% in the 20-year simulation. According to Table 3, the EFISCEN model underestimates growth in the 30-year simulation in the Alps by 16% and in the 20-year simulation by 0%. Therefore, the underestimation of increment by the EFISCEN model in the 30-year simulation is not caused by the growth function, but by other model processes. In the 20-year simulation, the overestimation by the growth function is compensated by an underestimation by the other growth components of 8%. The main difference between these two simulations is the amount of harvest. In the 30-year simulation, the harvest level is close to the reality, whereas in the 20-year simulation, the harvesting amount is much higher. Apparently, the high harvesting level has a stimulating influence on the increment. In the EFISCEN model simulations, growth stimulation in connection with a high harvesting amount can be due either to intensive thinning, since there is a growth boost after thinning, or to the young forest coefficient (outlined in the method section) because more forest is being regenerated. As the underestimation of growth in the 30-year simulation is larger than in the 20-year simulation, one or both of these parameters may be too low.

In the Plateau, the EFISCEN model overestimates growth by 21%. However, as the application of the growth function on the initialization data shows, the growth function alone overestimates the increment in the Plateau by 23%. Therefore, the growth function (which was calibrated with Swiss NFI data and expert knowledge for the EFSOS study), applied in the EFISCEN model, does either not optimally represent growth in Switzerland, or the data from Canton Bern are not representative for Switzerland. However, in a regular application of

EFISCEN, we would have used a growth function derived from the initialization data themselves.

6.4 Natural mortality

The level of natural mortality was simulated rather well in the Plateau, but it was strongly underestimated in the Pre-Alps and the Alps. The simulated natural mortality is influenced primarily by the mortality function, and to some extent also by the distribution of the forest area over volume classes (matrix initialization) and the simulation of the stand age class distribution. In this study, we were able to show that the initial distribution of the forest area over age and volume classes is reasonable; therefore, we can expect that the mortality functions we used have had the largest influence on the simulated level of natural mortality.

Although natural mortality plays a minor role in the estimation of the growing stock, it is a very important source of litter. A soil carbon model can be and has been coupled to EFISCEN (Liski et al. 2004), and in that case a correct simulation of natural mortality is of crucial importance for good estimates of soil carbon. Modelling natural mortality in a more realistic way should be based on regional data describing the empirical correlation between growing stock and mortality or on theoretical assumptions regarding competition. In the dense forests which currently prevail in Switzerland, the modelling of density-related mortality should be supported with corresponding data, such as from primary forests (Korpel 1995).

6.5 Limitations

In age-class models such as EFISCEN, stand age is a crucial variable. Such models are therefore particularly useful in forests that experience stand-replacing disturbances such as clearcut-harvest, fire, windthrow or severe insect outbreaks (Goodale et al. 2002). Due to these stand-replacing disturbances, forests tend to be even-aged, and stand age can therefore quite easily be defined. This is often not the case in Switzerland. First, not all Swiss forests are even-aged. While in the Plateau most of the forest area (96%) fulfils this condition, the percentage is only 71% in the Pre-Alps and 64% in the Alps. Therefore, the percentage of the forest area that can be modelled well by EFISCEN is large in the Plateau but smaller in the Alpine region. Second, even on the so-called even-aged sites, stand age is difficult to estimate in Switzerland. Often the stands were not planted at a known time but have developed naturally. Many stands have a highly heterogeneous structure due to (1) the above-mentioned harvesting regimes, (2) site conditions, or (3) non-stand-replacing natural hazards such as storms or insect damage. Moreover, clearcutting tends to play a small role in the forest management and, until now, fire, severe insect outbreaks and windthrow have been restricted to relatively small areas. Therefore, it is often difficult to estimate stand age. As a result, the validity of the surveyed stand age is questionable and difficult to verify. In many forest growth models, the variable stand age is therefore omitted intentionally to avoid problems with uneven-aged forests (Wykoff 1990, Monserud and Sterba 1996, Zhao et al. 2004). Vanclay (1995) even suggests that in mixed species forests exhibiting a wide range of life forms and stem sizes, age is irrelevant as a predictor variable.

As we had no records for stand age for the data from Bern, this variable was modelled using a function derived from the NFI. The function was calibrated with the even-aged sites from the NFI and is therefore suitable for modelling just these sites. As the percentage of even-aged stand decreases from the Plateau to the Alpine region, the stand age estimations for the data from Bern are probably more accurate in the Plateau than in the Pre-Alps and the Alps.

In this study, only spruce-dominated sites were taken into account. However, 34% of all Swiss forests are dominated by mixed species (Brassel and Brändli 1999), and simulating mixed species forests with a high diversity would be even more complex and may yield even larger uncertainties (Vanclay 1995, Zhao et al. 2004).

The fundamental aim underlying the development of EFISCEN was to simulate forest development over large areas and to enhance the comparability of the estimates of growing stock and increment across European countries. To diminish the problems of data acquisition, management and quality control (Nelson 2003), the model was aimed at using a limited number of input variables that are available for most of the areas or countries. To mirror biotic and environmental processes with a limited number of input variables, these models often incorporate many implicit assumptions contained in the parameters or model rules (Bolliger et al. 2003). In the EFISCEN model, these rules were adjusted to Scandinavian forest conditions. However, as shown in the present study, not all these internal processes and interactions between the model units are generally applicable to all forest types. In most cases, additional exogenous specifications are needed.

EFISCEN is based on the assumption that the initial mean volume per age class as given by inventory data represents the optimum stocking density as assumed by Assmann (1968). If this assumption is met, EFISCEN depicts the growth-density relationship quite well (Sterba 2003). If the mean initial volume of a stand is lower than the optimum stocking density, EFSICEN tends to underestimate growth (Sterba 2003). Particularly in the Alps, where thinning is the most important management method, stocking density may often be underestimated, resulting in an underestimation of growth.

Forest areas in the top volume class cannot grow to a higher volume class. The lower the amount of clearcutting is, the more area is accumulating in the highest volume class. This can result in a growth reduction. If the EFISCEN model is applied to simulate a more nature-oriented approach of forest management, this artificial growth reduction may cause an underestimation of growth. However, this effect can be mitigated by setting the parameters for natural mortality to more realistic values, e.g., by using a higher mortality in dense stands.

As shown in the 30-year simulation in the Alps, where the implemented harvest volume was equal to the observed amount, adjusting the harvest volume generally improves the simulation results. We therefore recommend running the model per region and using region-specific information about the distribution of harvesting amounts. Moreover, the simulation results could also be improved if the mortality was based on region-specific data, especially for dense forests where density-related mortality plays an important role. Furthermore, more flexible tools to specify the forest management could ensure a better reliability of the model simulations. One critical point of EFISCEN remains the use of the variable stand age, which is difficult to determine in many forests.

To keep the input data and initialization data simple, large-scale models often aggregate processes on the stand level or on higher levels and condense the assumptions about the system behaviour into single parameters. This may lead to simplifications at the expense of model flexibility to account for different systems. If these aggregated assumptions do not agree with reality, e.g., because of boundary conditions changing in space and time, model applications may not be trustworthy anymore. In this study, for example, the harvesting module of the large-scale model did only contain a dichotomous way to implement management practices. This module was therefore not flexible enough to reproduce harvesting regimes as applied in reality. Modules like this may be designed more flexibly by allowing for process-based assumptions that can be fitted to real data. This is already possible for the growth function, which can be optimally calibrated for each data set.

7 Conclusions

The aim of this study was to evaluate the applicability of the EFISCEN model outside the area for which it was developed. Moreover, we evaluated the model not only on an aggregated (country) level, but we also looked at sub-regions and evaluated single parts of the model and tested some model assumptions.

Overall, the initialisation procedure of EFISCEN seems to work quite well for Switzerland, except for sites with poor soils in the Alps. Deviations are especially pronounced in the plots with low growing stocks, and to a smaller extent in the plots with high growing stocks.

The results of the summarized model output for all the matrices and regions indicate that for the entire Canton Bern, the observed growing stock of the independent data is often estimated accurately as compared to independent data. Moreover, the overall results for the 30-year simulation in Canton Bern did not deviate much from the observed values. However, at the regional level, major differences to the observed values occurred, e.g. the thinning percentages, the distribution of the harvesting amount among the regions, the age class distribution, and the mortality. Therefore, the model outputs growing stock and increment seem to be reasonable at the country scale, but not at a regional scale. Detailed additional information, e.g. derived from plot data as in this study, can help to pinpoint sources of differences. If this information is used to improve the parameterization of the model (for example, for management regime and mortality), it is likely that the results on the regional level will become more realistic. However, the restriction to either thinning or clearcut as it is assumed in the EFISCEN model is not flexible enough to adequately characterize the management practices common in the Alpine region. Therefore, to apply the EFISCEN model for assessing different management practices, the current version of the EFISCEN model should be improved.

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The impact of windthrow on carbon sequestration in Switzerland: a model-based assessment

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Abstract

Carbon sequestered in biomass is not necessarily stored infinitely, but is exposed to human or natural disturbances. Storm is the most important natural disturbance agent in Swiss forests. Therefore, if forests are taken into account in the national carbon budget, the impact of windthrow on carbon pools and fluxes should be included. In this article the forest scenario model MASSIMO and the soil carbon model YASSO were applied to assess the effect of forest management and an increased storm activity on the carbon sequestration in Swiss forests. First, the soil model was adapted to Swiss conditions and validated. Second, carbon fluxes were assessed applying the two models under various forest management scenarios and storm frequencies. In particular, the influence of clearing after a storm event on the carbon budget was analyzed. The evaluation of the model results showed that the soil model reliably reproduces the amount of soil carbon at the test sites. The simulation results indicated that, within the simulated time period of 40 years, forest management has a strong influence on the carbon budget. However, forest soils only react slightly to changes in the aboveground biomass. The results also showed that a storm frequency increase of 30% has a small impact on the national carbon budget of forests. To develop effective mitigation strategies for forest management, however, longer time periods must be regarded.

Keywords: windthrow; validation; soil organic carbon; forest management; MASSIMO; YASSO

1 Introduction

Temperate forests play an important role in the global carbon cycle (Tans et al. 1990). Their contribution ranges from accumulating biomass and acting as a carbon sink to releasing carbon in decay processes and acting as a carbon source (Houghton 1993, Ciais et al. 1995). Compared to other European countries, the growing stock in Swiss forests is high (366 m^3 stemwood ha^{-1}) and the annual increase in growing stock large (3.2 m^3 stemwood $ha^{-1}year^{-1}$) (Brassel and Brändli 1999). This means that, at present, despite the age structure and the annual harvesting of 5.1 m^3 stemwood ha^{-1}, Swiss forests still accumulate aboveground biomass. Old forests potentially act as significant carbon sinks (Knohl et al. 2003), on the one hand, but, on the other hand, the risk of losing wood as a result of natural hazards increases. Therefore, if forests are to be accounted as carbon sinks, it is important to estimate the potential risk that they may become sources of carbon if natural disturbances such as windthrow occur. Li et al. (2003) analyzed temporal changes in forest net ecosystem productivity (NEP) for Canadian forests over a period of 75 years and their responses to natural disturbances. They found that the quantity of carbon sequestered in forests is overestimated if disturbances are ignored.

Storms are the most important natural disturbances in Swiss forests (Brassel and Brändli 1999). According to the Swiss National Forest Inventory (NFI), two thirds of all unplanned felling in Switzerland are due to windthrow (Brassel and Brändli 1999). Recent studies have found an increase in extreme climatic events (Zwiers and Kharin 1998, Schär et al. 2004) which means the probability of severe storms occurring may also increase (WSL and BUWAL 2001). A literature review by Schelhaas et al. (2003) indicates that windthrow damage in Europe has increased in the past century. However, they point out that the data in the literature is not all objectively reproducible and not continuously consistent. In Switzerland, three severe storms during the last 40 years, (in 1967, 1991 and 1999) have taken place (Pfister 1999). With the help of Swiss storm data for the last 500 years, Pfister drew a Gumbel-diagram and derived a frequency of severe storms of 12-15 years (Pfister 1999, p. 47). Whereas the local effect of heavy storms can be very high and can have profound impact for (private) forest owners (WSL and BUWAL 2001), the national effect of storms is usually less pronounced and can even have positive ecological effects (Schönenberger 2001, Frey and Thee 2002).

To assess the vulnerability of future forest stands model simulations are a useful tool. As the last three storms in Switzerland varied strongly in their severity, recurrence time and area affected, average rates of disturbances can be misleading. Instead, the spatial patterns and variations over time should be taken into account in simulating carbon pools and fluxes (Li et al. 2003). In this study, we used a scenario model (MASSIMO) to estimate the amount of the aboveground carbon (Kaufmann 2000a). The growth function of this model was validated by Thürig et al. (2005). They found that the basal area per ha of independent data was underestimated by 0.65%. These findings indicate that the estimates of the aboveground biomass are reliable. To estimate the dynamics of belowground carbon, we adapted the soil carbon model (YASSO) (Palosuo et al. 2001, Masera et al. 2003). This model is designed to work in a large sector of conditions, ranging from boreal to tropical regions (Liski et al. 2003). It has been applied already at many different sites (Nabuurs and Schelhaas 2002), but has never been tested in alpine conditions. So it was validated for alpine conditions fore the first time in this study.

Traditionally, windthrow areas in Switzerland have been cleared the by forest service. The 1990 storm (Vivian) resulted in an enormous amount of windthrow timber. As timber prices were low, many windthrow areas were not cleared. Since then, public acceptance of forest management where windthrow areas are not cleared has increased, acknowledging both economical and ecological points of views (Schönenberger 2001, Frey and Thee 2002). There have, however, been only a few studies of the effects of the two management alternatives on carbon sequestration. For example, Janisch and Harmon (2002) examined C gains and losses from tree boles and coarse woody debris (CWD).

This study aims to assess the influence of an increased frequency of storms on the permanence of forests to act as carbon sinks. The focus is on: (1) adapting and evaluating the applicability of the soil carbon model YASSO for Switzerland; (2) investigating the influence of different management regimes and storm effects on the fluxes and pools of carbon in forests. This leads to the following research questions: a) How does an increased harvesting of large trees affect the C balance? b) How does no-clearing influence the belowground C budget? c) How does an increasing storm frequency affect above- and belowground C?

2 Models, Methods and Data

2.1 Study area

Model simulations were done for the accessible forest areas in Switzerland surveyed in the first and the second NFI (1986, 1996). Norway spruce (*Picea abies*, 40%), beech (*Fagus silvatica*, 18%) and silver fir (*Abies alba*, 11%) are the dominant tree species in Swiss forests (Brassel and Brändli 1999). These forests can be divided into five productivity regions; the Jura, Plateau, Pre-Alps, Alps and Southern Alps (Fig. 1). These regions not only differ in elevation and geology (limestone versus granite), but also in the growing stock of the forests and in the climate. In the Plateau and the Jura temperate conditions dominate, whereas the other regions are affected by a marked altitudinal gradient ranging from intra-Alpine and continental (annual precipitation < 500 mm), through insubrian (July temperature > 20 °C, annual precipitation > 1600 mm) to cold climates (Alps) (Brzeziecki et al. 1993).

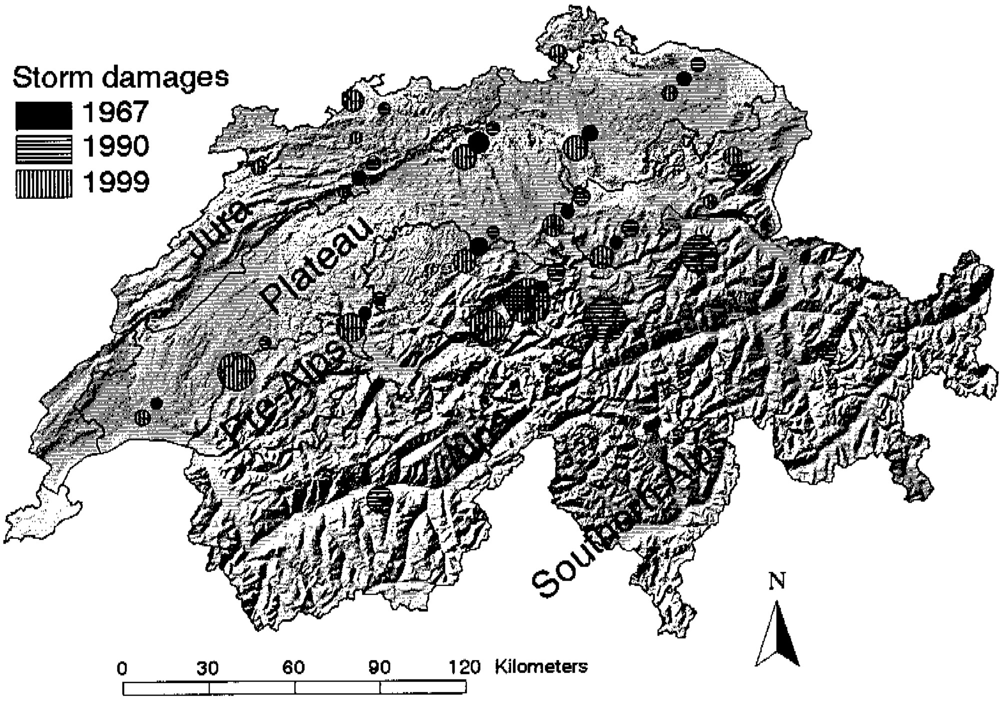

Fig. 1. Study areas and damage severity of storms relative to the average felling amount per year. The points indicate the severity of the observed storms in the years 1967, 1990 and 1999, relative to the average felling amount per year (1.1 - 6.7 x the average felling amount) as listed in the statistical yearbook of BUWAL (1963-2002).

2.2 Management scenario simulation model (MASSIMO)

MASSIMO (Management Scenario Simulation Model) (Kaufmann 2000a) is a stochastic and dynamic single tree model. It consists of four sub-models: Regeneration, growth, mortality and management scenarios (including harvesting). These four processes are simulated on the basis of empirical formulations derived from data of the first and the second Swiss NFI, recorded at 4400 sample plots (EAFV 1988, Brassel and Brändli 1999). MASSIMO has been used to assess scenarios of forest development in Switzerland (Brassel and Brändli 1999). The time period for projections is limited to approx. 40 years because the model is based on empirical assumptions which do not explicitly take into account changes in environmental conditions.

The growth model constitutes the core of MASSIMO. The implemented growth function was derived from the inventory data and describes the decadal basal area increment (Kaufmann 1996). The increment was estimated on an individual tree basis as a function of site conditions and forest structures. These are updated after each projection decade to take into account their influence on growth in the subsequent decade.

Harvesting is defined as the empirical probability of every single tree for being cut. The probabilities are estimated using logistic regression models, where the explanatory variables are the stand and site characteristics as well as harvest conditions. The models were derived from the NFI data and provide probabilities for regulated (planned logging) and unregulated felling (due to natural disturbances). These probabilities reflect "business as usual" (BAU). By changing these probabilities, various management scenarios can be defined. Mortality is defined as the probability that a single tree will be lost naturally. By selectively increasing the probability for irregular felling, the effects of various types and amounts of natural disturbances can be estimated, and the implications of different management strategies and storm scenarios can be investigated.

2.3 Model of soil organic carbon dynamics (YASSO)

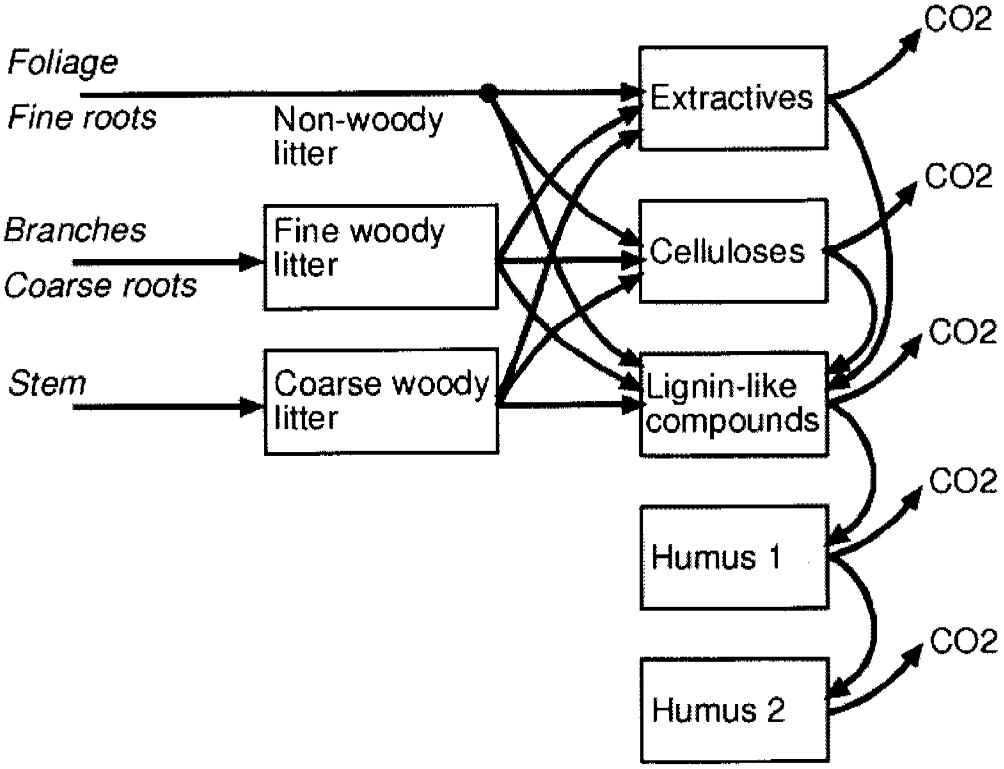

Fig. 2. Flow chart of soil model YASSO. The boxes represent carbon compartments and the arrows the carbon fluxes.

YASSO is an empirical, dynamic, soil carbon model (Karjalainen et al. 2002, Masera et al. 2003), with two litter compartments describing the physical fractionation of litter and five compartments describing microbial decomposition and humification processes in the soil (Fig. 2). The model requires only basic information on litter quality (percentages of extractives, cellulose and lignin-like compounds) and basic climate information such as mean annual temperature and summer drought (precipitation minus potential evapotranspiration between May and September). It can easily be linked to any calculation system that provides estimates of litter production. The climatic dependency of the decomposition rates was determined from an analysis of litterbag data from across Europe and tested using data from Canada and Central America (Liski et al. 2003).

2.4 Model adaptation and validation

2.4.1 MASSIMO

The output of MASSIMO is wood volume. To estimate total tree volume, stemwood volume was expanded using allometric single-tree functions. Functions for twigs (diameter < 7 cm) and branches (diameter > 7 cm) were based on measurements from approx. 12,000 trees (Kaufmann 2000a). Bark volume was estimated using the model by Altherr et al. (1978). Additional allometric functions were used to estimate the volume of coarse roots, based on data from 100 trees, as well as of foliages, based on samples from 400 trees (Perruchoud et al. 1999). Fruit and seed volume were estimated from Rohmeder (1972), depending on DBH and productivity region. To convert total tree volume into carbon, conversion factors for wood density were used as given in Vorreiter (1949), and a carbon content of solid wood of 50% was assumed (Körner et al. 1993). Fine-root biomass was estimated at the stand level as a constant fraction (5%) of the coarse root biomass, following Perruchoud et al. (1999).

Table 1. Average annual litter input originating from living trees, harvest residues, natural tree mortality, but not from understory vegetation.

	Average annual litter input in [g C m^{-2} $year^{-1}$]			
	Non-woody litter Foliage, needles, fine roots	Fine woody litter Branches < 7cm, fruit and seedlings, bark	Coarse woody litter Branches > 7cm, coarse roots, stem	Total C
Jura	226.6	107.4	67.4	401.4
Plateau	245.0	132.8	117.8	495.6
Pre-Alps	243.9	128.2	86.4	458.5
Alps	229.8	94.1	66.9	390.8
Southern Alps	237.9	57.7	55.0	350.6

To calculate the annual litter input for the soil model (Fig. 2), the biomass of the different tree tissues was multiplied by specific lifespans. The lifespan for needle turnover were estimated to be 3 y for Pinus, 7 y for Picea, and 10 y for Abies. Leaves, fruit and seedlings were assumed to be replaced every year. For twigs (diameter < 7 cm) the lifespan was assumed to be 25 y and for fine roots (diameter < 5 mm) 1.36 y (Perruchoud et al. 1999). The lifespan of coarse wood (branches > 7 cm, stemwood, coarse roots, and bark) was derived from the mortality observed between the NFI I and II (Brassel and Brändli 1999). Harvesting residuals (whole tree biomass minus merchantable timber) were assumed to remain in the forest. Table 1 shows the calculated average annual litter input per production region between 1986 and 1996.

2.4.2 Parameterization and validation of YASSO for Switzerland

The specific chemical compositions of the non-woody litter (needle, leaf and fine roots) for deciduous and broadleaf trees were based on Heim and Frey's (2004) findings, which are summarized in Table 2. This chemical extraction data were treated as follows: The sum of the non-polar and water-soluble extractives was used for the compartment called extractives in

YASSO, the acid hydrolysable fraction was used for the compartment called cellulose, and the acid un-solvable residue was used for the compartment called lignin-like compounds.

Table 2. Chemical composition of Picea abies (coniferous trees) and Fagus silvatica (deciduous trees), as given in Heim and Frey (2003).

	Extractives	Cellulose	Lignin-like compounds
Picea abies	31%	44%	24%
Fagus silvatica	17%	47%	36%

Modelled decomposition is sensitive to the climate variables given to the model. As mentioned above, Switzerland is characterized by strong climatic gradients. Therefore, instead of stratifying the entire area of the country according to climate variables, the model was run for each of the 4400 sample plots separately. To evaluate the climate dependency implemented in YASSO, the simulated rates of decomposition in the extractable and the cellulose pools were compared with litterbag data from one site in the Plateau and one site in the Alpine region (A. Heim, unpublished data). As the analytical measurement of lignin is not solely lignin, but a conglomeration of lignin-like compounds, we did not compare the rate of decomposition in the lignin pool.

Climate indices in the form of mean monthly values of temperature and precipitation over a thirty-year period (1960-1990) were calculated for every single sample plot (Zimmermann and Kienast 1999). These values were kept constant for the assessment period from 1996 to 2036. Effective temperature sums with a threshold of 0°C were calculated from the mean monthly temperatures. For this purpose, mean daily values were linearly interpolated from the monthly data as in Liski et al. (2003). The effective temperature sum ranged from 1070 to 4443 degree days. Accumulated potential evapotranspiration between May and September was calculated from mean monthly temperatures according to the Thornthwaite method (Bugmann and Cramer 1998), using bioclimatic variables from Zierl (2001). The summer drought variable (i.e. precipitation minus potential evapotranspiration between May and September) ranged from minus 206 to plus 649. As this variable accounts for the effects of drought, all sample plots with drought values greater than zero (90% of the plots) were assumed to suffer no drought (i.e. summer drought index was assumed to be zero).

The soil carbon stocks were initialised by assuming them to be in a steady state. The steady state was calculated by the average annual litter-fall observed between 1986 and 1996 ((NFI I & II). To achieve mean litter input, averaged values were applied for the five regions Jura, Plateau, Pre-Alps, Alps and Southern Alps (Table 1). As a spin-up run, we started the model with empty C pools and let it run with constant litter input till the pools did not change anymore. This model equilibrium was achieved after approx. 5000 years.

To assess the plausibility of the estimates of the initial soil carbon stocks, these stocks were compared with measurements of soil organic carbon (Perruchoud et al. 2000) sampled in 1993 in a 8x8 km grid during the Swiss Sanasilva-Inventory (Lüscher et al. 1994, Zimmermann 1997).

It is not clear whether dead wood originating from stand-replacing storms decays faster or more slowly than harvest residues left in the stands. If the logs have no contact with the soil, the rate of decomposition could be less due to a lower humidity (Frey and Thee 2002). However, stand-replacing storms drastically change the light management and the nutrient-balance towards an optimum site for herb layers or forbs such as *Rubus idaeus* (Wohlgemuth et al. 2002). This leads to higher humidity close to the forest floor and thus to a higher decay rate. Exponential decay rates implemented in YASSO are 0.077 y^{-1} for logs with diameters larger than 20 cm and 0.03 y^{-1} for logs smaller than 20 cm. Published decay rates of windthrown timber were derived from mass-based studies (Janisch and Harmon 2002, Knohl et al. 2002) and vary from 0.013 to 0.043 y^{-1}. We therefore implemented an additional litter pool for "storm wood" and performed a sensitivity analysis to investigate the effect of different decay rates on the soil organic carbon stock. We ranged the rates between 0.015 and 0.045 for large logs and between 0.0385 and 0.115 for small logs. This is equivalent to varying the decay rate between minus 50% and plus 50%.

2.5 Storm damage

2.5.1 Observed storm damage in Switzerland

The mean area affected by each of the three severe storms in Switzerland was approx. 20,000 km^2. Severe storm activity tends to be restricted to the northern and central parts of Switzerland (Fig. 1). The storm of 1967 covered only the northern part of the country, the storm of 1990 covered the plateau and the pre-Alpine part, while the storm of 1999 covered the pre-Alpine and the Alpine part. This can be explained by the Swiss topography, as the Alps act as a storm barrier (WSL and BUWAL 2001). The amounts of wood thrown in these three severe storms formed the basis for the severity classes used in the modelling.

2.5.2 Implementation of storm damage in the model

To estimate carbon pools and fluxes under various levels of storm severity, two management scenarios were combined with a range of different storm scenarios. First, a storm perimeter of 20,000 km^2 was empirically defined with a random position in the northern or central part of the country. Second, the three severity classes of the past three storms were randomly applied in each decade.

According to the observed damage, we distinguished three types of storm severity and applied them stochastically. Two frequencies were simulated: the observed frequency over the past 500 years of 15 years (Pfister 1999) and an increased frequency of 10 years. Additionally, two treatments after windthrow were distinguished: "clearing" and "no clearing". "Clearing" denotes that the merchantable timber is removed from the forest, whereas the rest of the windthrown trees (i.e. roots, snags, bark, branches and foliages) are left in the forest. As a conservative estimate, we assumed that the woody biomass exported form the site would be released to the atmosphere immediately and thus accounted for it as negative carbon flux.

2.6 Management scenarios

2.6.1 Business as usual (BAU)

Empirical felling probabilities for single trees through planned clear-cut, thinning or unregulated felling due to natural damage events were derived from the NFI I and II. To simulate so-called "business as usual" (BAU), these probabilities were implemented in the simulation model MASSIMO and kept constant for the next 40 years (Kaufmann 2000b). Since it had been estimated that the growing stock will increase, it is predicted that 11% more timber will be harvested between 2006-2036 than between 1986-1996.

2.6.2 Reducing the number of large logs (RLL)

In Swiss forests, the percentage of large logs (> 50 cm BHD) is increasing. Due to changed techniques of wood processing, the demand of wood has changed towards smaller log dimensions. Today, only large logs of a very good quality, amounting to less than 20%, have a high economic value. Therefore, the Swiss Forest Industry is endeavouring to reduce the abundance of these large logs, and to achieve a more balanced stand age structure. To simulate such a scenario, the BAU scenario was used as the basic scenario. After 2006, the planned felling of large logs was increased by 54%.

2.7 Simulation scenarios

Table 3. Scenarios to assess the above- and belowground carbon budget in Switzerland according to different forest management, treatments and storm frequencies.

	No storm	Storm frequency		Business as usual (BAU)	Reducing the number of large logs (RLL)	No clearing (NC)	Clearing (C)
		15 y	**10 y**				
I BAU	X			X			
II BAU		X		X			X
III BAU		X		X		X	
IV BAU			X	X			X
V BAU			X	X		X	
I RLL	X				X		
II RLL		X			X		X
III RLL		X			X	X	
IV RLL			X		X		X
V RLL			X		X	X	

The combination the two management regimes, the two storm scenarios and the two treatments after windthrow resulted in 10 different simulation scenarios. The BAU scenario was simulated applying no storms (BAU I), a storm frequency of 15 years (BAU II & III, clearing and no clearing, respectively) and a storm frequency of 10 years (BAU IV & V, respectively). The RLL scenario was also simulated applying no storms (RLL I), a storm frequency of 15 years (RLL II & III, respectively) and a storm frequency of 10 years (RLL IV & V, respectively). In Table 3, all the combinations are summarized. Results were averaged out of 30 runs to account for the stochastic model parts. The total variability consists of the variability between the model runs and the variability between the sample plots.

3 Results

3.1 Validation of YASSO in Switzerland

The initialization values for soil organic carbon (SOC) and litter organic carbon (LOC) obtained with the assumption of steady state were compared with measured values (Lüscher et al. 1994, Paulsen 1994, Perruchoud 1996, Perruchoud et al. 2000), as listed in Table 4. The simulated SOC values for the Jura, the Pre-Alps and the Alps were very similar to the measured values. For the Plateau, the estimation of SOC by the model was higher than the measurement. However, as the variation of the measured values is extremely large, the model estimates still lie within ±1 standard deviation of the measurements. For the Southern Alps, the simulated SOC was about half as high as the measured one. All estimates of LOC are smaller than those measured.

The measured rates of decomposition were compared with decomposition values used in the model YASSO (Table 5). On these two sites (Vordemwald and Beatenberg), the decomposition rates of extractable compartments and cellulose in the model were similar to the measured rates, indicating that the climate dependency of those compound groups is plausibly implemented in the model.

Table 4. Results of the spin-up run. Simulated versus measured values. YASSO SOC: Extractable, cellulose, lignin and humus I & II; YASSO LOC: fine woody litter & coarse woody litter.

	Soil organic carbon (SOC) and litter organic C (LOC) in [kg C m^{-2}] ± SD				
	YASSO SOC	YASSO LOC	Measured SOC* (N)	Modelled LOC**	Measured LOC***
Jura	8.94±0.6	1.0±0.1	9.1±5.9 (35)	-	1.9±2.0
Plateau	10.3±0.5	1.4±0.1	7.3±3.7 (27)	3.3	1±1.3
Pre-Alps	10.6±0.7	1.5±0.2	9.8±6.3 (32)	2.8	2.7±2.7
Alps	9.9±1.3	1.4±0.2	9.8±7.3 (53)	1.8	2.7± 2.4
Southern Alps	7.7±0.9	0.8±0.2	14.9±8.5 (20)	-	-
Total	9.7±1.2	1.3±0.3	9.9±6.9 (167)	-	-

* Measured by Lüscher et al. (1994), analyzed by Perruchoud et al. (2000)

** Litter quantities taken from Perruchoud, modelled with ForClimD (Perruchoud 1996); Plateau: Basel and St.Gallen, Pre-Alps: Einsiedeln, Alps: Davos and Bever

*** Litter amounts as given in Paulsen (1994); Jura: 800-1200m, Plateau: 400-800m; Pre-Alps: 800-1600m, Alps: 1600-1800m.

Table 5. Decomposition rates: modelled versus measured.

	Chemical compartment	Simulated	Measured*
Plateau	Extractable components	0.74	0.76
(Vordemwald)	Cellulose	0.46	0.43
Pre-Alps and Alps	Extractable components	0.52	0.61
(Beatenberg)	Cellulose	0.33	0.36

* Measured by Alexander Heim (unpublished, personal communication).

Table 6. Simulation of aboveground biomass and roots with MASSIMO. BAU: Business as usual, RLL= Reducing the number of large logs.

	kg C in Biomass (aboveground and roots) m^{-2} ± SD				
	1996	2006	2016	2026	2036
I BAU	12.8±0.2	14.3±0.2	15.8±0.3	17.3±0.3	18.5±0.4
II / III BAU	12.8±0.2	14.2±0.3	15.6±0.3	17.0±0.4	18.2±0.4
IV / V BAU	12.8±0.2	14.2±0.3	15.7±0.3	17.0±0.4	18.1±0.4
I RLL	12.8±0.2	14.3±0.2	14.1±0.3	13.4±0.3	12.3±0.3
II / III RLL	12.8±0.2	14.2±0.3	13.9±0.3	13.3±0.3	12.2±0.3
IV / V RLL	12.8±0.2	14.1±0.3	13.9±0.3	13.3±0.3	12.3±0.4

3.2 Simulation of carbon sequestration under different scenarios

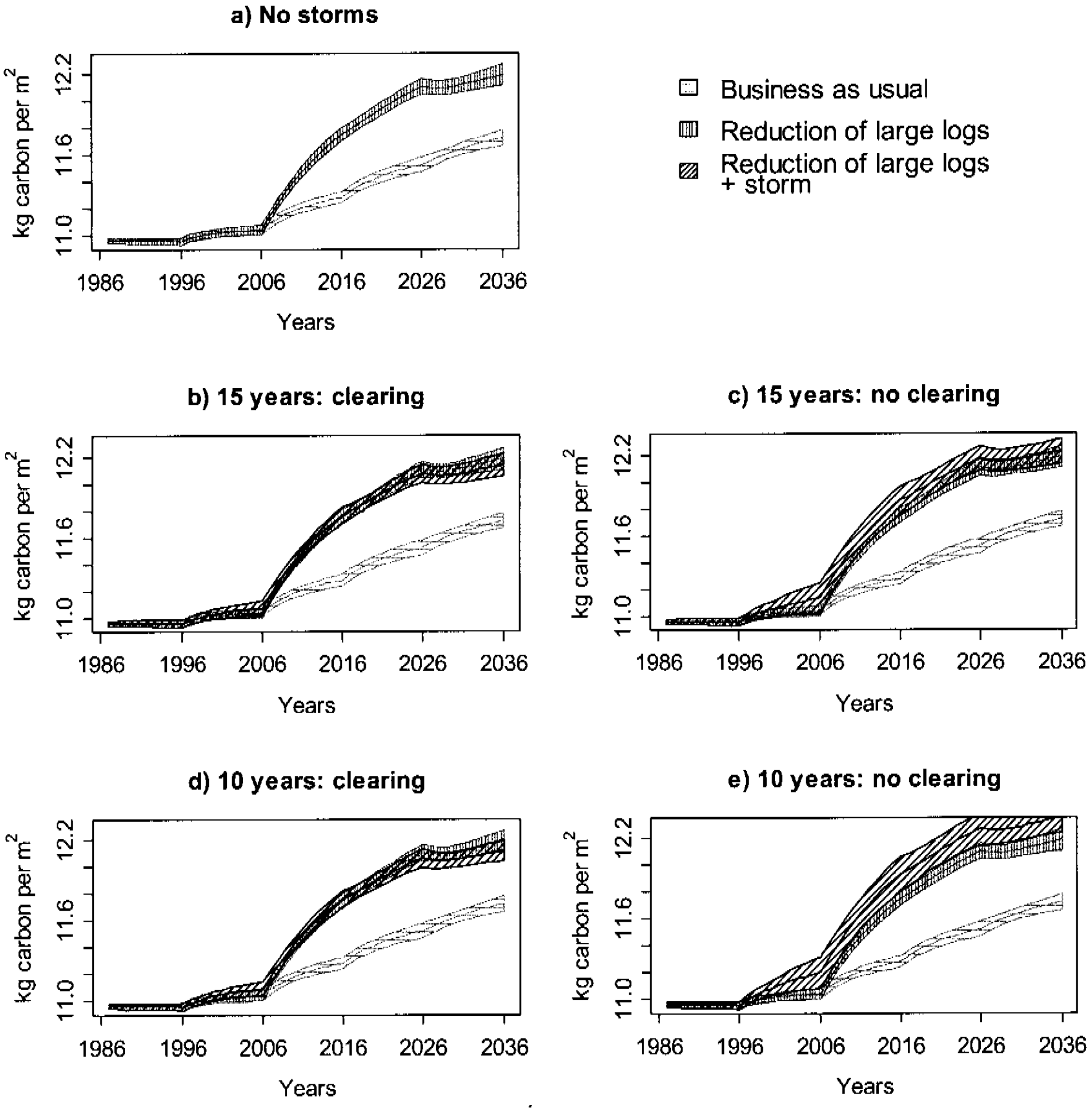

Fig. 3. Predicted soil carbon quantities to 2036. Error bands are standard errors. a) Scenario I: BAU and RLL b) Scenario II, c) Scenario III, d) Scenario IV, e) Scenario V. Scenario I is mapped on all the panels as reference value.

3.2.1 Carbon stock of biomass and soil

To assess the influence of storms on the carbon sequestration of forests, different scenarios were assessed. With the BAU scenario the predicted increase in biomass (aboveground and roots) is up to 44% till 2036 (Tab. 6). Within the same time period, the increase of soil carbon is less pronounced (Fig. 3). The amount of soil carbon starts at a level of 10.96 kg C m^{-2} y^{-1}. As the soil model was initialized to be in equilibrium with the NFI data from 1986 to 1996, the amount of carbon is constant during this period in all scenarios. With the BAU scenario the amount of soil carbon increases slightly by 770 g C m^{-2} (19 g C m^{-2} per year) from 1996 till 2036 (Fig. 3a). This increase is caused by the increase in the aboveground biomass (Tab.

6), which leads to a higher amount of litter input into the soil. The RLL scenario (Fig. 3a) shows a larger increase in soil organic carbon (31 g C m^{-2} y^{-1}) because of the augmented amount of harvesting residuals (coarse roots, branches, stump), which enter into the soil as litter. However, after 2026, the increase slows down, indicating that the soil carbon approaches a new equilibrium point. The results from scenarios II and IV (Fig. 3b and d) indicate that if the merchantable timber is cleared after a storm, the storm has almost no effect on the sequestration of soil carbon in forests. Without clearing, the BAU and RLL scenarios had the largest increase of all scenarios with 27 and 35 g C m^{-2} y^{-1}, respectively (Fig. 3c and 3e). These results suggest that if windthrown timber is not cleared after storms, more soil carbon accumulates than without storms. However, to assess the influence of storms on forest carbon budgets, the soil carbon fluxes must be combined with the biomass fluxes.

3.2.2 Carbon budgets of biomass and soil

To assess the influence of the scenarios on the total carbon budgets, the biomass and the soil carbon pools of 2006 were compared with those of the subsequent three decades.

The soil carbon reference values of the year 2006 vary slightly because in the simulation, the treatments "clearing" and "no clearing" were differentiated from 1996 onwards. The RLL management scenario does not differ from the BAU scenario until 2006. Therefore, this year was taken as the reference year to assess total carbon budgets. All BAU scenarios result in much larger positive carbon fluxes than the RLL scenarios (Fig. 4), because in the RLL scenario the loss of biomass carbon through harvesting is large. However, within the first two decades, this loss is compensated for by the accumulation of soil carbon, resulting in a positive carbon budget for all scenarios. Within the first 20 years, carbon sequestration in the BAU scenarios ranges from 164-174 g C m^{-2} y^{-1}, and in the RLL scenarios from 8-14 g C m^{-2} y^{-1}. Within the third decade, the budget becomes negative for all RLL scenarios (-22 to -29 g C m^{-2} y^{-1}) because there is considerable loss of carbon in the biomass for which the soil can no longer compensate. In the BAU scenario, the biomass also increases in the third decade. This results in a positive carbon budget of 154-164 g C m^{-2} y^{-1}, which varies according to the different storm frequencies and treatments after storm events.

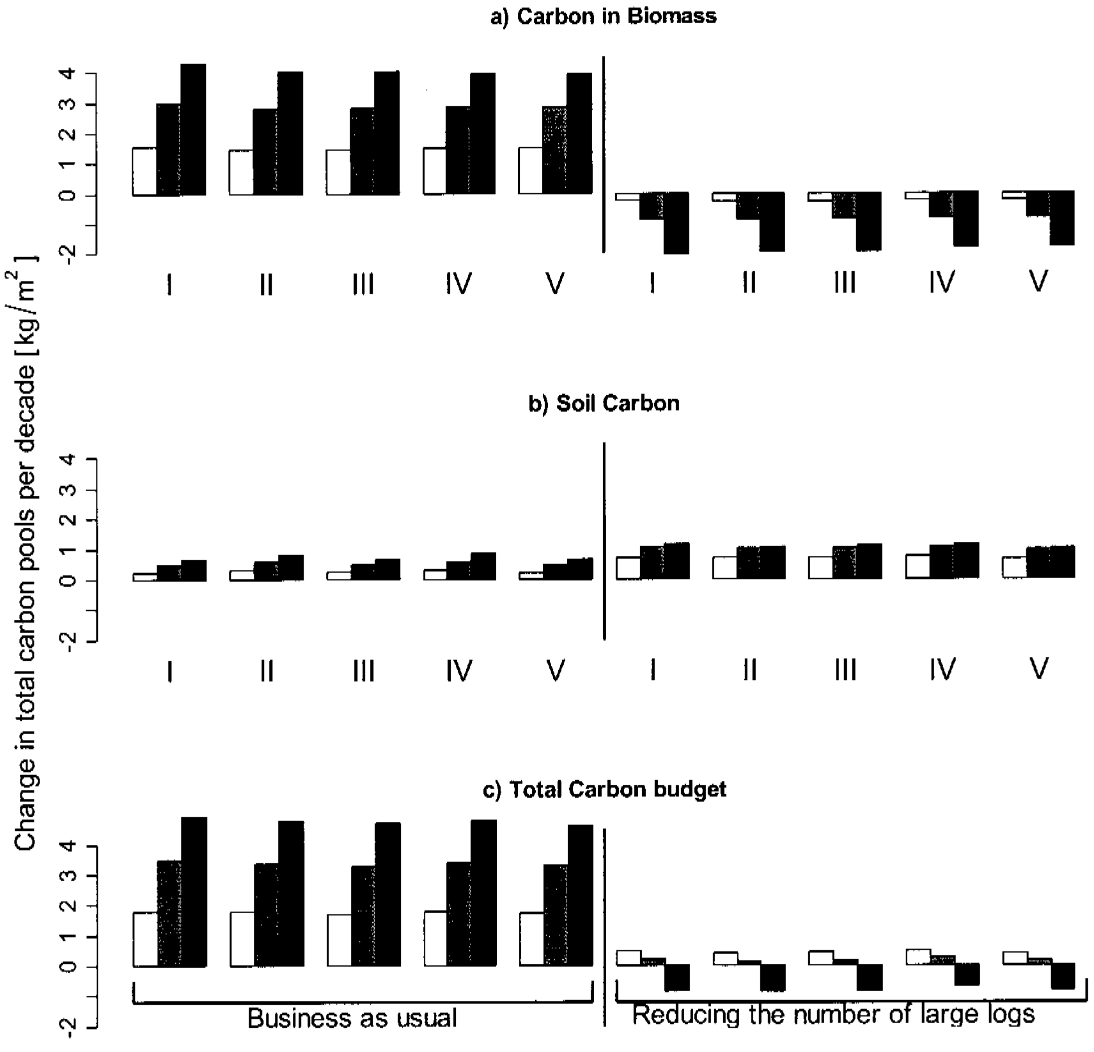

Fig. 4. Differences in total carbon pool in 10 years (2006-2016), 20 and 30 years, respectively. X-axes: Scenarios according to Table 3. Accumulated carbon after: □ 10 years [2006-2016], ▨ 20 years [2006-2026], ■ 30 years [2006-2036].

3.2.3 Sensitivity analysis of the decay rate of windthrown timber

To investigate the sensitivity of our results concerning the uncertainty of the decay rate of windthrown timber, we simulated carbon amounts with varying decay rates (±50%, see method section). To assess the maximum effect of a change in decay rate, we used the scenario with the largest amount of windthrown timber, which is the BAU scenario with a storm frequency of 10 years and without clearing. After 40 years of simulation, the absolute carbon stock changed from -0.5% (decay rate increased by 50%) to +0.9% (decay rate decreased by 50%) (Fig. 5). The corresponding changes in the carbon fluxes in the forest soil were -6% and +10%. The variability of the results of the scenarios is quite high and exceeds the effect of changes in the decay rates.

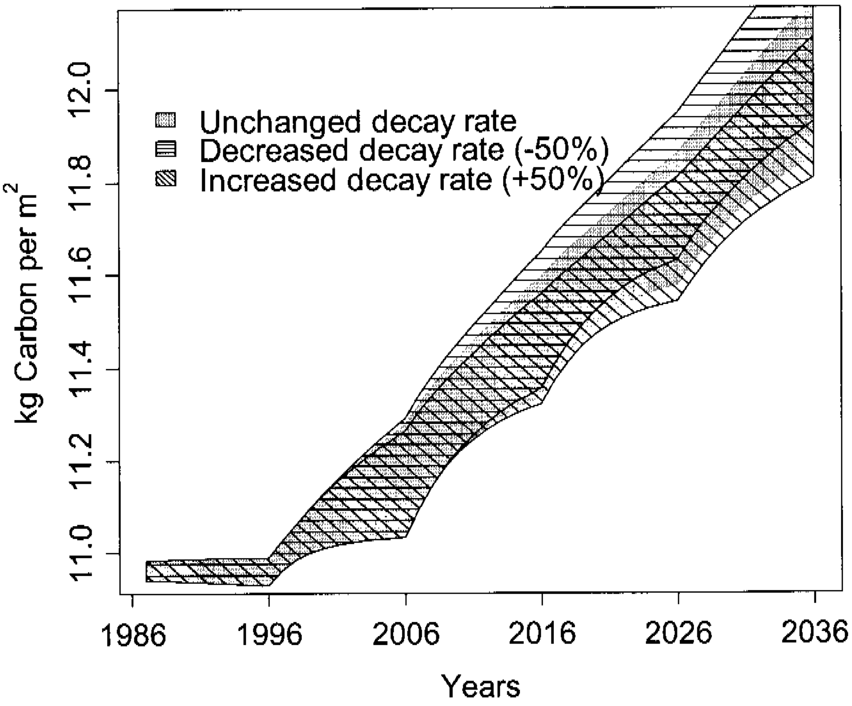

Fig. 5. Sensitivity analysis of the model parameter "decay rate of windthrown timber". The decay rate of windthrown timber was set at +50% and -50%. Decay rates of all the other model compartments were unchanged. The scenario is the business as usual with a simulated storm frequency of 10 years. Standard error of simulated carbon is plotted.

4 Discussion

4.1 Evaluation of the YASSO model

We found that in the Jura, the Pre-Alps and the Alps, the simulated soil carbon values correspond well with the measurements. In the Plateau, SOC is slightly overestimated by the model and in the Southern Alps, SOC is strongly underestimated (Table 4). Possible explanations for these discrepancies are given below.

The assessment of initial soil carbon stock is one of the most important sources of uncertainty in this type of modelling process. Here we created those values by assuming the stocks to be in steady state and calculating that state with an assumed average historical litter input. The difference between the model calculated steady state values and measured soil carbon values can result either from the fact that the assumption itself is not valid, i.e. in reality, carbon stocks are not in equilibrium, or from the under- or overestimation of the average historical litter input, or from inaccurate decomposition rates implemented in the model. For example, the overestimation of SOC in the Plateau could be due to past land-use. After the great population migration (between 300 and 500 AD), large regions were subjected to clear-cut (Schuler 1988). Moreover, until the first half of the 19th century many clear-cut areas in the

Plateau were used for a short time as arable land (3-4 years, "Waldfeldbau") (Grossmann and Krebs 1965). For this purpose, the forest floor was cleared of stumps, branches and ground vegetation and the upper soil-layer was tilled. This cultivation could have decreased the litter input to soil, which was not taken into account when calculating the average historical litter input to soil, and though lead to the overestimation of the current stock.

The Alpine region, on the other hand, was simulated very well. However, this area has also undergone drastic changes in land-use. The Alpine region was scarcely populated until the late Middle Ages, but afterwards it became increasingly populated. This led to forest management practices such as clear-cutting, forest pasturing and litter collecting. Forest pasturing and litter collection continued until the middle of the 20th century (Stuber and Bürgi 2002). The soils of the Plateau and of the Alpine region are probably still accumulating carbon and may therefore not yet be in a state of equilibrium. This is supported by Schuler's (1977) findings that, during the last century, growing stocks in Switzerland have been continually increasing. The modelled decomposition rates of extractives and celluloses at these areas where though very near to those measured (Table 5).

The underestimate of soil carbon in the Southern Alps was almost 50%. It is unlikely that all of this is because of the uncertainty in historical litter input given to the model, but the underestimation could also be related to an insufficient description of the effect of climate on decomposition or the characteristics of the Southern soils. First, the insubrian climate of this region is characterized by mild temperatures and heavy precipitation in summer and therefore, decomposition in the soil model is limited neither by temperature nor by drought. This may lead to an overestimation of the decomposition rate and the resulting amount of soil carbon may be too low compared to the available measurements. Second, the distribution of the summer precipitation in time is not homogeneous, but clustered. Most of the rain falls within a very short time period (a few hours) and there is always an extensive run-off (Zierl 2001). The drought index however is calculated on a monthly basis. Therefore, most of the time the soil conditions are much drier than indicated by the drought index of the model. A third explanation for the underestimation of soil carbon in Southern Alps is given by Blaser et al. (1997). The soils of the Southern Alps are characterized by the iron- and aluminium-rich acid bedrock and a litter layer providing dissolved organic matter rich in polyphenolic substances with strong metal-binding properties. This, combined with the mild climate, may result in an exceptional stability of the soil organic matter, which is not taken into account in the soil organic model.

In most of the sites used to calibrate the climate effects on litter decomposition in the model, drought was an important factor that limits decomposition processes (Liski et al. 2003). However, in Switzerland, 90% of the sites studied did not suffer from drought according to the drought index, so that drought had no decelerating impact on the model calculated decomposition. In this case decomposition is solely defined by temperature. Thus, this constraint does not have a strong influence on the simulation results.

We are aware that the litter input values used are very uncertain. The parameters for estimating the quantity of fine-roots and the fine-root turnover rate are especially uncertain. Results from Matamala et al. (2003) indicate that the fine-root turnover rate can vary from 1.2 to 9 years. Furthermore, the litter input from ground vegetation was ignored in the calculations, which means that we systematically underestimate the litter input since the annual litter production of understory vegetation in forests may represent considerable proportion of the total litter production, varying from 4% to 30% (Hughes 1970).

Empirical decomposition rates are always subject to marked variation because they stem from litterbag experiments. As only parts of the meso- and macro-fauna (e.g. earthworms) enter these bags, the influence of these elements of the fauna on the decay process is not fully taken into account. However, such fauna can accelerate decomposition processes significantly, so that models ignoring them will overestimate soil carbon (Bradford et al. 2002).

The sources of uncertainty in our method mentioned above affects the soil carbon accumulation during the studied period. However, for all the different scenarios, identical initial values as well as driving variables were used. Therefore, the comparison of the modelled fluxes and pools of carbon between the scenarios is still reasonable. Due to the high spatial and temporal variation in soils, the variation in measurements of soil carbon is large. This emphasizes the reasonability of approaching the questions of soil carbon stocks and stock changes by modelling them.

4.2 Carbon budgets according to different management and storms scenarios

The two management scenarios we used in this study have a strong influence on the carbon budget. All BAU scenarios result in an aboveground as well as a belowground carbon sink (Fig. 4). The RLL scenario aims to reduce the number of large trees and therefore leads to a marked biomass decrease. Although soil carbon increases, the total carbon budget of the RLL scenarios becomes negative after thirty years. Our results indicate that forest soils can profit only in a limited way from the increase in litter input. One reason could be that much of the litter consists of short-lived tissues, such as foliage and fine roots. They decompose fast and normally only a small portion of their carbon contributes to persistent organic materials such as humus (Schlesinger 1990). Schlesinger et al. (2001) even suggest that significant long-term net carbon sequestration in forest soils is unlikely.

Our results further indicate that, at the level of the national carbon budget, the scenario without clearing after storms shows only a slightly more positive carbon budget than the cleared scenario. The reason is that the amount of windthrown timber is large only on the local scale. On a national scale, windthrown timber from the past three storms made up only a small amount of the average annual timber harvest. The sensitivity of the decay rate of windthrown timber implies that the uncertainty of the decay rate has no significant impact on the national soil carbon budget (Fig. 5). However, the decomposition of timber on storm areas could be even higher. With the absence of the tree layer, soil temperatures rise, which, provided there is enough moisture, causes more rapid mineralization of the accumulated organic debris and thus faster decomposition (Lüscher 2002).

Findings from Janisch and Harmon (2002) suggest that the more coarse woody debris is left in a forest, the longer the net ecosystem productivity (NEP) of the forest will remain negative, which means that the forest will be a carbon source. However, they accounted neither for off-site decomposition nor belowground carbon pools and fluxes, which may both play important roles in the assessment of forest carbon fluxes.

To simulate a strong effect of climate change on storm frequencies, we increased the storm frequency by 30%. On a national scale, even such a strong increase of storm frequency has only a small impact on carbon sequestration in forests. Soil models usually do not take into account soil disturbances such as uprooting or harvesting. These factors can release critical amounts of sequestered carbon. Two years after a windthrow, eddy-flux measurements from Knohl *et al.* (2002) in European Russia indicated a carbon loss of 180 g C m^{-2} over a period of three months in summer. Therefore, the positive effects of the increase in litter quantity from windthrown timber on soil carbon could even be largely offset or exceeded by the loss of carbon through soil disturbance.

5 Conclusion

The aim of this study was to assess the influence of both forest management and wind disturbance on the carbon sequestration of Swiss forests. We applied an empirically based forest scenario model and a soil carbon model. The validation of the soil model showed a good agreement between the modelled and the empirical data. The results indicated that forest management has a significant effect on the aboveground carbon budget. Forest soils, however, reacted very slowly to changes of the litter output. Furthermore, differences in soil carbon between the clearing and no-clearing scenario are small due to the fact that windthrown timber makes up only a small percentage of the annual harvesting amount.

Based on our results, we cannot recommend a final mitigation strategy for forest management until models are included to take into account the mitigating effects of increased use of fuelwood and other wood products and models accounting for the effects of soil disturbances. Moreover, the time period of forty years of our study may be too short to assess long-term forest development, and a simulation over the next 100 years would be required. However, the approach used in this study combines aboveground and belowground carbon fluxes and is an important step towards calculating scenarios of CO2 mitigation in Swiss forests.

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Effect of forest management on future carbon pools and fluxes: A model comparison

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Abstract

Currently, there is a strong demand for estimates of the current and potential future carbon sequestration in forests, the role of management practices, and the temporal duration of biotic carbon sinks. Different models, however, lead to different projections. Model comparisons allow us to assess the range of potential ecosystem responses, and they facilitate the detection of the strengths and weaknesses of particular models. In this study, the empirical, individual-based forest model MASSIMO associated with the soil model YASSO and the process-based, ecophysiological model Biome-BGC were used to assess the above- and belowground carbon pools and fluxes of several forested regions in Switzerland for the next 100 years under four different scenarios. Harvest was (1) intensified by reducing the amount of large logs, (2) reduced to a minimum by only maintaining the protection function in mountain forests and avoiding pests and diseases, and (3) adjusted to achieve maximum sustainable growth. The results show that the two models projected similar patterns of carbon fluxes. The models estimated that in the absence of large-scale disturbances the forest biomass and soil carbon can be increased, and therefore, forests can be used as carbon sinks. These sinks were estimated to last for a maximum of 100 years. Differences between the management scenarios are related to the time period considered: either carbon fluxes are maximized at a short term (30-40 years) or at a longer term (100 years or more). Therefore, to find the optimum strategy in terms of not only maximizing carbon sequestration but climate protection, it is essential to account for wood-products and particularly substitution of fossil fuel in the model simulations. The carbon pools projected by the models differed. These differences in model behaviour can be attributed to model-specific responses to the strongly heterogeneous Swiss climate conditions and to different model assumptions.

Keywords: Carbon budget; forest management; Biome-BGC; YASSO; MASSIMO; Switzerland

1 Introduction

Forest management influences the sequestration and release of carbon in forest biomass, soil, and wood products (Houghton 1996, Harmon and Marks 2002, Kaipainen et al. 2004). In the framework of the Kyoto Protocol, countries can decide to credit managed forests as carbon sink/source according to Article 3.4 of the Protocol (UNFCCC 1997). Therefore and for the annual green house gas inventory to the Climate Change secretariat, countries are obliged to assess their carbon pools with a high precision. Models are important to estimate changes of these pools and the associated carbon fluxes. Models can also be applied to assess the influence of different management regimes on long-term carbon sequestration.

There is a suite of techniques for predicting carbon pools and fluxes (c.f. Ruimy et al. 1999, Landsberg 2003). Such approaches include inverse modelling based on a network of atmospheric CO_2 measurements (Gurney et al. 2002), or on detailed measurements of gas exchange above the forest (eddy correlation measurements, Baldocchi 2003), biogeochemical models (Churkina et al. 2003), models for the analysis of land-use change (Houghton 2003a) and for the analysis of forest inventory data (Fang et al. 2001, Goodale et al. 2002, Shvidenko and Nilsson 2002).

All the models used for such purposes are situated somewhere on the gradient between empirically-based models and process models (Korzukhin et al. 1996). Process-based models emphasize particular processes such as photosynthesis, carbon allocation or nitrogen mineralization. Empirical models, in contrast, are based on functions such as basal area increment of single trees that are fitted to large amounts of field data. These model types diverge in their assumptions, that is in their driving variables and internal processes. And, most importantly, the different models may result in different carbon estimates at the ecosystem scale (Houghton 2003b).

Each model has been built to answer specific questions and therefore is based on specific assumptions. Many of the models used to estimate ecosystem carbon relationships (e.g., forest inventory based models) were not originally developed for this purpose and also not well evaluated for this purpose. Therefore, it is important to use not only one specific model in carbon assessments, but to run different models and to relate each model's output to the differences in model assumptions. In the present study, we applied two different models: the empirical model MASSIMO (Kaufmann 2000b) associated with the soil carbon model YASSO (Liski et al. 2005), and the process model Biome-BGC (Thornton 1998). All models were applied in Switzerland for the next 100 years, implementing four different forest management scenarios. To show both the effects of forest management on carbon sequestration and to demonstrate differences between the models, the default management scenario “business as usual” was modified to reflect possible alternative future management regimes. Harvesting was (1) intensified by reducing the amount of large logs (diameter at 1.3 m > 50 cm), (2) reduced to a minimum by only maintaining the protection function in mountain forests and averting pests and diseases, and (3) adjusted to achieve maximum sustainable growth (i.e., maximum carbon flow into the forest over a long time period).

Although such comparisons can be misleading because of different model assumptions and methods (Houghton 2003b), they are capable of indicating the range of possible future carbon fluxes under the different management scenarios. Therefore, for a model comparison, the initialization of the models and the input variables such as harvesting amounts needs to be standardized across all models within a model comparison.

The aim of this study was to apply the selected models on common forest types in Switzerland and to compare the simulated carbon pools and fluxes as a function of the different forest management practices. We focused on the following research questions: (1) How large is the effect of different model assumptions on the assessment of carbon sequestration? (2) What is the potential range of the influence of different management scenarios on the carbon budget? (3) How do the simulated carbon fluxes differ between the different forest types?

2 Data, Models & Scenarios

2.1 Study area

In Switzerland, forests cover about 30% or 12,340 km^2 of the area and extend from 200 to 2200 meters above sea level (Brassel and Brändli 1999). The Swiss forest area is commonly divided into five productivity regions: Jura, Plateau, Pre-Alps, Alps and Southern Alps (Fig. 1). These regions differ in elevation, stocking density of the forests, management regime and climate. In the Plateau and the Jura, temperate conditions prevail, whereas the other regions are affected by a marked gradient in both altitude and continentality. They range from intra-Alpine and continental (annual precipitation < 500 mm), through insubrian (July temperature > 20 °C, annual precipitation > 1600 mm) to cold climates (Alps) (Brzeziecki et al. 1993). About 5,500 forest sample plots were measured in both NFI I (1983-1985) and NFI II (1993-1995). The sample plots are located on a regular grid over the whole country. However, as attested in the sampling theory, random samples can not be interpreted plot by plot, but they have to be stratified.

Therefore, the NFI plots were stratified into four different forest types (Fig. 1) for which the output of all models could be analyzed. To further simplify the task according to horizontal and vertical structure, we selected even-aged plots, which represent the majority of the plots. In the Plateau, we distinguished mixed deciduous stands (more than 50% of the growing stock is deciduous) and coniferous stands (more than 90% of the growing stock is coniferous) between 300 and 1100 m altitude. These stands account for 64% of the NFI plots in the Plateau. In the Pre-Alps, we selected beech (*Fagus silvatica*) and fir (*Abies alba*) dominated stands (together more than 50% of the growing stock) between 800 and 1200 m altitude, which make up 9% of the pre-alpine NFI plots. In the Alps, we selected coniferous sites (>90% conifers, mostly dominated by *Picea abies*) between 1200 and 1800 m altitude, accounting for 32% of the Alpine NFI plots.

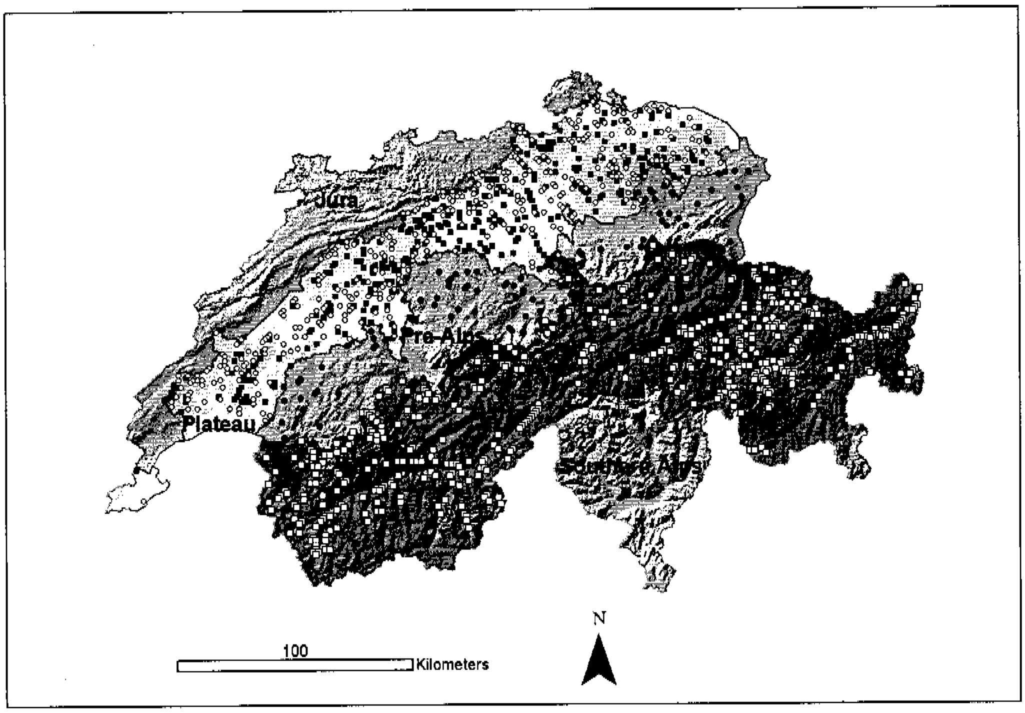

Fig. 1. Study areas in Switzerland. Four forest types were distinguished: ○ Coniferous plots (N=334) and ■ mixed deciduous plots (N=373) in the Plateau; ● Beech and fir plots in the Pre-Alps (N=83); □ Coniferous plots in the Alps (N=466).

2.2 MASSIMO

MASSIMO (Management Scenario Simulation Model) (Kaufmann 2000a, b) is an empirical, individual-based, stochastic, and dynamic forest model. It consists of four sub-models: Regeneration, growth, mortality, and management scenarios (including harvesting). These four processes are simulated on the basis of empirical formulations derived from data of the first and the second Swiss national forest inventory (NFI), recorded at 4400 sample plots (EAFV 1988, Brassel and Brändli 1999). MASSIMO has been used to assess various scenarios of forest development in Switzerland (Kaufmann 1999). The present study simulates longer time frames and new management scenarios that focus on carbon sequestration. The growth model constitutes the core of MASSIMO. The growth function was derived from the inventory data and predicts decadal basal area increment as a function of site conditions and forest structure (Kaufmann 1996). The MASSIMO growth function has been validated by Thürig et al. (2005a).

In MASSIMO, harvesting is defined as the empirical probability of being cut for every single tree. This probability is estimated using logistic regression models, where the explanatory variables are the stand and site characteristics (development stage, species composition, stand age, site quality) as well as harvest conditions such as accessibility, applied harvesting method, harvesting costs and protection functions. The models were derived from Swiss NFI data and provide probabilities for planned (planned logging) and unplanned felling (due to natural disturbances). Since these probabilities refer to the actual practices between the two NFI surveys, 1985 and 1995, they reflect the so-called business as usual (BAU). By changing these probabilities, various management scenarios can be defined.

In the MASSIMO version used in previous studies (Kaufmann 2000b, Thürig et al. 2005b), natural mortality was based on empirical data from the NFI I & II. In 100 years of forward simulation (1996-2095), however, simulated stand structures may change considerably, especially if the harvesting amount is reduced. This may increase the density-dependent mortality. Therefore, in this study, the natural mortality module in MASSIMO had to be adjusted to account for denser stands in the future that are rare or absent from the calibration dataset. Thus, an additional, density-dependent mortality function was implemented based on long-term forest yield research plots from the Swiss Federal Research Institute (WSL), selected NFI plots with a high growing stock, and expert knowledge. These data were used to empirically define the upper limit of stand densities in terms of stand basal area. The following relations were derived: When a simulated stand reaches the maximum basal area (50-75 m^2/ha, estimated depending on species composition and development stage), the mortality rate increases exponentially with increasing basal area. Mortality also increases exponentially in very old stands (older than 150 years in the Plateau, older than 250 years in the Alps).

2.3 YASSO

YASSO is an empirical and dynamic soil carbon model (Liski et al. 2005). Two litter compartments describe the physical fractionation of litter, and five compartments describe microbial decomposition and humification processes in the soil. A detailed description of the model is given in Liski et al. (2005). As the model requires only basic information on litter quality and climate, it can be linked easily to any calculation system that provides estimates of litter production (in this study calculated with MASSIMO as described below). The climatic dependency of the decomposition rates was determined from an analysis of litterbag data from across Europe and tested using data from Canada and Central America (Liski et al. 2003). The performance of YASSO with the Swiss NFI data was described and validated in Thürig et al. (2005b). The soil carbon model YASSO was used to estimate soil carbon in conjunction with the model MASSIMO.

2.4 Biome-BGC

Biome-BGC (Running and Hunt 1993, Thornton 1998, White et al. 2000) is a deterministic process-based ecosystem model that simulates above- and belowground daily storage and fluxes of carbon, nitrogen, and water of various vegetation types from the stand to the global scale. This modelling approach integrates biological and geochemical considerations to describe processes of the carbon (e.g., assimilation and respiration), nitrogen (e.g., mineralization, denitrification), and water (e.g., evaporation, transpiration) cycles in a mechanistic manner. Therefore, the model requires detailed information on soil properties, atmospheric conditions (i.e., climate data, CO_2 concentration, and nitrogen deposition), and the ecophysiological characteristics of the vegetation.

The approach for modelling vegetation dynamics in Biome-BGC is based on some simplifying assumptions regarding spatial structure. Trees are not simulated individually, but vertical stand structure is composed of a number of layers between the rooting system and the top of the canopy, and in the horizontal dimension, the stand is assumed to be homogeneous. Therefore, harvesting consists of removing certain fractions of the biomass carbon and nitrogen pools from the growing stock. This is done using a harvesting routine implemented and described in detail by Thornton et al. (2002). Furthermore, the model currently includes no species-specific parameterization, but forests are divided into four vegetation types (evergreen and deciduous or broadleaf and needleleaf forests, respectively). The temporal framework of the Biome-BGC model is based on a dual discrete time step approach (Thornton 1998). While most ecosystem processes are calculated on a daily basis (e.g., soil water balance, photosynthesis), there are a few processes - including the determination of phenological timing and the allocation of carbon and nitrogen for the growth of new tissue - that are simulated with an annual time step.

The Biome-BGC model version 4.1.2 (used in this study) and earlier model versions have extensively been tested for several carbon cycle components, and the model has been applied in different forest ecosystems (Hunt et al. 1991, Korol et al. 1991, Running 1994, Cienciala et al. 1998, Law et al. 2001, Thornton et al. 2002, Churkina et al. 2003, Schmid et al. in prep.).

A comparison of the three models used in this study is given in Table 1.

Table 1. Conceptual comparison of some important model processes and variables in the present study

	MASSIMO	YASSO	Biome BGC
Original purpose	Update of the Swiss NFI and evaluation of the effect of management scenarios	Estimate soil carbon as a function of litter input and climate	Simulate carbon, nitrogen, and water pools and fluxes, below- and aboveground
Modelling approach	Empirical, distance-independent, individual-based forest model	Empirical soil carbon model	Ecophysiological, process-based, biogeochemical model
State variable	Tree diameter at breast height (1.3 m), DBH	Soil carbon in 5 different compartments	A number of carbon and nitrogen pools (e.g., stem carbon, leaf nitrogen), foliage
Growth	Tree-level function for basal area increment	–	Ecophysiological function for net photosynthesis
Competition	Basal area of trees larger than the observed tree	–	Explicit consideration of light availability
Mortality	Density related mortality, calibrated with empirical data	–	Constant mortality rate
Decomposition functions	–	Decomposition rates for extractives, cellulose, lignin and humus, depend on climate	Temperature- and precipitation-dependent decomposition rates

Input variables	Felling probabilities,	Climate (precipitation, temperature), litter quality	Harvesting amounts, mortality rate, climate, soil conditions
Model output	Growing stock, age-class distribution, felling, increment	Stock and stock changes of soil carbon	Daily and annual carbon, nitrogen, and water pools and fluxes
Time step	10 years	1 year	1 day
Repetitions due to stochastic model terms	15	–	–

2.5 Management scenarios

Management scenarios were implemented differently in the two models MASSIMO and Biome-BGC. MASSIMO used felling probabilities, whereas for Biome-BGC, only the absolute harvesting amount (biomass carbon) needed to be specified. However, comparing the two models required equal harvesting amounts in all management scenarios. Therefore, all scenarios were defined by the total harvesting amount per decade. A short description of the four management scenarios applied in this study is given in Table 2.

Table 2. Description of the four forest management scenarios

Scenario	Description	Harvesting amount
Business as usual	Harvesting amount constant as between 1985 and 1995 (NFI I and II)	Today's harvesting amount
Minimum forest management	Only sanitary fellings, minimum harvesting in Alpine protection forests	55% of today's harvesting amount
Maximum C flow	Maximization of sustainable wood production by equal distribution of forest areas according to age classes	Today's harvesting amount
Reduction of large logs	Sustainable wood production by reducing over-mature timber and achieving a uniform age class structure	130% of today's harvesting amount

In the following, the four scenarios are described further based on the felling probabilities as required in the model MASSIMO. During the first ten years of the simulation (1996-2005), the same felling and damage probabilities were applied in all scenarios (i.e., "business as usual"). For the years 2006-2095, however, the felling probabilities and felling amounts differed according to the scenarios, as described further below.

The "business as usual" scenario as well as the "minimum forest management" and the "reduction of large logs" scenario were driven by the total harvesting amount. Probabilities for planned fellings (thinnings and clearcuts) in MASSIMO were adjusted in such a way that a constant amount of merchantable wood was harvested throughout the whole century (2006-2095). The mean annual average of harvested merchantable timber from the entire Swiss forest area was 5.4 m^6 in the "business as usual" scenario, 3.0 m^6 in the "minimum forest management" scenario, and 7.0 m^6 in the "reduction of large logs" scenario. The average harvesting amounts per decade, per forest type and per scenario, converted to carbon using species specific density factors (Assmann 1968) and a carbon content of the biomass of 50% (IPCC 2003), are given in Table 3.

Table 3. Harvested merchantable timber per decade, converted to kg C ($m^{-2} \cdot 10yrs^{-1}$), mean and standard deviation over the 100 years of simulation, according to the four management scenarios for the four forest types.

	Plateau, deciduous	**Plateau, coniferous**	**Pre-Alps, mixed**	**Alps, coniferous**
Business as usual	3.6±0.2	3.1±0.4	1.5±0.3	0.8±0.1
Minimum forest management	1.7±0.7	1.5±0.7	1.1±0.3	0.7±0.1
Maximum C flow	4.0±0.4	3.5±0.1	2.3±0.3	1.1±0.2
Reduction of large logs	3.3±1.3	2.7±0.8	2.2±0.8	1.1±0.1

2.5.1 Business as usual

In this scenario, the demand for timber was assumed to remain at today's level, and therefore the harvesting amount was kept constant on the today's harvesting amount for the entire simulation period (Table 3).

2.5.2 Minimum forest management

In this scenario, the demand for timber was assumed to collapse. Therefore, forest management was reduced to a minimum by only maintaining the protection function in mountain forests and averting pests and diseases. As dense forests and old trees tend to be more sensitive to natural disturbances, unplanned fellings due to natural disturbances were assumed to double in old coniferous stands in the Plateau. Planned fellings were reduced to the minimum demand of protection forests, having a low intensity in young stands (on average about 15% of the trees were removed) and a high intensity in old stands (up to 60% of the trees), so as to enhance natural regeneration. No clearcutting was performed.

2.5.3 Reduction of large logs

In Swiss forests, the percentage of large logs (DBH > 50 cm) is increasing. Due to changed techniques of wood processing, the demand for wood has changed towards smaller log dimensions. Today, only large logs of a very good quality, amounting to less than 20% of the harvesting amount, have a high economic value. Therefore, the Swiss Forest Industry is seeking to reduce the abundance of these large logs, and to achieve a more balanced stand age structure. To simulate a "reduction of large logs" scenario, the BAU scenario was used as the basic scenario, but oversized timber (trees with DBH > 50 cm) is removed gradually in the period 2006-2095. The average volume per hectare is thereby reduced from currently 360 m^3/ha to 310 m^3/ha until 2095.

2.5.4 Maximum C flow

This scenario aimed at maximizing sustainable growth. Therefore, forest management was adjusted to get a uniform distribution of stand age classes, meaning equal stands in all age classes. Based on simulations with a series of different scenarios, having varying rotation lengths and harvesting techniques, the following strategy resulted in the highest growth rates. First, rotation lengths, specific for site classes, are defined (Table 4). Second, in each decade the forest area necessary to achieve a uniform stand age class distribution within one rotation period is cut, beginning with the oldest stands. The amounts of thinnings are reduced as in the "minimum forest management" scenario, which leads to a high natural (density-dependent) mortality. This leads to the average harvesting amounts of merchantable timber shown in Table 3, which is coincidentally the same amount as harvested today.

Table 4. Rotation length of the maximum C flow scenario for different site qualities given as annual dry wood production values

	Poor site quality (< 2.25 t ha^{-1} yr^{-1})	**Medium site quality (2.25 - 4.5 t ha^{-1} yr^{-1})**	**Good site quality (>4.5 t ha^{-1} yr^{-1})**
Plateau	120 years	100 years	80 years
Pre-Alps	140 years	120 years	100 years
Alps	170 years	150 years	130 years

2.6 Model initialization and simulation setup

The aboveground parts of MASSIMO and Biome-BGC were initialized with NFI II data from the selected sites (Fig. 1).

2.6.1 MASSIMO

Massimo was initialized with NFI II data and run on each NFI sample plot. The output of the model was converted to carbon in aboveground biomass and roots. The conversion was performed using the following procedure. To estimate total tree volume, stemwood volume was expanded using allometric single-tree functions. Functions for twigs (diameter < 7 cm) and branches (diameter > 7 cm) were based on measurements from approximately 12,000 trees (Kaufmann 2000a). Bark volume was estimated using the model by Altherr et al. (1978), and additional allometric functions were used to estimate the volume of coarse roots, based on data from 100 trees, as well as of foliages, based on samples from 400 trees (Perruchoud et al. 1999). To convert total tree volume to carbon, conversion factors for wood density were used as given in Assmann (1968), and the carbon content of biomass was assumed to be 50% (IPCC 2003).

2.6.2 YASSO

The biomass values simulated by MASSIMO were used to calculate the annual litter input for the soil carbon model. Turnover rates of the different tree tissues were calculated from specific lifespans, as described in Thürig et al. (2005a). Estimates of the chemical composition of non-woody litter (needle, leaf and fine roots) for deciduous and broadleaf trees were based on Heim and Frey's (2004) findings. Climate indices in the form of mean monthly values of temperature and precipitation over a thirty-year period (1960-1990) were calculated for every sample plot (Zimmermann and Kienast 1999). From these climate values, a drought index and the mean annual temperature were calculated according to Thürig et al. (2005b). These values were kept constant for the assessment period from 1996 to 2095. The model was run on all the selected sample plots, but the output was averaged per forest type.

The soil carbon stocks were initialized by assuming them to be in a steady state calculated by a spin-up run prior to the actual simulation run. The steady state was calculated using the average annual litterfall observed between 1985 and 1995 (NFI I & II) for the three regions Plateau, Pre-Alps, Alps (Table 1). We started the model with empty carbon pools and let it run with constant litter input until the pools reached an equilibrium, which required about 5000 years. The resulting initial values (soil organic carbon and litter organic carbon) averaged per region were 11.7 kg C m^{-2} in the Plateau, 12.1 kg m^{-2} C in the Pre-Alps and 11.3 kg m^{-2} C in the Alps (Thürig et al. 2005a).

2.6.3 Biome-BGC

Although it would have been best to run the Biome-BGC model on each of the NFI II sample plots, as done for MASSIMO and YASSO, this would have been quite demanding from a technical point of view due to the availability of input data necessary for these simulations. Therefore, simulations with this model were restricted to the four forest types as described above. Due to the high heterogeneity within these forest types, mainly with respect to climate conditions, and since in Biome-BGC growth is strongly sensitive to climate, we divided these forest types into a number of bioclimatic strata. This stratification was based on a cluster analysis of the NFI sample plots within each forest type (partitioning method according to Kaufman and Rousseeuw 1990). The cluster analysis was done with the variables 'mean temperature during the vegetation period' and 'total precipitation during the vegetation period' of each sample plot. The two climate variables were derived from the same monthly climate indices as used in YASSO (Zimmermann and Kienast 1999). Additionally, all sample plots were stratified into altitudinal bands of 200 m. In the case of the mixed fir-beech forest type in the Pre-Alps, the NFI sample plots were divided into coniferous and deciduous stands. This stratification of the four "basic" forest types according to climate, elevation and species resulted in a total of 23 bioclimatic strata.

To each of these strata, a number of atmospheric variables (daily climate data, CO_2 concentration, and nitrogen deposition), specific soil conditions, and a plant functional forest type were assigned. Daily climate data were taken from the NFI sample plot that was characterized by climatic conditions most similar to the average conditions within the respective stratum in terms of 'mean temperature during vegetation period' and 'total precipitation during vegetation period'. Daily climate data of the selected NFI sample plot were generated by extrapolating climate measurements of a close-by meteorological station of MeteoSwiss (the national weather service of Switzerland) from the years 1961 to 1990 to the NFI sample plot by means of the weather generator MTCLIM 4.3 (Running et al. 1987, Thornton and Running 1999). The atmospheric CO_2 concentration was set to 296 ppm for the spin-up run, thus approximating the level at the end of the 19th century (Erhard et al. in prep.).

For the simulation run we used 361 ppm, the CO_2 concentration of the year 1996 (Erhard et al. in prep.). The annual nitrogen deposition rate was assumed to be 2 kg N ha^{-1} for the spin-up run accounting to Holland et al. (1999), and for the simulation run we applied the mean nitrogen deposition rate of each stratum derived from the nitrogen deposition map of Switzerland (BUWAL 1996, Rihm and Kurz 2001). Concerning the soil properties required for model initialization (soil depth and soil texture), we applied the mean value or the most frequently occurring value, respectively, within the stratum. These values were derived from the soil suitability map of Switzerland (BFS 1992). The ecophysiological forest types occurring in this study were 'deciduous broadleaf forest' and 'evergreen needleleaf forest'. For each forest type, we used the default set of 44 ecophysiological parameters. The only exception was the annual whole-plant mortality rate, which was replaced by values from the Swiss NFI (Brassel and Brändli 1999) for unmanaged (spin-up run) and managed (100-year simulation run) stands (Table 5). However, the mortality rate for the simulation run was not held constant. According to the density related mortality functions of the MASSIMO model (Kaufmann 2000a, b), the mortality rate was increased when the aboveground biomass exceeded a certain amount.

Table 5. Annual whole-plant mortality rates based on Swiss NFI data (Brassel, 1999).

	Plateau	**Pre-Alps**	**Alps**
Spin-up run	1.20%	0.74%	0.81%
Simulation run	0.16%	0.27%	0.42%

In order to obtain the initial biomass (aboveground and living roots) and non-living organic soil carbon values, a spin-up run was performed on each bioclimatic stratum. Then, the different biomass carbon and nitrogen pools were equally adapted to the initial values. The averaged initial values for the four forest types, calculated from the NFI II data amount to 14.5 kg C m^{-2} (Plateau, deciduous stands), 14.4 kg C m^{-2} (Plateau, coniferous stands), 16.1 kg C m^{-2} (Pre-Alps, mixed stands), and 12.1 kg C m^{-2} (Alps, coniferous stands). The same was done for the litter and soil carbon and nitrogen pools. As initial values we used the soil organic carbon values measured by Lüscher et al. (1994): 7.3 kg C m^{-2} (Plateau), 9.8 kg C m^{-2} (Pre-Alps), and 9.8 kg C m^{-2} (Alps). The litter organic carbon values were taken from Paulsen (1994): 1 kg C m^{-2} (Plateau), 2.7 kg C m^{-2} (Pre-Alps), and 2.7 kg C m^{-2} (Alps).

2.7 Model comparison

At each forest type, the four forest management scenarios described above were applied. Then, the model outputs were compared regarding biomass carbon budgets (MASSIMO and biomass part of Biome-BGC), soil carbon budgets (YASSO and soil part of Biome-BGC) and total carbon budgets. For each decade of the simulation period, carbon fluxes were calculated as the differences between the carbon pool at two time points ((t + 10 years) - t). We then visually analyzed the dynamics and the values of the simulated annual carbon fluxes, and we compared the corresponding carbon pools.

3 Results

3.1 Carbon fluxes

The carbon fluxes simulated with the models MASSIMO / YASSO and Biome-BGC are shown in Figures 2 to 5. Positive fluxes indicate a carbon sink; negative fluxes indicate a carbon source. The first two bars of each panel represent the simulated annual carbon flux from 1996-2005, and the last two bars that from 2086-2095, respectively. The general patterns of the fluxes simulated by the models were very similar. Both models projected the largest carbon fluxes in the "minimum forest management" scenario and the smallest carbon fluxes in the "reduction of large logs" scenario. The models also agreed in most of the regions by estimating negative carbon fluxes in the "maximum C flow" scenario. In most cases, biomass carbon fluxes were more similar than soil carbon fluxes. As the differentiation of the management scenarios started only after 2005, the model results for the first ten years were identical within each model.

In most cases (regions and scenarios), MASSIMO showed a larger increase in the aboveground carbon than Biome-BGC over the 100 simulation years. Especially in the first 40-50 years, MASSIMO estimated a much larger aboveground carbon sink than Biome-BGC. However, after 70-90 years, Biome-BGC projected a slightly larger aboveground carbon sink than MASSIMO. Moreover, after 70-90 years, MASSIMO even produced a decrease in the aboveground carbon in most of the scenarios (other than the business as usual). Except for the Alps (Figure 5), the forest types exhibited similar aboveground carbon fluxes. In the Alps, the changes in aboveground carbon were much smaller. This is mainly due to climatic conditions, which slow down biological processes.

Regarding soil carbon fluxes, YASSO showed stronger dynamics than the soil part of the Biome-BGC model. Especially in the Plateau (Figure 2), the minimum forest management as well as the maximum C flow scenario resulted in large flux differences between the two soil models. Here, YASSO estimated strongly positive soil carbon fluxes already after 20 simulation years. In the second part of the simulation period, the fluxes were slightly diminished. However, also Biome-BGC estimated a soil carbon sink, but it was smaller than that of YASSO and clearly appeared later. Generally, soil carbon fluxes in the Alps (Figure 5) were remarkably smaller than in the other regions. This is again caused by climatic conditions.

In general, total carbon fluxes (biomass and soil together) represented a carbon sink, except for the "reduction of large logs" scenario. Under this scenario, also strongly negative fluxes were estimated. The negative fluxes were especially pronounced in the MASSIMO/YASSO simulations in the Pre-Alps and the Alps (Figures 4 and 5).

3.1.1 Business as usual

In all forest types and with all the models, simulated growth under the "business as usual" scenario was quite similar. Most of the biomass carbon fluxes as well as the soil carbon fluxes were small but slightly positive. In all forest types, towards the end of the 100-year simulation period, the fluxes tended to zero, indicating that the harvesting amount plus mortality nearly balanced the gross increment.

3.1.2 Minimum forest management

In the short term, this scenario leads to the sequestration of the largest amounts of biomass carbon. This large and even increasing carbon sink was estimated to last for approximately 40 years. Thereafter, the biomass carbon fluxes were estimated to become smaller. MASSIMO simulated that after 60-80 years of minimum forest management, biomass carbon was reaching a plateau or was even decreasing, and therefore, biomass carbon fluxes were estimated to either converge asymptotically to zero, or even to become negative. The soil carbon fluxes were simulated to increase, showing maximum fluxes after approximately 70-80 simulation years. These positive soil carbon fluxes partly compensated the negative biomass carbon fluxes at the end of the simulation period. Biome-BGC also estimated a strongly decreasing biomass carbon growth after 60-70 simulation years, but no decrease in biomass carbon and therefore no source effect within the 100-year simulation period.

3.1.3 Maximum C flow

For MASSIMO as well as for Biome-BGC, this scenario led to relatively strong positive carbon biomass fluxes in the first part of the simulation. However, after 50-60 years of simulation, a depression in the development of the growing stock was found in all forest types. At the same time, the soil carbon fluxes were simulated to be increasing, partly compensating the negative biomass fluxes (Figure 2 and 3). However, at least in the Plateau, the forests again became an increasing carbon sink after 60-70 simulation years (Figure 2).

3.1.4 Reduction of large logs

This scenario revealed the largest differences between the two models. Especially in the Pre-Alps and the Alps, MASSIMO showed a strong decrease of biomass carbon, whereas Biome-BGC simulated a permanent biomass increase (Figures 4 and 5). In the Plateau, both models resulted in negative carbon biomass fluxes after 40 simulation years (Figure 2). The soil carbon fluxes were small according to both model simulations.

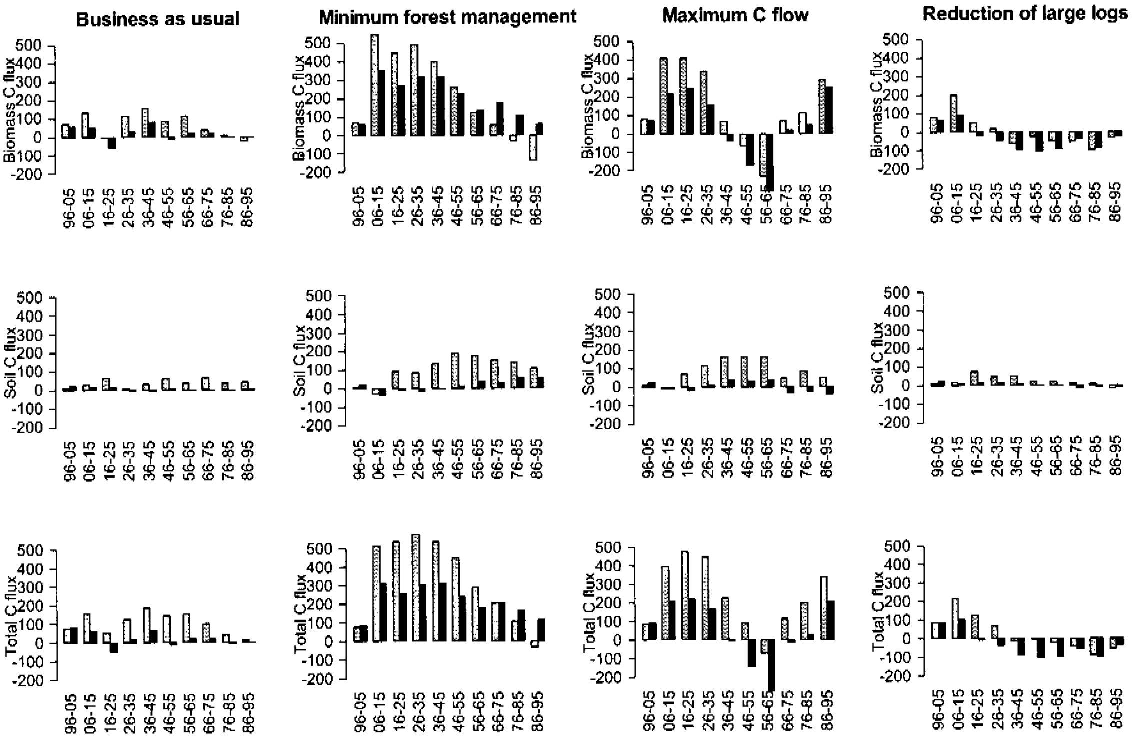

Fig. 2. Plateau, deciduous dominated stands. Annual C fluxes, averaged over 10 years [g per m^2]. X-axes: simulation years. ▨ MASSIMO / YASSO; ■ Biome-BGC.

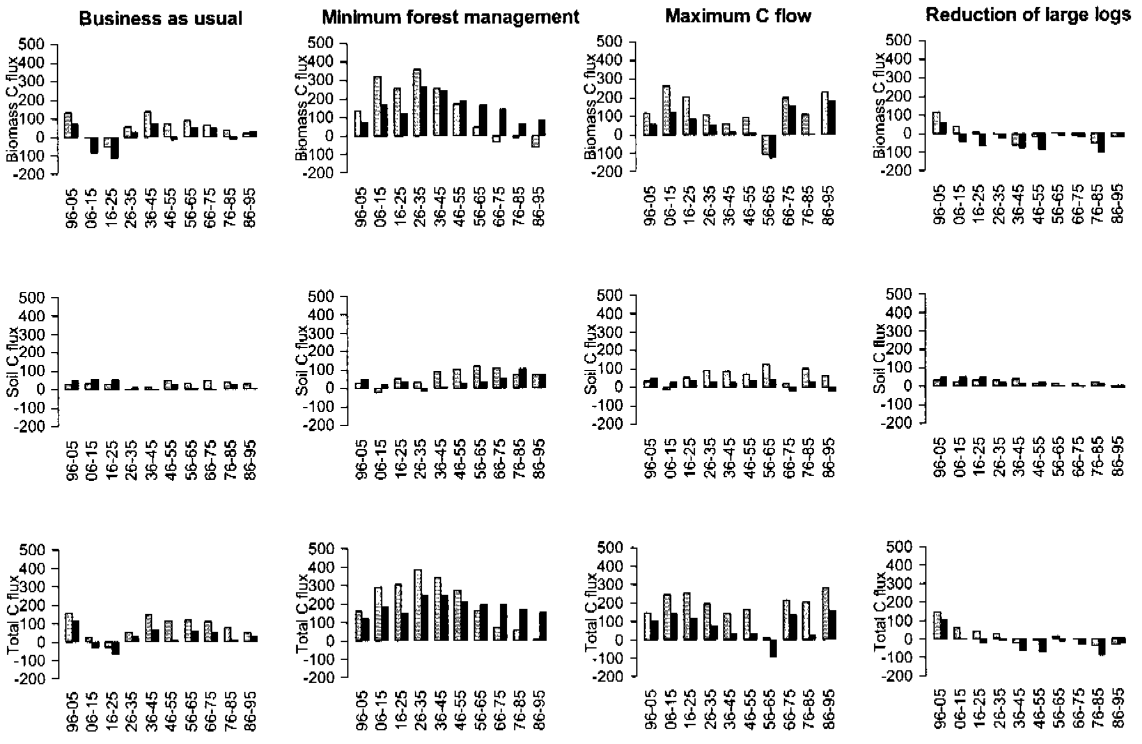

Fig. 3. Plateau, coniferous dominated stands. Annual C fluxes, averaged over 10 years [g per m^2]. X-axes: simulation years. ▨ MASSIMO / YASSO; ■ Biome-BGC.

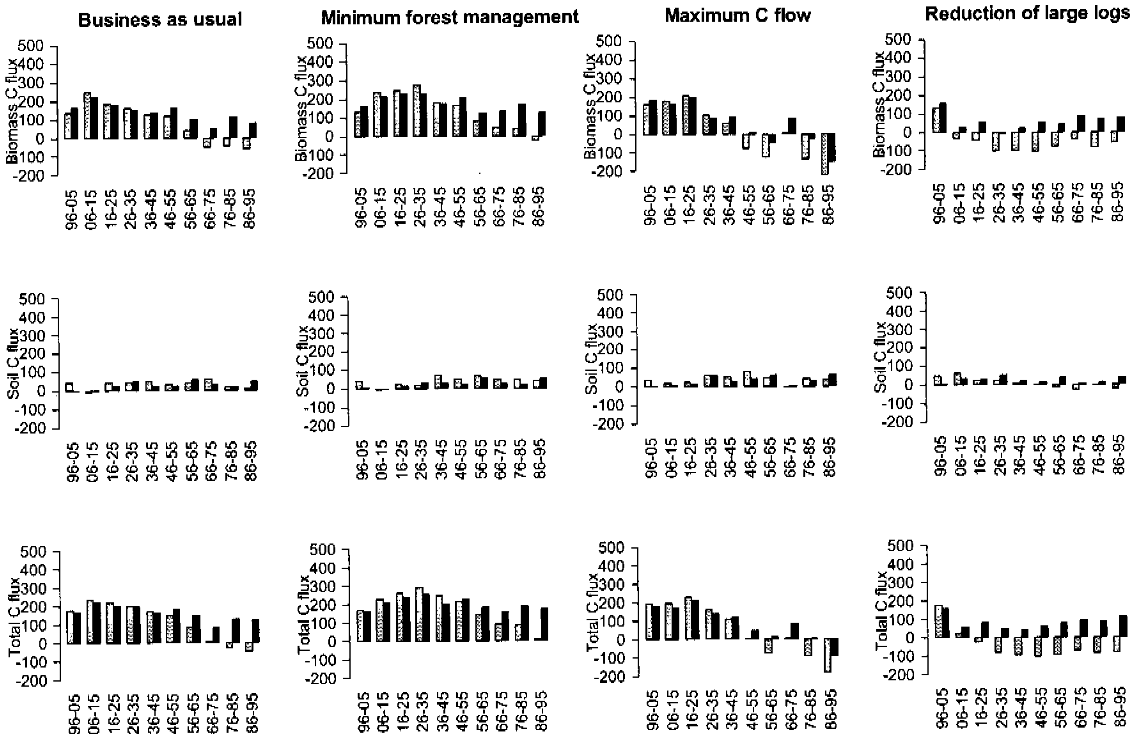

Fig. 4. Pre-Alps, mixes species stands. Annual C fluxes, averaged over 10 years [g per m^2]. X-axes: simulation years. ▨ MASSIMO / YASSO; ■ Biome-BGC.

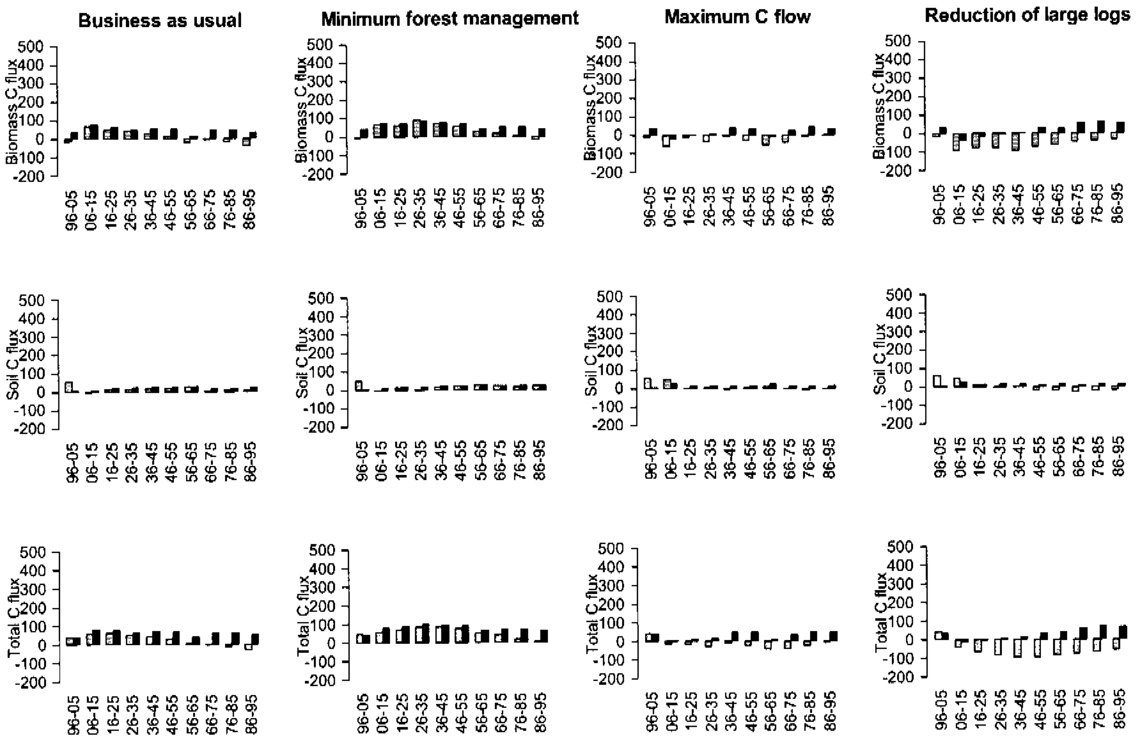

Fig. 5. Alps, coniferous dominated stands. Annual C-fluxes, averaged over 10 years [g per m^2]. X-axes: simulation years. ▨ MASSIMO / YASSO; ■ Biome-BGC.

3.2 Development of above- and belowground carbon pools

As indicated by the carbon fluxes, the amounts of biomass simulated by MASSIMO and Biome-BGC (biomass part) were more similar than the soil carbon amounts simulated by YASSO and Biome-BGC (soil part) (Tables 6 to 9). This is partly due to the fact that the initialization of the biomass led to very similar values, which was not the case for the soil carbon pool (cf. Table. 6). However, the increase of soil carbon in YASSO is much more pronounced than in Biome-BGC.

In the Plateau, MASSIMO generally estimated larger biomass carbon pools than Biome-BGC, with the largest absolute differences between the two models found in the "maximum C flow" scenario (10.1 kg m^{-2} and 7.2 kg m^{-2}; year 2095) (Tables 6 and 7). In the Pre-Alps and the Alps, the largest differences between the models were found in the "reduction of large logs" scenario (9.9 kg m^{-2} and 7.3 kg m^{-2}; year 2095) (Tables 8 and 9). However, in all forest types, differences in biomass carbon pools between the scenarios exceeded the differences between the models.

Table 6. Plateau, deciduous stands. Absolute values of biomass and soil carbon in kg m^{-2}. Bold numbers indicate differences between the model results larger than 4 kg m^{-2}.

		2015		2055		2095	
Scenario	Models	Biomass	Soil	Biomass	Soil	Biomass	Soil
Business as usual	MASS/YASSO	16.5	12.1	20.0	13.7	**21.3**	15.6
	Biome-BGC	15.5	8.7	15.9	8.7	**16.2**	8.7
Min forest management	MASS/YASSO	20.7	11.5	**36.7**	16.6	36.6	22.3
	Biome-BGC	18.6	8.2	**29.9**	8.0	34.7	9.9
Maximum C flow	MASS/YASSO	19.4	11.7	**26.8**	16.7	**29.2**	20.2
	Biome-BGC	17.3	8.4	**19.1**	9.0	**19.1**	8.4
Reduction of large logs	MASS/YASSO	17.3	11.9	17.1	13.9	14.7	14.2
	Biome-BGC	16.0	8.6	13.2	8.9	10.8	8.6

Table 7. Plateau, coniferous stands. Absolute values of biomass and soil carbon in kg m^{-2}. Bold numbers indicate differences between the model results larger than 4 kg m^{-2}.

		2015		2055		2095	
Scenario	Models	Biomass	Soil	Biomass	Soil	Biomass	Soil
Business as usual	MASS/YASSO	15.7	12.3	17.7	13.1	**19.8**	14.6
	Biome-BGC	14.3	9.3	14.0	10.1	**15.1**	10.4
Min forest management	MASS/YASSO	19.0	11.7	**29.3**	14.5	28.6	18.2
	Biome-BGC	16.9	8.9	**25.0**	9.3	29.5	12.0
Maximum C flow	MASS/YASSO	18.2	11.9	**22.8**	14.9	**27.0**	17.9
	Biome-BGC	16.2	9.0	**17.7**	10.2	**19.8**	10.4
Reduction of large logs	MASS/YASSO	16.0	12.2	15.2	13.4	**14.3**	13.7
	Biome-BGC	14.5	9.2	11.9	10.3	**10.3**	10.2

Table 8. Pre-Alps, mixed stands (fir and beech). Absolute values of biomass and soil carbon in kg m^{-2}. Bold numbers indicate differences between the model results larger than 4 kg m^{-2}.

		2015		2055		2095	
Scenario	Models	Biomass	Soil	Biomass	Soil	Biomass	Soil
Business as usual	MASS/YASSO	19.9	12.0	25.8	13.6	**24.7**	14.9
	Biome-BGC	20.0	12.5	26.3	13.7	**29.7**	15.2
Min forest management	MASS/YASSO	19.8	12.1	28.4	13.7	29.8	15.6
	Biome-BGC	19.9	12.5	28.2	13.5	33.7	15.0
Maximum C flow	MASS/YASSO	19.5	12.2	22.4	14.4	**17.7**	15.7
	Biome-BGC	19.6	12.6	23.5	14.0	**22.0**	15.6
Reduction of large logs	MASS/YASSO	17.1	12.8	**13.5**	13.3	**10.9**	12.6
	Biome-BGC	17.9	12.9	**19.1**	14.0	**21.8**	14.9

Table 9. Alps, coniferous dominated stands. Absolute values of biomass and soil carbon in kg m^{-2}. Bold numbers indicate differences between the model results larger than 4 kg m^{-2}.

		2015		2055		2095	
Scenario	Models	Biomass	Soil	Biomass	Soil	Biomass	Soil
Business as usual	MASS/YASSO	12.6	12.1	13.9	12.8	13.0	13.3
	Biome-BGC	13.2	12.6	15.2	13.5	16.6	14.3
Min forest management	MASS/YASSO	12.7	12.1	15.4	12.7	15.7	13.7
	Biome-BGC	13.2	12.6	16.1	13.4	17.9	14.4
Maximum C flow	MASS/YASSO	11.4	12.7	10.5	12.7	**9.4**	12.7
	Biome-BGC	12.2	12.8	12.9	13.3	**13.7**	14.0
Reduction of large logs	MASS/YASSO	11.1	12.7	**7.8**	15.6	**6.0**	11.7
	Biome-BGC	11.9	12.8	**11.9**	13.3	**13.9**	13.8

4 Discussion

The aim of this study was to investigate the range of responses of Swiss forests to different forest management scenarios. The two models provided comparable output that generally did not differ strongly, and especially the patterns and dynamics of the models were almost identical. Within the simulated years, both model estimated the "minimum forest management" scenario to produce the largest carbon fluxes and the "reduction of large logs" scenario to produce the smallest fluxes. In most of the regions, the models also agreed in projecting negative carbon fluxes in the "maximum C flow" scenario. This enhances our confidence in the projections of these models. However, the models show some salient differences in their behaviour that are discussed below.

4.1 Differences due to specific model formulations

4.1.1 Carbon fluxes

In the Plateau, the Biome-BCG model estimates smaller fluxes of biomass carbon than MASSIMO (Figures 2 and 3). However, in the Alps and the Pre-Alps the Biome-BGC estimates of carbon fluxes are higher than those of MASSIMO (Figures 4 and 5). These results agree with a quantitative validation of the Biome-BGC model based on data from

Switzerland (Schmid et al. in prep.), showing that tree growth was underestimated in the Plateau but overestimated at higher elevations.

The differences in the biomass carbon flux between the two models are particularly large in the "reduction of large logs" scenario in the Pre-Alps and the Alps. There, MASSIMO predicts a collapse of biomass carbon increment, while Biome-BGC simulates a constant growth. In this specific scenario, large logs, having an above-average growth rate, are systematically removed, and therefore the growing stock becomes smaller. Since Biome-BGC has no information about forest structure, not exclusively the large logs are taken out, but just "average" biomass. Therefore, Biome-BGC simulates only a small decrease in biomass growth. This indicates that mainly the scenarios with a tree-specific harvesting regime lead to large differences in the projections from the two models.

In the "minimum forest management" scenario, we found that for the last 40 simulation years, biomass carbon fluxes estimated by Biome-BGC were higher than those of MASSIMO in all forest types. We surmise that this is due to the non-linear density-dependent mortality that becomes effective when stand basal area or aboveground biomass, respectively, exceeds a certain value. Biome-BGC does not run on each NFI sample plot, but is upscaled and runs on 23 strata, each representing a biomass value averaged over a number of sample plots. As the density-dependent mortality is a non-linear function, these averaged biomass values do rarely reach the critical value to switch to the higher mortality. The model MASSIMO, however, running on each NFI sample plot, incorporates not only an averaged biomass value, but the distribution of the biomass as described in the input data. Due to the non-linearity of the mortality function, the right and the left tail of this distribution have different probabilities for density-dependent mortality, and averaging the distribution leads to different results. Therefore, the density-dependent mortality differs between the two models. This is a general problem of upscaling non-linear functions.

The strongly negative biomass carbon fluxes after 60-70 years of "maximum C flow" management observed in both models can be explained by the current stand age distribution. Today's Swiss forests have no uniform distribution, but there is a large gap between the 0 and 60 year old sites (Brassel and Brändli 1999). Since this scenario aims at a uniform age class distribution, the current gap leads to a depression in the development of the growing stock after 50-60 simulation years. As the stratification of sample plots for the Biome-BGC simulations did not account for stand age, the time course of C fluxes simulated by this model was caused mainly by the harvesting amounts.

YASSO estimates higher soil carbon fluxes compared to Biome-BGC (Figures 2 to 5). The differences between the two models become particularly apparent in the "minimum forest management" and in the "maximum C flow" scenarios in the Plateau (Figures 2 and 3). The increased litter input to the YASSO model, which is caused by the increased growth of biomass in MASSIMO, leads to largely positive fluxes of soil carbon during the first part of the simulation. Although in the later part of the simulation the estimated biomass increment becomes lower, soil carbon fluxes are still positive. This is due to increased natural mortality (as a result of high stand density), where the majority of the tree biomass remains in the forest (logs and stumps). Since Biome-BGC has a lower increase of biomass than MASSIMO, the increase of soil carbon is relatively small. However, the enhanced increase of soil carbon fluxes in the later part of the Biome-BGC simulation probably results from the increased density-dependent mortality.

4.1.2 Carbon pools

At the end of the 100-year simulation period, large differences in biomass carbon pools between the two models were found not only under extreme management scenarios (such as the "reduction of large logs" scenario), but also under the "business as usual" scenario (Tables 6 to 9). While biomass carbon pools of MASSIMO exceeded those of Biome-BGC in the Plateau, Biome-BGC had the larger amounts in the Pre-Alps and the Alps. The different climate sensitivities of the models are the likely reason for this different behaviour. These large differences in carbon pools are the result of differing carbon fluxes, as shown above. Regarding absolute biomass growth, MASSIMO is affected much more by the varying climate conditions than Biome-BGC. Since MASSIMO has been developed with the NFI sample plots used in this study, it is optimally adapted to the current climate conditions of the entire study area. Additionally, the study of Schmid et al. (in prep.) showed that Biome-BGC tends to underestimate growth at low elevations but overestimates growth at high elevations. Therefore, we assume that the MASSIMO results are generally more accurate than the Biome-BGC results under the current climatic and other environmental conditions such as CO_2 and N deposition in the study area.

4.2 Differences due to model approaches

Comparing models with different theoretical approaches helps to better understand model behaviour, its limits and sensitivities (Bolliger et al. 2000, Matala et al. 2003). Both model types applied in this study, empirical individual-based and ecophysiological process-based, have their advantages and disadvantages. Process models, for example, rely on mechanism constancy and empirical models on parameter constancy (Korzukhin et al. 1996), which has consequences for the predictive strength of the model.

The main advantage of empirical forest models is that they are typically based on large data sets representing the full range of forest types, climate zones, and disturbance and management regimes of the current landscape (Goodale et al. 2002). Models based on such data are initialized and run with sound and representative values for carbon pools, and therefore short-term carbon budgets are quite reliable (Körner 2003). However, if environmental conditions change, the parameterization of the statistical model, which is based on the conditions prevailing today, is likely to fail to accurately predict variables such as future carbon storage (Lischke 2001, Matala et al. 2003).

Ecophysiological models, which are based one knowledge about the underlying biological and ecological processes, can account for effects of environmental changes such as elevated

CO_2 concentrations or increased temperatures. However, as many ecophysiological models produce aboveground biomass integrated over large regions and over different tree heights as their primary output and lack information about stand structure, the application of these models to estimate the effect of different forest management scenarios is limited, as shown by the "reduction of large logs" scenario in this study.

Therefore, a combination of ecophysiological models with statistical models could be a way to partition the pooled output of the ecophysiological models into stem numbers or stem size distributions. Hence, forest models should in the future combine the predictive power and flexibility of ecophysiological models with the empirical information and descriptive accuracy of conventional mensuration-based models (Landsberg 2003). Especially for the development of operational models, it is necessary to get away from the pure dichotomy between ecophysiological and empirical modelling, and accept that at some level all models have both empirical and causal components (Mäkelä et al. 2000).

4.2.1 Strategies for carbon sequestration

Our results indicate that the sink capacity of the "minimally managed" forests becomes zero after 100 simulation years, and extrapolating the trend during the last simulation years, these forests even tend to become a carbon source. The managed systems sequestered less carbon within the simulated years, but as shown in the "maximum C flow" scenario, these forests may have the potential to still sequester carbon after the simulated 100 years. Karjalainen (1996) simulated forest growth over 300 years. His results both indicate a similar pattern during the first 100 simulation years and corroborate our hypothesis about trends after 2095. This indicates that forests have a certain capacity to sequester carbon which, in case of a "minimum forest management", might be used up within the next 100 years. Therefore, strategies to sequester carbon in forests can either tend to maximize short-term fluxes as in the "minimum forest management", or they can concentrate on sequestering carbon on a longer time-scale, such as in the maximum C flow scenario (Dewar and Cannell 1992). Our results also show that there is not one optimum strategy to maximize carbon sequestration in all forests, but different strategies according to the current growing stock and the productivity of the stands (Marland and Marland 1992). However, to find the optimum strategy for forest management in terms of maximum carbon sequestration, it is important to account not only for the above- and belowground carbon in the forest, but also for wood products and particularly the substitution of fossil fuels (Liski et al. 2001).

4.2.2 Restrictions and Limitations

As models can not exactly mirror reality but have to be based on simplifications and assumptions, there are a lot of limitations and uncertainties. A large source of uncertainty in all soil carbon models is the lack of accounting for losses of carbon due to soil disturbances. However, windthrow and other disturbance processes can strongly influence the soil organic carbon balance (Kramer et al. 2004). Therefore, due to large-scale disturbances such as windthrow or harvesting, soils may lose large amounts of sequestered carbon and therefore switch from a carbon sink to a source of carbon (Knohl et al. 2002, Kramer et al. 2004). In this study, we also neglected the effect of anthropogenic climate change on carbon budgets. Yet, there is strong evidence that elevated atmospheric CO_2 and air temperature consistently increase forest soil CO_2 efflux (Niinisto et al. 2004) and influence forest growth (Körner 2000, Bergh et al. 2003). Joos et al. (2001) estimated that due to global warming feedbacks, the terrestrial biosphere could become a carbon source during the second half of this century. Houghton (1996) assumed that additional release of carbon caused by the warming itself, through increased respiration, decay, and fires, may even cancel the intended above- and belowground effects of forest management.

5 Conclusions

Our study showed that different forest management scenarios resulted in both different strength of forests to act as carbon sink as well as in different time scales of the forests acting as either a sink or a source. Although the absolute values showed some differences, the temporal and spatial patterns of the responses of the different models were quite similar. This enhances our confidence in the applicability of the models. In the Alps, we assume that MASSIMO better reflects the special conditions than Biome-BGC and should therefore be preferred to estimate the future carbon development. The models project that in the absence of large-scale disturbances, forest biomass and soil carbon can be increased, and therefore forests can be used as carbon sinks. However, in the "minimum forest management" scenario, the limits of this potential sink effect are shown. Furthermore, the differences between the management scenarios can be related to the time which is considered: either carbon fluxes are maximized in the short (30-40 years) or in the longer term (100 years or more). Therefore, to find the optimum strategy in terms of not only maximizing carbon sequestration but climate protection, it is essential to account for wood-products and particularly substitution of fossil fuel in the model simulations.

Moreover, in long-term predictions up to 100 years, changing climatic conditions should be taken into account. The ideal solution would be to use a single-tree model incorporating physiological processes. However, the drawback of such more “biological” and usually more complex models is that they are sensitive to uncertainties in structure, parameter values and input data, are difficult to handle in simulations and time consuming, particularly for large-scale applications. There is a need for research to substitute empirical process functions by physiology-based ones and to fit the physiological functions with empirical data. Furthermore, complex and detailed models might be simplified by controlled upscaling to compensate for these drawbacks (Lischke 2001).

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Synthesis

The major goals of this thesis were to evaluate and apply two empirical forest models to assess the middle- to long-term (50-100 years) development of the above- and belowground carbon budget in forests as a function of forest management for Switzerland, assuming the continuation of current environmental conditions. The forest models rely on different concepts and structures, including an aggregated large-scale matrix model and an individual-based forest growth model. The models were investigated with respect to their projection reliability for long-term scenarios (chapters I, II & III), and they were applied to evaluate the assets and drawbacks of possible future management regimes (chapter IV). The assessment of the aboveground carbon budget relied on the models MASSIMO (Kaufmann 2000) and EFISCEN (Pussinen et al. 2001), whereas the soil carbon model YASSO (Liski et al. 2004) was used to estimate the belowground carbon budget.

The major aims of chapter I were (1) to validate the growth function of the model MASSIMO and (2) to detect the causes for possible deviations. The study showed that stemwood volume per ha was predicted quite accurately compared to independent data from a neighbouring region. This result enhances our confidence that this model is a reliable tool to predict forest growth and to perform estimations of the aboveground biomass in Swiss forests. However, MASSIMO is mainly based on empirical correlations. Therefore, the effect of changing environmental conditions (e.g., climate, CO_2, nitrogen deposition), which are likely to be important for long-term projections, can not be assessed. Moreover, the applicability of MASSIMO is restricted to conditions resembling those in Switzerland.

The main focus of chapter II was to evaluate the EFISCEN model with independent data. This study indicated that the model accurately estimated the growing stock for the entire study region in Switzerland. However, within that region major differences occurred. These scale-dependent effects were particularly pronounced for the spatial allocation of the harvesting amounts, the mortality and the age class distribution. Moreover, the EFISCEN model was not flexible enough to characterize the management practices that are common in Switzerland, especially in the Alpine region. Thus, the EFISCEN model was not applied to estimate the effect of different management scenarios within Switzerland.

The main focus of chapter III was (1) to adapt and evaluate the soil carbon model YASSO for Switzerland, and (2) to investigate the influence of different management practices and windthrow on the ecosystem carbon balance in forests. The validation of the soil carbon model YASSO showed that the size of the carbon pools was reproduced accurately. The results indicated that forest management has a significant effect on the aboveground carbon budget after windthrow. For the next 40 years, assuming a "business as usual" forest management scenario (111% of current harvesting amount) and a moderate storm frequency of 15 years, the aboveground carbon fluxes, averaged of 40 simulation years, were estimated at 135 g m^{-2} yr^{-1} and belowground fluxes at 20 g m^{-2} yr^{-1} and 27 m^{-2} yr^{-1} with and without clearing after windthrow, respectively.

The major goals of chapter IV were (1) to assess the effect of different models and different forest management scenarios on carbon source/sink relationships in Swiss forests, and (2) to identify differences between the regions. The application of the models MASSIMO/YASSO and the process-based model Biome-BGC (Schmid et al. In prep.) showed that the dynamics of the two models were very similar, although at different levels. Although the models differ strongly in their structure and approaches, they were found to react in a similar manner to the different forest management scenarios. This enhances our confidence in the model projections. The differences between the regions were found to be small, except for the Alps, were growth is low due to climatic conditions, and carbon fluxes therefore are smaller.

Reliability of carbon budget projections using empirical models

Empirical models contain many functions that typically are derived using large data sets. The key advantage of empirical individual-based forest growth models is their incorporation of horizontal as well as vertical structure, i.e. the distribution and variability of diameter at breast height (DBH), and the fact that they are species-specific. However, the environmental conditions are contained implicitly in the explanatory variables of the regression functions. Deviations from these conditions can not be accounted for explicitly, and therefore empirical models are restricted in their application to the conditions under which they have been fitted (Bossel 1991).

Process models, on the other hand, are more flexible in their application (Lischke 2001). In the process model Biome-BGC (Thornton 1998), functional relationships are incorporated at a high process resolution, normally based on experimental data, to describe the effects of factors such as CO_2, nitrogen and light availability on the rate of photosynthesis. Therefore, the impact of changes in these factors can be assessed. However, when "first order principles" such as photosynthesis and respiration are accounted for, the resulting model behavior often becomes difficult to understand, and the simulations can be quite time-consuming, especially when the models are to be applied at large spatial scales or over long periods of time (Lischke 2001, Matala et al. 2005). This often leads to simplifications at the expense of spatial heterogeneity, structural detail or temporal variability (e.g., fine-scale spatial variability is neglected, or leaves, stems, and branches are assumed to be distributed homogeneously across the entire simulation patch). These models often integrate over all trees of all heights and species in entire stands or regions, neglecting horizontal and vertical structure and species composition (Lischke 2001). However, dynamic global vegetation models such as the Lund-Potsdam-Jena model (Sitch et al. 2003) have recently started to combine biogeochemical process description with those that are required for simulating the dynamics of vegetation structure in a computationally efficient manner.

Thus, the choice of the model type is mainly defined by the weighting of changing environment and structure, which is defined by the research question. If changing environmental conditions are the main focus, models allowing for such processes have to be applied. If the influence of specific management practices on carbon sequestration is assessed to be most important, the model applied has to track a minimal degree of structural forest properties. The aim of this thesis was to assess the influence under a range of various forest management practices on the development of carbon pools and fluxes. Therefore, MASSIMO was assessed to best fulfill these requirements.

Effects of forest management regimes on carbon pools and fluxes

The results of this thesis suggest that there is not one single forest management strategy that is best to optimize carbon pools and fluxes in Swiss forests. Rather, different strategies may be preferable depending on the environmental conditions. For example, in the Alps, where current biomass is large but growth is low, the best strategy would be to continue the "business as usual" management as applied today, or to even reduce harvesting amounts to further increase the existing Alpine forest biomass (cf. chapter IV). These results agree with findings from Marland and Marland (1992), who found that protecting such forests is the most effective strategy. Moreover, the “optimal” strategy strongly depends on the time scale under consideration. For example, the results from chapter IV indicate for the Plateau that the sink capacity of "minimally managed" forests tends to become zero after 100 simulation years, and extrapolating the trend of the last simulation years, these forests would even turn into a carbon source. Forests that are managed intensively were simulated to sequester smaller carbon amounts than extensively managed forests. However, as shown in the "maximum C flow" scenario, the intensively managed forests may have the potential to still sequester carbon after the simulated 100 years. In addition, to identify the optimum long-term strategy for forest management in terms of maximum carbon budget, it would be essential to also account for wood products and especially the substitution of fossil fuels (Liski et al. 2001). Marland and Marland (1992) even suggested that in regions with a high productivity and low harvesting costs, such as in the Swiss Plateau, the most effective strategy for using forests as a carbon sink is to keep forests in a state of maximum increment (e.g., by the "maximum C flow" scenario) and to use the harvest either for long-lived construction purposes or to substitute fossil fuels.

The results from chapter III can be used to extrapolate an annual carbon budget for Switzerland for the next 40 years. Assuming the "business as usual" with a slightly increased harvesting amount (111% of today's amount) and a storm frequency of 15 years (clearing of the stormwood), the model simulations indicate that the Swiss forests sequester 155 g C m^{-2} yr^{-1}, of which 85% is living biomass and 15% is soil carbon. The Swiss forest area accessible for standard forest harvesting (not by helicopter) is approximately 80% of the productive forest amounting to 8,000 km^2. Extrapolating our plot-based estimates to the entire forest area, 1.24 MT C would be sequestered in the managed Swiss forests per year. If the stormwood is not cleared, this amount would even increase to 1.3 MT C per year. This amount would correspond to 10.4% of the Swiss CO_2 emissions of the year 2002 (SAEFL 2004). As suggested by the results in chapter IV, this rate may continue for the next 50-80 years. However, as chapter IV provides results for selected forest types only, this simplistic spatial extrapolation of the simulation results should be viewed with caution and must not be interpreted literally. Rather, to arrive at national carbon estimates, the models MASSIMO/YASSO would have to be applied to all forests in Switzerland.

Relevance of the results in regard to Article 3.4 of the Kyoto Protocol

The extrapolated country-wide values discussed above may not be directly accountable under Article 3.4 of the Kyoto Protocol in the first commitment period (2008-2012). As stated in the Kyoto Protocol, only "additional human induced" forest management activities since 1990 can be accounted for. The interpretation of this formulation is still subject to many uncertainties, such as (1) how to identify forests managed after 1990, (2) which "additional human induced" activities will be accounted for, and (3) how to distinguish between "direct human induced" and "human induced". The basic idea of the Kyoto Protocol was to stimulate forestry activities for enhancing carbon sequestration that exceed the activities before 1990. However, the wording of the Kyoto Protocol can be interpreted differently (Schulze et al. 2002). One possible interpretation is that most activities are in some way "human induced", even nature protection and biodiversity conservation. This would result in a system where nearly all changes in carbon storage since 1990 could be accounted for, also referred to as "full carbon accounting" (Schulze et al. 2002). Thus, for Switzerland "full carbon accounting" covers almost the entire forest area. In a different interpretation, only specific projects showing a change in forest management since 1990 could be accounted for, also referred to "partial carbon accounting" (Schulze et al. 2002). Therefore, the assessment area in "partial carbon accounting" is always equal or smaller than the assessment area in "full carbon accounting"; Schulze et al. (2002) stated that "... in contrast to "full carbon accounting", such "partial carbon accounting" (restricted to specific activities) can create loopholes that conceal emissions. ...".

Under the Kyoto Protocol, the "cap" for Switzerland was set to 0.5 MT C per year. A "full carbon accounting" according to this study would result in a sink of approximately 1.24 MT C per year (see above). Fischlin et al. (2003) found that a "partial carbon accounting" would result in an annual carbon sink of 0.3 MT C. The difference between the two assessments is mainly due to the differences in the forests area or forest management accounted for. The main question therefore is whether under the Kyoto Protocol, the accounting system will be a "partial accounting" or a "full accounting". As long as no decision is taken, the amount of carbon sequestered in forests that is accountable under the Kyoto Protocol cannot be estimated for Switzerland. For the first commitment period (2008-2012), the countries can decide whether they want to include additional activities such as forest management. However, for the following periods, countries probably will have to account for all management practices (Fischlin et al. 2003).

General conclusion

The results of this thesis indicate that the models MASSIMO and YASSO can be applied to estimate the development of carbon pools and fluxes in Swiss forests on the time scale of several decades to one century, given that the effect a changing environment is negligible. Thorough model validations and evaluations under different management practices provide the range of forest carbon pool estimations for the next century and increase our confidence in the reliability of the simulations from models of radically different concepts and structures. However, the environmental conditions can not be assumed to remain constant during the 21st century; the impact of changing conditions on carbon pools and fluxes is assessed in the thesis by Stéphanie Schmid.

Although the models were found to be useful for predicting future carbon sequestration scenarios, the results have to be interpreted with caution. The approach of sequestering carbon in forests to reduce atmospheric CO_2 is only an interim strategy for the coming decades, during which sustainable strategies should be developed and implemented. The main goal, however, should be a direct reduction of carbon emissions (Breshears and Allen 2002). Finally, increasing the carbon pools in forests also bears considerable risks. Disturbances such as forest fires or windthrow are processes by which large amounts of terrestrial carbon can be lost rapidly (Breshears and Allen 2002, Körner 2003), and such disturbances are likely to become more significant due to the increasing probability and magnitude of extreme climatic events in a changing climate (Easterling et al. 2000, Schär et al. 2004).

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