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**Bridging the gap between forest growth and forest  
succession models**

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# Summary

In the coming decades the forestry sector will face the challenge to maintain its status as a green economy under the pressure of providing more bioenergy and other goods and services. Some suggestions have been made on how this could be achieved, yet to implement these suggestions appropriate tools need to be supplied by science and experts that are capable of extrapolating forest dynamics into the future. Based on the strength and weaknesses of the tools currently in use in forest science and the nature of the problem, hybrid models, and especially gap models as established hybrid models, present themselves as tools with high potential. However, they suffer from a lack of testing regarding their practical application in long-term strategic planning and yield projection in forestry, and also from some limitations in their structure.

With this work I therefore wanted to contribute to closing this gap by developing a succession model into a tool that can be used in such a context. By doing this I wanted to firstly combine the strengths of growth and succession models to acquire a climate sensitive model with high prediction capabilities for forest yield, secondly to apply the resulting model, i.e. a new version of the gap model FORCLIM, for the simulation of scenarios that a growth model would typically be employed for and thus show its potential, and thirdly to provide incentives with this work for further gap model development towards establishing them as valid tools in forest management planning.

In Part 1 of the thesis, I implemented a wide range of cutting and thinning techniques, including continuous cover forestry ('plentering') into FORCLIM, to lay the basis for its application in practical forestry. The new routines were tested against long-term data from eight growth and yield research plots across climatic conditions ranging from subalpine to colline in Switzerland. I could show (1) that the management submodel adequately depicted silvicultural treatments, including continuous cover forestry; (2) that a generic harvesting setting can be substituted for a very detailed one, thus eliminating a major source of uncertainty in assessments of future forest dynamics; and (3) that the new version of FORCLIM is able to deal with forests under widely differing settings of current climate, suggesting that it may be employed with reasonable confidence to simulate future management strategies under scenarios of anthropogenic climatic change.

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In Part 2 I tackled some of the limitations in the structure of gap models and focused on an area that had not yet received appropriate attention: the formulation of height growth and maximum tree height, which are of high importance in forest management. In most gap models, every tree approaches a fixed maximum height regardless of site conditions, and tree height as such is approximated via stem diameter. I developed approaches to deal with these issues that are based on climatic information alone and allow for dynamic adjustments under a changing climate, tested the new model formulations against data from the Swiss National Forest Inventory (NFI) and a forest growth and yield research plot, and applied the new model version to study productivity changes due to climate change along an environmental gradient. I concluded that implementing a dynamic height growth and site-specific maximum tree height can significantly improve simulation results of forest succession models, especially with regard to forest management under climate change.

In Part 3 I applied the improved version of FORCLIM to study issues related to adaptive forest management planning under climate change. I simulated forest stands on six climatically different sites in Central Europe under several scenarios of species diversity, management, and climatic change. I evaluated if one of the factors influenced the provision of forest ecosystem goods and services (EGS) – represented by indicators of harvested basal area, biomass, stand diversity and productivity – more strongly than others. I also evaluated if negative influences could be mitigated by adaptive management measures. The results showed that not many stands – represented by their unique combination of factors – may perform significantly worse regarding EGS compared to today, and that species diversity is key to this response.

Based on these results, I feel positive that gap models may complement the range of decision support tools available today and contribute to the development of management strategies to alleviate risks associated with climate change. They perform predictably, climatic conditions have a direct influence on forest dynamics, and their complexity is such that there is a chance of tracing problems to their source. Furthermore, this work has shown that their potential is by no means fully realized and that it is still possible to significantly improve their performance through simple means. Gap models may not be able to match the absolute short-term accuracy of forest growth models, but they are very well able to work in combination with them and provide help concerning long-term strategical planning in forestry.

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# Zusammenfassung

Dem forstlichen Sektor wird in den nächsten Jahrzehnten mehr Leistung abverlangt werden, zum Beispiel als Lieferant für Bioenergie. Trotzdem bleibt der Anspruch bestehen, die Waldbewirtschaftung nachhaltig zu gestalten. Beide Aspekte zu vereinbaren ist nicht trivial und erfordert geeignete Instrumente. Schon heute verfügt die Forstwissenschaft über eine breite Palette an Instrumenten für die Vorhersage von Waldwachstum, die sich durch individuelle Stärken und Schwächen auszeichnen. Sie sind deshalb gut oder weniger gut für den Einsatz als Entscheidungshilfen geeignet. Die Familie der Hybridmodelle, mit Sukzessionsmodellen als deren älteste Vertreter, scheint in diesem Kontext besonders vielversprechend zu sein. Sukzessionsmodelle wurden allerdings nicht für die Simulation langfristiger Waldbewirtschaftungsstrategien entwickelt und ihr Aufbau ist deshalb bezüglich der Darstellung bewirtschafteter Wälder mangelhaft.

Um aus einem Sukzessionsmodell ein verlässliches Instrument für die forstliche Planung zu machen, wurde in der vorliegenden Arbeit eines dieser Modelle verbessert. Dabei wurde darauf geachtet, erstens die Stärken von Waldwachstums- und Sukzessionsmodellen zu verbinden und so ein klimasensitives Modell mit Fähigkeit zur Simulation von Waldbewirtschaftung zu erhalten; zweitens die Fähigkeiten dieses neuen Modells an einer Problemstellung zu demonstrieren, für die typischerweise ein Waldwachstumsmodell eingesetzt würde; und drittens neue Impulse für die Weiterentwicklung von Sukzessionsmodellen zu geben, um diese als verlässliche Instrumente in der Forstwirtschaft zu etablieren.

Zu diesem Zweck wurden zunächst im ersten Kapitel das neue Management-Submodul und dessen Implementierung in FORCLIM beschrieben. Es kann eine Vielzahl an Bewirtschaftungsarten simulieren, unter anderem die Plenterwirtschaft. Getestet wurde das Modell anhand von Inventurdaten von acht langfristigen (72-111 Jahre) Versuchsflächen der Waldwachstumsforschung der WSL Birmensdorf. Die Bestände befinden sich auf subalpiner bis kolliner Stufe und wurden entweder hoch- oder niederdurchforstet oder als Plenterwälder bewirtschaftet. Es konnte gezeigt werden, dass das neue Modul Waldbewirtschaftung realistisch wiedergeben kann.

Das zweite Kapitel wurde der Formulierung des Höhenwachstums und der maximal möglichen Baumhöhe gewidmet; zwei Schwachstellen im strukturellen Aufbau der Sukzessionsmodelle. In den meisten Modellen ist Wachstum so formuliert, dass zum

einen kontinuierlich wachsende Bäume unabhängig von ihren Standortbedingungen irgendwann ihre maximal mögliche Höhe erreichen, und dass zum anderen diese Höhe über eine fixe allometrische Beziehung vom Durchmesser abgeleitet wird. Da beide Annahmen besonders in bewirtschafteten Wäldern nicht realistisch sind, wird in diesem Kapitel eine verbesserte Formulierungen vorgestellt und diese mithilfe von Daten aus dem Landesforstinventar und Versuchsflächen der WSL getestet. Die Untersuchungen zeigten, dass die Implementierung einer dynamischen maximalen Höhe und eines variablen Verhältnisses von Durchmesser zu Höhe Simulationsergebnisse signifikant verbesserten, und dass die Veränderungen ebenfalls Auswirkung auf die Simulation von Produktivität unter Klimawandel haben.

Im dritten Teil zuletzt wurde die erweiterte und verbesserte Version von FORCLIM praktisch angewendet: Untersucht wurde, inwieweit verschieden bewirtschaftete Bestände mit unterschiedlichen Artenzahlen auf verschiedenen Standorten durch den Klimawandel in der Bereitstellung von Waren und Dienstleistungen beeinflusst werden. Es wurde ermittelt, welcher der Faktoren - Bewirtschaftung, Artenzahl oder Klimawandelszenario - den größten Einfluss auf eben jene Bereitstellung ausübte, um dann gezielt Maßnahmen zu entwerfen, die etwaigen negativen Einflüssen entgegenwirkten. In der Auswertung zeigte sich, dass viele Bestände nicht signifikant schlechter abschnitten als andere am gleichen Standort, und dass bei negativen Entwicklungen die Artenzahl eine Schlüsselrolle spielte.

Ausgehend von den hier vorgelegten Ergebnissen schließe ich, dass Sukzessionsmodelle geeignete Instrumente zur Bearbeitung von Fragestellungen bezüglich der Auswirkungen des Klimawandels auf Bestandesentwicklungen sind. Sie arbeiten verlässlich und klimatische Veränderungen üben einen direkten Einfluss auf das Baumwachstum aus. Diese Arbeit zeigte auch, dass das Potential der Sukzessionsmodelle noch nicht ausgeschöpft ist und diese durch einfache Maßnahmen verbessert werden können. Sukzessionsmodelle sind zwar nicht in der Lage, die Präzision von speziell auf die Standorte angepassten Waldwachstumsmodellen zu erbringen, können aber in Kombination mit anderen Modellen durchaus zur langfristigen forstlichen Planung beitragen.

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# General introduction

## Background

After such events as the catastrophic oil spill of the Deepwater Horizon platform in the Gulf of Mexico in April 2010 or the nuclear accident in the Fukushima power plant in spring 2011, there is more pressure than ever on society to create and maintain green economies. Such economies are generally speaking low in carbon, resource efficient, and socially inclusive, and thus represent a way to achieve sustainable development (UNEP, 2011). In this respect, the forest sector is in a very good position.

And yet, its current good standing may be jeopardized in the future: The pressure on other areas of society to transform into green economies will put more and more pressure on the forest sector as well, for example to provide more material for bioenergy or to store elevated amounts of carbon. In fact, already today foresters caution against designating additional areas as nature reserves or parks for fear of losing too much productive area (e.g. Bont, 2011). Thus the challenge the sector now faces is to retain its status as a green economy, and also to facilitate the transformation of the overall economic framework into such a new economy.

To this end, an action plan has recently been proposed (Anonymous, 2011). In this plan many points are raised that may help with the challenges faced by forestry now and in the coming decades, for example (i) ensuring that the regional wood supply can meet society's needs, (ii) helping the sector to deal with risks associated with climate change, and (iii) determining the best practice for every region. These topics are relevant not only at the European scale, but at the national and regional scales as well. It is, for example, projected that the consumption of woody raw materials in Switzerland will increase in the next years (UNECE/FAO, 2005), a trend that may be even more pronounced now that there are political efforts to abandon nuclear power.

This is where forest science comes in. In the last three centuries, yield tables served as the tools of choice to project timber yields of forest stands and to assess which thinning intensity and rotation length would serve best. These static approaches have been complemented in the second half of the last century by computer models

of various designs, ranging from those mainly recreating yield tables, to very complex models aiming to simulate the underlying processes of forest growth. Which of these tools serves best depends on the question being asked.

In our case with the three points mentioned in the action plan as topics of interest, a model of choice should firstly be able to accurately simulate forest dynamics, and thus yield, in different regions, secondly do this under the presumption of a changing climate, and thirdly be able to consider different management options in order to choose the most appropriate one for the further strategic planning of forest management. The question arises which type of model would be most suitable in this context.

## Model types

The categorization of specific models is a matter of convention and thus will never be settled; also, it tends to depend on the point of view of the author. There is, however, a consensus in forest ecosystem science on the major model types that are being used (cf. Fontes et al., 2010): empirical or management models (EM), biogeochemical or process-based models (PM) and hybrid models (HM). EM were developed with the goal to substitute yield tables for even-aged single-species stands and to also consider uneven-aged mixed stands, PM to understand the interactions between the cycles of energy, water and nutrients, and HM to analyze vegetation patterns by combining elements of the other two approaches (Hasenauer and Pietsch, 2009; Mäkelä, 2009). All three kinds of models have particular strengths and weaknesses, as reviewed briefly below.

EM are based on empirical data and serve particularly well for short-term tactical planning. They are used mainly in age-class forestry as practiced e.g. in the U.S. and Canada, with large monoculture stands that are harvested with clear cuts and replanted afterwards (Kimmins et al., 2010). Their biggest constraint is their applicability in structurally diverse stands, as the high number of potential combinations between management, species and site quality cannot all be included in the dataset used to parameterize such models. In addition, strictly speaking these models can only be applied to cases they have been parameterized for (Kimmins et al., 2010), thus disqualifying them for simulations under climate change. There have been efforts, however, to achieve more flexible EM by using a dynamic state-space approach (Fontes et al., 2010).

PM strive to be independent from empirical calibration data at the level of the simulated output variables; instead, they are built to incorporate the processes responsible for tree growth based on first principles. By doing so, effects of climate change are automatically accounted for in the model, and even factors such as wood structure and wood properties – desirable to know e.g. for bioenergy considerations – can be simulated. Yet, there is considerable debate on which of these processes are actually limiting tree growth and tree population dynamics (e.g. Bugmann and Bigler, 2011; Reynolds et al., 2001) and should therefore be included in the modeling framework. The solution of including as many factors as possible is not feasible due to computational limits and lack of data, but even with only the most important ones explicitly considered, PM are sometimes viewed as being overly complex and highly demanding regarding physiological data that are hard to come by, particularly if more than just the commercially most relevant species are being considered.

With the development of HM, scientists have attempted to overcome the disadvantages of the former two model types and simultaneously reap the benefits of both (Mäkelä, 2009). Mäkelä distinguishes three different types of HM:

- 1) Hybridized EM that use PM as providers for additional input
- 2) Hybridized PM that use functions derived from empirical data and modify them by using physiologically based functions
- 3) Reduced-form process models that aggregate complex PM to core components.

The type of HM with possibly the longest standing is the hybridized PM, and one of its main representatives is the family of so-called “gap” – or forest succession – models. They were first developed in the early 1970s (Botkin et al., 1972a, b) and have been improved structurally and expanded in their applications ever since. Their formulation is based on the concept that stand dynamics as a whole can be represented by the individual succession of trees on small patches of land. The main driver of this succession is the competition for light between the trees, and thus the growth efficiency of different species under different climatic conditions. This primary reliance on climatic conditions to drive forest dynamics is their strongest point, as it renders them capable to firstly consider scenarios of climate change, and secondly to be easily transferable from one location to another without the need of elaborate site-specific parameterizations that need to be done by the user

beforehand. For these reasons this model family was selected to serve as the basis for this work, and they will thus be discussed in more detail in the next section.

## Gap models

The development of these models has been steadily advancing in the last four decades, beginning with the ancestor model JABOWA (Botkin et al., 1972a, b). From then on gap model development flourished, and improvements were made for example in the formulation of tree growth (Lindner et al., 1997), the response to growing-season temperature (Bugmann and Solomon, 2000) or the response to drought (Bugmann and Cramer, 1998). Other changes include that in models for high-latitude forests, the simplistic assumption of light coming from straight above was changed to accommodate low sun angles (FORSKA, Leemans and Prentice, 1987; SORTIE, Pacala et al., 1996; ZELIG, Smith and Urban, 1988).

One topic that received broad attention in the gap model community is the question whether these traditionally spatially implicit models should be converted to spatially explicit ones. In most gap models the position of trees on a patch is not known. When spatial aspects were included in the models, this mainly was in the sense of a connected grid of patches (e.g. SEEDSCAPE, Easterling et al., 2001; TreeMig, Lischke et al., 2006; ZELIG, Smith and Urban, 1988) where light and/or seeds can cross patch borders. There are some models, however, where the position of each tree is tracked (e.g. SORTIE, Pacala et al., 1996), yet there is still debate whether this is a feature gap models need to capture in a realistic manner, or whether it is only adding computational time without significantly increasing the quality of the model output (Busing and Maily, 2004).

In recent years, most model improvements were made in more specialized areas of the gap model framework, for example in the explicit simulation of juvenile tree growth (SORTIE-ND, Beaudet et al., 2002; Seagle and Liang, 2001; FORCLIM, Wehrli et al., 2007), or of processes such as damage caused by ice storms (LINKADIR, Lafon, 2004). In SORTIE-ND (Beaudet et al., 2002) routines for tree fern establishment, masting years, and insect outbreaks were added and the model TreeMig is able to consider land abandonment and its consequences for seed dispersal (Rickebusch et al., 2007). Management routines were added to several gap models as well (see Introduction of Chapter I for details).

When looking at the model improvements published in the last two decades, it appears that an undisputed consensus was reached about ten years ago, and from then on core functions such as mortality and growth, even though not perfect, were nevertheless viewed as more or less consolidated, in spite of explicit claims to improve on these elements (Keane et al., 2001; Price et al., 2001). Consequently, more effort was put into improving or adding details, such as those discussed above, and into increasing the accuracy of models for specific regions, rather than into their general applicability.

Two noteworthy exceptions to this trend are the models FAREAST and FORCLIM. The FAREAST model was developed with the explicit goal to expand its applicability to the whole of northeastern China, and subsequently also tested in parts of Russia (Xiaoding and Shugart, 2005). FORCLIM was developed for Switzerland (Bugmann, 1996) and tested in parts of Europe (e.g. Didion et al., 2009), the Colorado Front Range (Bugmann, 2001), the Pacific Northwest of the United States (Busing and Solomon, 2005), and Northeastern China (Shao et al., 2001).

When choosing an appropriate tool for this study, the long standing of FORCLIM, its original development for Switzerland, its wide application, and its thorough testing of not only local accuracy, but also general applicability recommended the model. Like many other gap models, which were originally designed to examine patterns of successional dynamics in natural forests, at the outset of this thesis the model completely lacked a focus on the simulation of forest management and the requirements that come with it, a prerequisite for the development of adaptive management strategies and thus an issue that had to be addressed in my thesis.

## Research aim

With this work I aimed to further develop a gap model into a tool that can be used in a context such as mentioned in the action plan mentioned above. By doing this I wanted to (1) maintain the original idea behind hybrid models: to overcome the specific disadvantages of EM and PM while coming close to the quality of their results; (2) to evaluate the potential for doing so by using the gap model FORCLIM for the simulation of scenarios an EM would typically be employed for; and (3) to apply it to a problem that may be characteristic for those that the forest sector will be faced with in the future. Lastly, I wanted to provide incentives for further gap model

development, thus contributing to their corroboration as valid tools that may complement others to achieve the best possible decision support for stakeholder groups in the future.

To achieve this goal, I did the following:

## **Chapter I**

To serve as a decision support tool in forestry, it is indispensable for any model to simulate forest management. The gap models currently available that feature management options typically restrict themselves to a limited selection of silvicultural treatments, whereas in the context of decision support for the regional, national or continental level it is important to include the widest possible range of common and possible novel silvicultural treatments. I therefore firstly implemented an extensive management submodel in the gap model FORCLIM and tested it against data from several long-term forest growth and yield research plots. This kind of problem – to predict basal area, diameter distribution and yield of a forest stand – typically falls into the domain of EM, and serves as an excellent test for the capabilities of FORCLIM as a tool in forest management planning.

## **Chapter II**

As described above, over the last years the development of gap models shifted to details and the improvement of local accuracy, while leaving the actual core functions mostly unchanged. For example, an important area that has not received the attention it deserves is the formulation of height growth and maximum tree height. In most gap models, every tree approaches a fixed maximum height regardless of site conditions (that may change with a changing climate), and tree height as such is approximated via stem diameter. In this chapter I therefore present approaches to deal with these issues, and test the new model formulations both for their improvement of local accuracy and also for their general applicability.

## **Chapter III**

Lastly I tested if the model is capable to serve as a tool to support decision making in the context of the challenges that forestry is likely to face in the future. I therefore applied FORCLIM to the question of how sensitive forest stands are under different management regimes and with different species diversity under climate change, and if the choice of climate change scenario influences results significantly. Subsequently

I aimed to identify adaptive management scenarios for those stands whose provision of ecosystem goods and services suffered most under climate change, thus showing that a gap model is indeed capable of serving as a tool in adaptive management planning in forestry.

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## Chapter I

# Getting a virtual forester fit for the challenge of climatic change

Livia Rasche, Lorenz Fahse, Andreas Zingg, and Harald Bugmann. 2011.

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**Abstract.** The empirical study of forest ecosystem dynamics is difficult because of the longevity of trees. Many types of models were developed to assist with this problem, all of them with advantages and disadvantages. The strengths of gap models are that they are able to simulate forest dynamics under changing climatic conditions and are therefore suitable for exploring future forest dynamics.

Most temperate and boreal forests are managed, making it important to incorporate harvesting functions depicting a wide range of silvicultural practices into the models and to test them under different climatic conditions. This is a necessary prerequisite to the application of these models under climatic change scenarios. Most gap models, however, do not feature such submodels, which disqualifies them as decision support tools.

We implemented a management submodel in the gap model FORCLIM that is able to simulate a wide range of cutting and thinning techniques, including continuous cover forestry ('plentering'). We tested the new submodel against long-term data (72–111 years) from eight growth and yield research plots across climatic conditions ranging from warm-dry to cold-wet.

Stem numbers were simulated accurately in nearly all cases, basal area showed a good fit on *Quercus*-dominated plots, but an over/underestimation on *Fagus sylvatica*-dominated and *Picea abies*-dominated plots. The diameter distributions simulated for the time of the most recent inventory did not differ significantly from empirical data except for two cases. Harvested basal area and stem numbers mostly agreed well with empirical data, but showed the same deviation from reality as simulated basal area.

Simulations run with an accurate management plan taken from foresters' reports for the plots yielded nearly the same results as those run with a generic management setting.

We have demonstrated that (i) the management submodel adequately depicts silvicultural treatments, including continuous cover forestry; (ii) a generic harvesting setting can be substituted for a very detailed one, thus eliminating a major source of uncertainty in assessments of future forest dynamics; and (iii) as the new version of FORCLIM is able to deal with widely differing current climates, it can be employed with reasonable confidence to simulate future management strategies under

climatic change. Overall, this modelling work is a major step towards the use of succession models as decision support tools in forest management.

**Keywords.** *climatic gradient, FORCLIM, gap model, long-term inventory data, thinning, uneven-aged forest management, validation.*

## Introduction

Projecting forest growth from stand initiation to the final cutting is at the heart of forest science, going back to the first yield tables in the late 18th and early 19th centuries. In recent decades, dynamic models have been replacing static yield tables and a wide variety of forest growth models exists today, ranging from highly aggregated models that focus on even-aged, single-species stands (e.g. Grote, 1998) to individual-based models that incorporate a detailed consideration of the local environment of every single tree (e.g. Pacala et al., 1996). This reflects the increasing tendency of modern forestry towards mixed-species, uneven-aged stands and the fact that climatic conditions are changing.

Accurately projecting the dynamics of managed forests under strongly changing management and climatic drivers remains a challenge. In the past 20–30 years, dynamic forest growth models have increasingly been used for this purpose (Pretzsch et al., 2008). The formulation of these models is based on past experience embodied in empirical data sets, thus making it difficult to use them under a rapidly changing future climate. Purely mechanistic models, however, tend to be quite complex and are calibrated for a few sites only, are not widely and freely available, or they are costly to calibrate and not easy to use (Kimmins et al., 2005).

The concept of forest gap models (Bugmann, 2001; Shugart, 1984) deviates strongly from that of forest growth models in the sense that they are formulated more generally and usually do not depend on site-specific parameterizations. Taylor et al. (2009) postulated that models used to simulate adaptive management ideally should run with data that are readily available to foresters, such as growth and stand inventory information, and Stage (2003) suggested that model complexity should be no greater than that essential to represent the effects of proposed actions, with planning horizons of 50–200 years (Davis et al., 2001). Thus, it appears that gap models are well suited to handle the complexity of rapid changes in management and climatic conditions.

To date, gap models have mainly been used to simulate the dynamics of unmanaged forests (e.g. Botkin et al., 1972; Bugmann, 1996; Shao et al., 2001). The gap models with harvesting options include KIAMBRAM (Shugart et al., 1980), ZELIG (Garman et al., 1992), FORSKA-M (Lindner et al., 1997), FORMIX 3-Q (Ditzer et al., 2000), JABOWA-3 (Grinter, 2001), 4C (Lasch et al., 2005), LINKAGES (Ranatunga et al., 2008) and PICUS (Seidl et al., 2008). However, few detailed descriptions have been published so the assessment of these management functions is difficult. In KIAMBRAM, JABOWA-3 and FORMIX 3-Q, single trees are removed; ZELIG eliminates percentages of the stand; and LINKAGES allows the removal of both whole trees and boles only, leaving branches, bark and leaves behind. In PICUS, harvesting regimes are simulated by reducing the number of trees in one or more of five diameter classes, and in FORSKA-M and 4C trees are removed based on a Weibull function defining the diameter distribution of the parting trees. Typical tests of these functions have covered only short time spans and one single site, which is insufficient to establish their credibility for simulations under global change.

In addition, what is missing in all these models is a function explicitly describing plentering, which is becoming increasingly important, as many forest agencies today promote the transformation of traditional silvicultural practices towards 'near-natural' forest management (Gadow et al., 2002). There are examples of gap models simulating this specific silvicultural technique, but they rely on approximations, e.g. by simulating several thinnings from above in the early development stages followed by a transition to target diameter harvesting (PICUS, Seidl et al., 2008) or by simulating thinnings in different canopy layers (4C, Kint et al., 2009). There are, however, some individual tree growth simulators capable of simulating uneven-aged forest management, notably SILVA (Pretzsch et al., 2002), MOSES (Hasenauer et al., 2006) and PrognAus (Ledermann, 2001). PrognAus, for example, simulates uneven-aged forest management by using target diameter harvesting combined with structural thinning following de Liocourt (1898) (Sterba and Ledermann, 2006). These functions yield good results when compared with desired uneven-aged forest structures (Hanewinkel and Pretzsch, 2000).

In this article, we, therefore, evaluate whether a detailed plentering function can be utilized in a forest gap model to depict uneven-aged forest management and whether the same model is able to adequately simulate a wide range of management scenarios subject to different climatic conditions over multi-decadal to

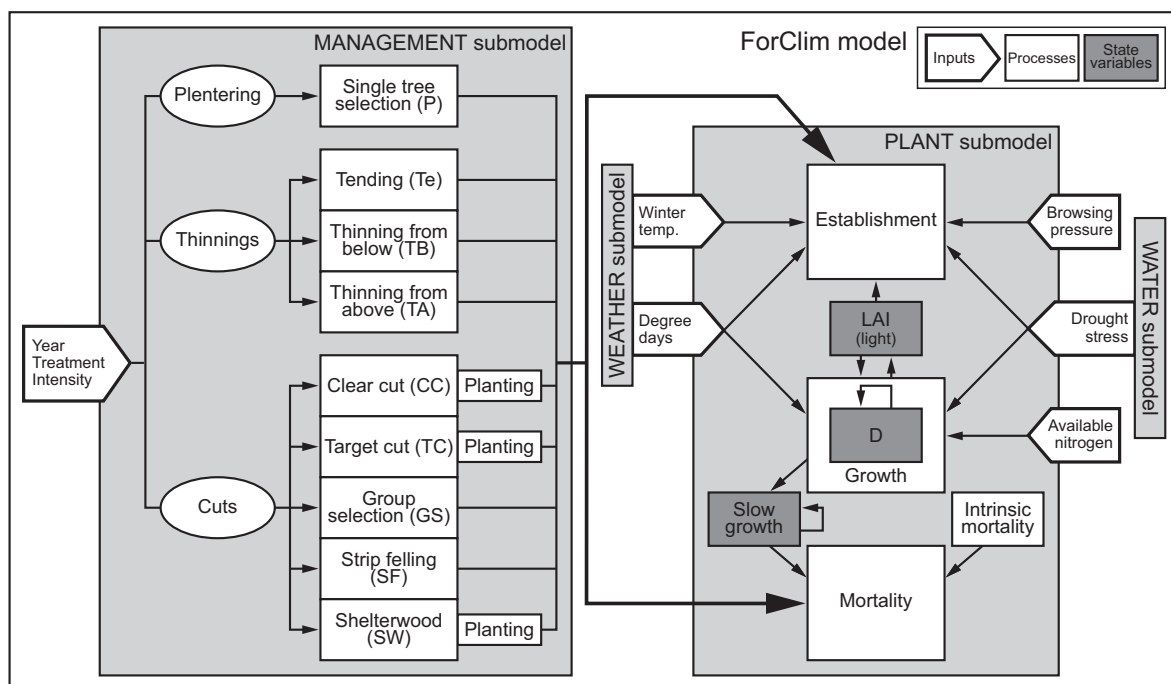
centennial time scales. Proof of the latter is a necessary prerequisite for modelling studies with climate change, because no trust could be placed in results from such studies if a model is not able to cope with different current climate conditions. Lastly, we explore whether a generalized harvesting setting can accomplish the same as a detailed one, thus reducing the uncertainty for simulations into the future.

## Material and Methods

### FORCLIM description

FORCLIM is a gap model designed to incorporate simple yet reliable formulations of climatic influences on ecological processes, while using only a minimum number of ecological assumptions (Bugmann, 1996).

The model consists of three submodels (Fig. 1, right): PLANT simulates establishment, growth and mortality of 30 European species on small patches of land. Tree establishment rates are determined from light availability on the forest floor, growing season temperature, soil moisture, minimum winter temperature and browsing pressure.



**Fig. 1.** Structure of the FORCLIM model with submodels management, plant, weather and water.

Growth is modelled based on the carbon budget approach by Moore (1989), modified by Risch et al. (2005) and Didion et al. (2009). In this approach, the species' optimal growth rate is decreased based on the degree to which environmental factors (nitrogen availability, growing season temperature and soil moisture) and crown size are at suboptimal levels. Tree mortality is modelled as a combination of an age-related and stress-induced component. The input data for these processes are provided by the submodels WEATHER and WATER, which calculate minimum winter temperature, growing season temperature and soil moisture based on long-term weather data and the stand-specific soil water holding capacity. For a detailed description of the model see Bugmann (1996), Bugmann & Solomon (2000), Risch et al. (2005) and Didion et al. (2009).

## Management submodel

We implemented functions describing the following harvesting techniques (Fig. 1, left) in the latest version of FORCLIM (Didion et al., 2009), resulting in FORCLIM v2.9.8. Unless otherwise stated, the definitions are taken from Leibundgut (1949).

- Thinning: Reduction in stand density of trees primarily to improve growth. Called 'thinning from below' if the individuals are removed from lower crown classes and 'thinning from above' if they derive from (co)dominant crown classes (Thornton et al., 1997).
- Clear cutting: All trees are removed on a certain area.
- Target cutting: Removal of trees that have reached a certain diameter.
- Group selection ('Swiss femel'): Gaps are cut into the forest and slowly extended in all directions over several decades.
- Strip felling: Parts of the stand are removed periodically, starting at one end and moving against the main wind direction.
- Shelterwood felling: The main forest body is removed step by step, leaving larger trees to protect the soil and regeneration.
- Continuous cover forestry (plentering): In an uneven-aged forest, basal area is held constant by removing the surplus ingrowth in each class, mainly from the highest diameter classes.

For a detailed description of the management submodel see Appendix 1 of this chapter.

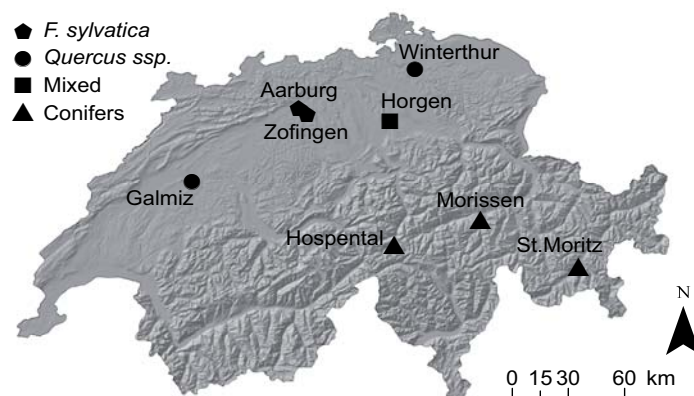
## Data used for model evaluation

### Long-term forest growth and yield research plots<sup>1</sup>

The study plots were located in Switzerland because there are a variety of climatic conditions, from warm-dry in the bottom of the central Alpine valleys to cold-wet at high elevations. Also, 14% of all Swiss forests are managed in a ‘near-natural’ way (Brändli, 2010), enabling us to test the plentering model function in detail. Data from eight forest growth and yield research plots were obtained from the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL). We chose the plots for their different species composition, environmental conditions, management regimes and sizes (Table 1, Fig. 2), selecting the largest ones where there was more than one plot in a specific stand. The plots extend from the colline to the upper subalpine zone (Ott et al., 1997) and were inventoried at intervals ranging from 1 to 13 years, starting when the stands were between 19 and 43 years old. The surveys include all trees on the plot with a diameter at breast height of at least two (Horgen), three (Aarburg, Galmiz, Hospental, Winterthur, Zofingen) or 8 cm (Morissen, St. Moritz).

### Management data

Generally, each time an inventory was made, a silvicultural intervention took place. For each plot, the condition and age of the stand was recorded together with an account of the silvicultural interventions undertaken. These qualitative data are com-



**Fig. 2.** Location of the eight study sites in Switzerland.

<sup>1</sup> For more details on these plots see Appendix I of the dissertation

plemented by single tree data, most importantly indicating the time at which they were removed. Thus, we were able to calculate the intervention intensities (fraction of basal area removed) and to determine the targeted species.

### **Climate and site data**

We obtained monthly data for mean temperature and precipitation sum from the database of the Land Use Dynamics Research Group at WSL, spanning the period 1960–2006. The data are interpolated spatially using DAYMET (Thornton et al., 1997) to a grid with a cell size of 1 ha. To derive long-term means of the variables mentioned previously, we chose data series from the grid cell directly covering the plot, plus those of its eight neighbours. The daily data from these cells were averaged, and from the resulting series we calculated averages, standard deviations and cross-correlations of monthly temperature and precipitation as required by FORCLIM. This allowed us to reduce the potential bias associated with using single grid cell data (M. Didion, unpublished).

The site-specific parameters needed for FORCLIM, available nitrogen [kg/ha\*yr] and bucket size [cm], were estimated from the descriptions available for each plot. Beyond these parameters, no other site parameters were adjusted for the simulations.

## **Simulation experiments**

### **Model initialization**

For each plot, patch size in the model was set to a value close to 800 m<sup>2</sup> so that it equalled plot size when multiplied by an integer number (Table 1); patch sizes thus varied from 750 to 833 m<sup>2</sup>, an unproblematic margin, as it can vary from 400 to 1500 m<sup>2</sup> without significantly affecting the results (L. Rasche, unpublished). Wehrli et al. (2005) showed that 50 runs is sufficient to reduce stochastic noise in FORCLIM; hence, we used the single tree information (species, diameter) of the first inventory of each plot to populate the patches representing one evaluation unit and subsequently used this unit 50 times. For a more detailed description of this method see Wehrli et al. (2005) and Didion et al. (2009) and Appendix II of this dissertation. Initial leaf area indices of the cohorts were derived from Breuer et al. (2003).

**Table 1.** Growth and yield research plots used in this study, their location, elevation, area, main species, simulation details on estimated bucket size (BS) or water holding capacity, available nitrogen (N), model patch size (PS), overall number of patches used in the simulation, number of patches representing the plot area once, and the simulation period and number of observations (n) available for comparisons.

Site	Location (°N, °E)	Elevation (m a.s.l.)	Area (ha)	Main species	BS	N (kg·ha <sup>-1</sup> ·a <sup>-1</sup> )	PS	Patch number	Patches /plot	Sim. period (n)
Aarburg ID 41024	47.3 7.9	475	0.25	<i>F. sylvatica</i>	10	80	833	150	3	1890-1994 (18)
Galmiz ID 42018	46.9 7.1	475	0.3	<i>Q. ssp.</i> <i>F. sylvatica</i>	12	80	750	200	4	1925-1999 (12)
Horgen ID 02021	47.3 8.6	630	0.5	<i>F. sylvatica</i> <i>P. abies</i>	10	100	833	300	6	1907-1999 (16)
Hospental ID 1002	46.6 8.6	1475	0.4	<i>P. abies</i> <i>L. decidua</i> <i>P. cembra</i>	10	80	800	250	5	1933-2005 (10)
Morissen ID 1012	46.7 9.2	1630	0.5	<i>P. abies</i> <i>P. cembra</i>	10	50	833	300	6	1929-2002 (10)
St. Moritz ID 1033	46.5 9.9	1810	1.0	<i>P. abies</i> <i>P. cembra</i> <i>L. decidua</i>	10	60	833	600	12	1921-1999 (10)
Winterthur ID 42005	47.5 8.7	505	0.5	<i>Q. ssp.</i> <i>F. sylvatica</i>	9	100	833	300	6	1928-2001 (11)
Zofingen ID 41018	47.3 8.0	510	0.25	<i>F. sylvatica</i>	1080	100	833	150	3	1890-2001(17)

### Simulation settings

For the simulation of forest management, we used the MANAGEMENT submodel with two different parameter settings: First, we kept to the empirical records, i.e. we let the management submodel intervene in the years the actual interventions had taken place with the same intensity and targeting the same species (below called 'specific management'). Secondly, to evaluate whether a generic setting leads to the same results as the detailed one, we calculated the mean number of years between interventions and the mean intensities of the treatments and made all species present on the stand eligible for harvesting. Where more than one kind of intervention had taken place during the observation time, we adopted the one used most of the time, or, when they were equally abundant, the one with the highest intensity (Table 2). This is referred to as 'generic management'.

**Table 2.** The management regimes used in the simulations (TB: thinning from below; TA: thinning from above; P: plentering; Te: tending), as recorded for the specific years (n)\*, as simplified to one regime, the intensity used for the generic thinning function as percentage of standing basal area to be removed, and the interval at which interventions take place in the generic setting

Site	Specific management (n)	Generic management	Mean intensity	Mean Interval (a)
Aarburg	TB (1895-1994)	TB	0.13	6
Galmiz	TA (1931-1999)	TA	0.16	7
Horgen	TA (1911-1989)	TA	0.12	6
Hospental	P (1940, 1951-75), TB (1933, 1945, 1985-1995)	TB	0.13	8
Morissen	P (1929-1940), TA (1945-65), TB (1975-92)	TB	0.13	8
St. Moritz	P (1927-1999)	P	-	9
Winterthur	TA (1928-2001)	TA	0.16	7
Zofingen	Te (1892-1945), TA (1954-2001)	TB	0.07	7

\*When management periods do not coincide with inventory periods (Table 1), stands were recorded without management taking place simulatenously.

The duration of the simulations was determined by the number of years between the first and the last inventory. As no distinction was made in the data between trees removed because of natural mortality, damage caused by hazards and damage/mortality caused by other disturbances such as beetles or fungi (all were referred to as 'incidental usage') and given that their numbers were relatively low, we decided to include those trees in the management plan and, in turn, switch off the natural mortality function in FORCLIM.

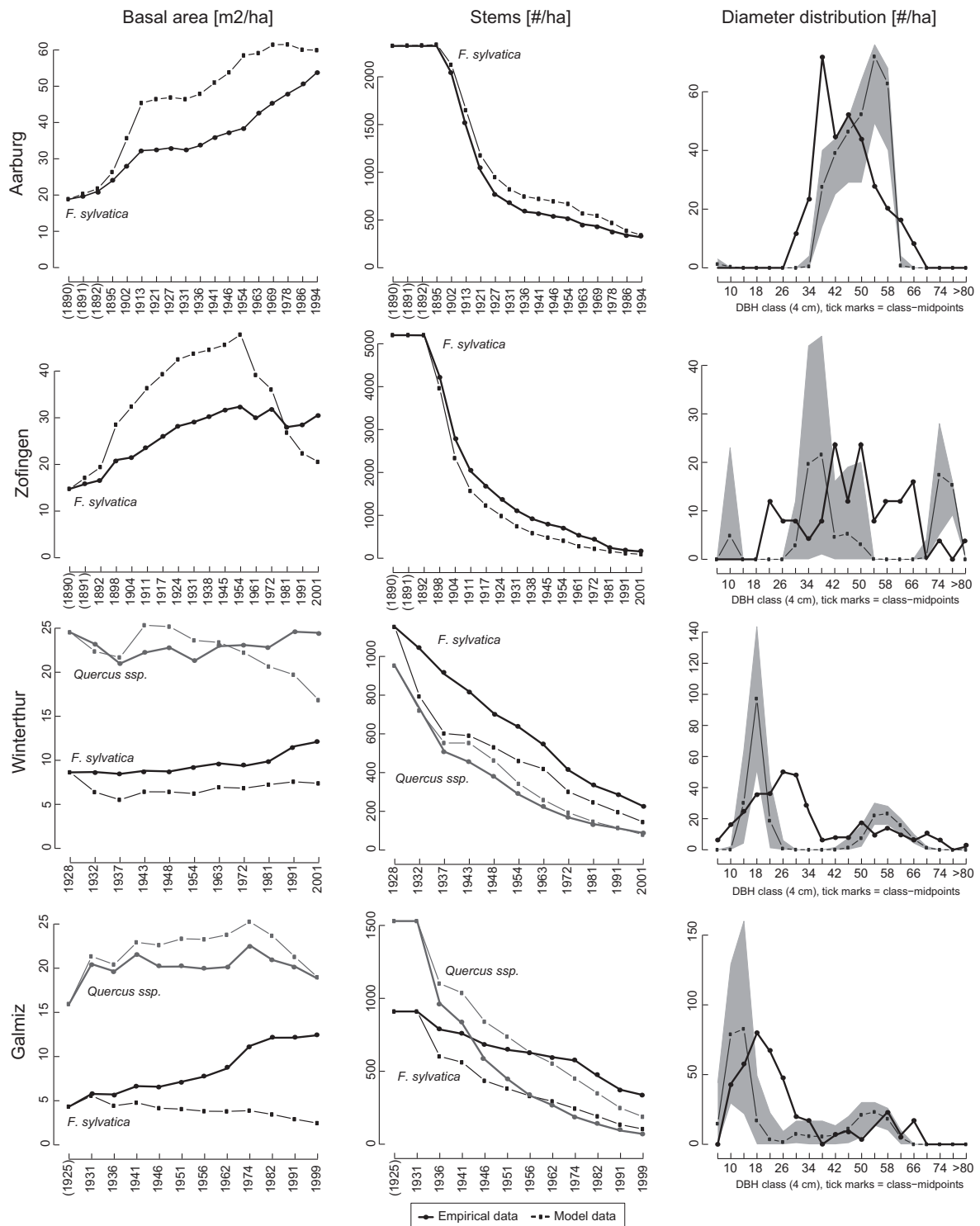
The records showed that except in Aarburg and St. Moritz, nearly no establishment took place on the sites; hence, in the simulations tree establishment was allowed solely there. For detailed simulation settings, see Appendix 2 of this chapter.

## Results

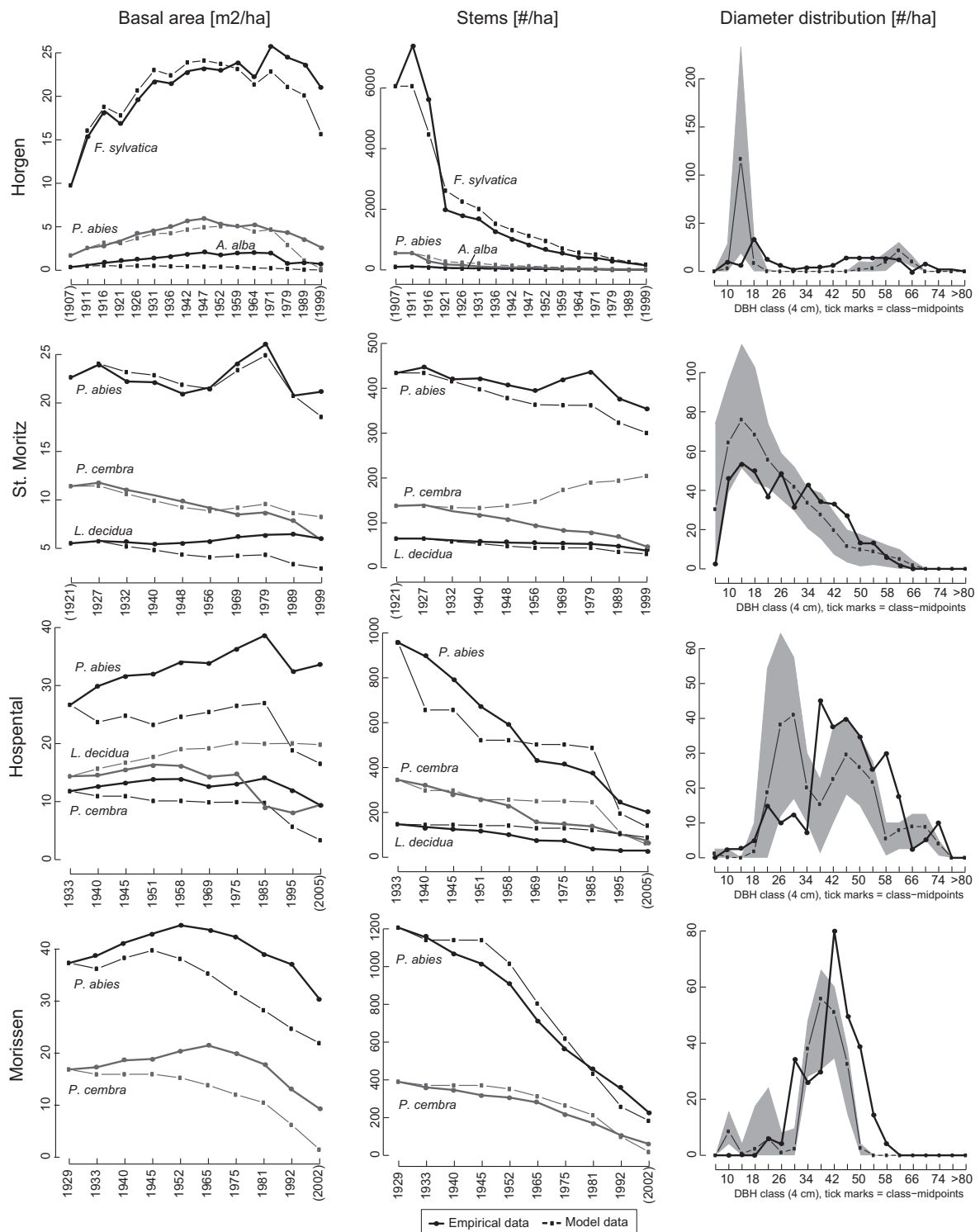
### Specific management

In the Aarburg plot, simulated stem numbers of *Fagus sylvatica* L. agreed well with those of the empirical data (Fig. 3). Basal area was overestimated from 1895 (first thinning) onwards. The gap widened between 1902 and 1913, when the heaviest thinning occurred and diminished again after 1969. The shape of the simulated diameter distribution at the end of the experiment corresponded to the distribution of empirical measurements, but the main peak of the simulation was located in diameter class 54, four diameter classes larger than the direct measurements. Over time, the diameter distributions (Fig. 4) diverged steadily from each other, indicating an exaggerated simulated growth rate of *F. sylvatica*.

In the Zofingen plot, simulated basal area increased consistently as long as thinning from below was applied (Fig. 3), similar to Aarburg, but it declined sharply with the switch to thinning from above in 1954. Simulated stem numbers, however, corresponded well to the measured data. The overstorey in Zofingen was also similar to Aarburg in experiencing an exaggerated simulated growth rate: the leftmost peak of the simulated diameter distribution preceded the empirical measurements by three classes. The understorey trees, however, lagged behind in their development leaving tree numbers in the medium diameter classes (42–66 cm) under represented.

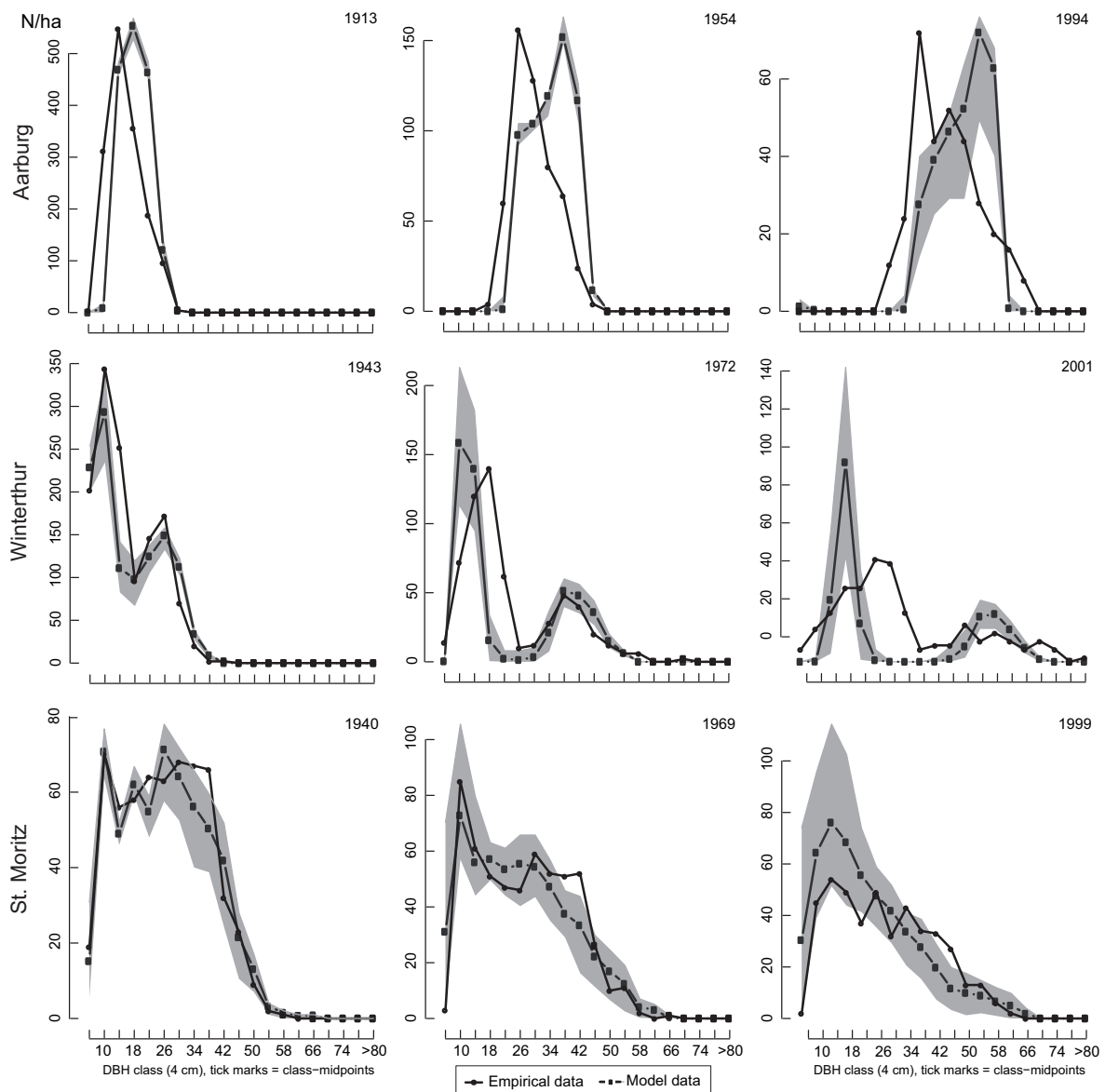


**Fig. 3.** Species-specific basal areas (left panels), stem numbers (middle panels) and overall diameter distributions in the final observation year (right panels) for the eight study sites. Years



in brackets: only inventory took place, no management. Grey area in right panel: 2.5<sup>th</sup> and 97.5<sup>th</sup> percentile of simulated data.

In Winterthur, stem numbers of *Quercus* ssp. L. followed the course of the empirical measurements well except for slight overestimates in 1943 and 1948. Basal area was overestimated from 1937 to 1963 and underestimated thereafter (Fig. 3). Simulated basal area and stem numbers were continuously underestimated for *F. sylvatica*. The simulated diameter distribution corresponded to empirical measurements in overall



**Fig. 4.** Diameter distributions for three points in time for the sites Aarburg (upper panels), Winterthur (middle panels) and St. Moritz (lower panels). Grey area: 2.5<sup>th</sup> and 97.5<sup>th</sup> percentile of simulated data. Initial simulation years: 1890 (Aarburg), 1928 (Winterthur), 1921 (St. Moritz).

shape, but there was a substantial underestimation of large trees (classes  $\geq 68$  cm) and an overestimation of small trees. This divergence developed particularly in the later years, i.e. after 1972 (Fig. 4). Thereafter, the model not only underestimated the growth rate of the overstorey trees but also started to underestimate *Quercus* ssp. basal area.

In Galmiz, the simulated basal area and number of stems of *Quercus* ssp. were constantly overestimated (Fig. 3), whereas for *F. sylvatica* the opposite applied, in this case more pronounced than in Winterthur. The diameter distribution for Galmiz showed the same characteristics as Winterthur, with a lack of large (classes 70 and 74 cm) and medium trees (classes 18–34 cm) and an overestimation of small trees.

In the mixed stand at Horgen simulated basal areas of all three species (*F. sylvatica*, *Picea abies* H. Karst. and *Abies alba* Mill.) tallied well with empirical measurements, although *F. sylvatica* basal area was slightly underestimated after 1964 (Fig. 3). Simulated stem numbers matched the empirical data also very closely, although there was a slight underestimation of *F. sylvatica* stem numbers in 1911. The diameter distribution showed that tree numbers in the medium diameter classes (18–54 cm) were underestimated, while the number of small trees (10–14 cm) was overestimated. The number of trees in the overstorey (classes 58–66 cm) matched those of the empirical data quite well.

Simulated basal area of all species in St. Moritz (*P. abies*, *Pinus cembra* L., *Larix decidua* Mill.) closely mimicked the empirical data (Fig. 3) although *L. decidua* was slightly underestimated from 1975 onwards. Nevertheless, stem numbers did not closely match the empirical data, there was an underestimation of stem numbers of *P. abies* and an overestimation of *P. cembra*. The diameter distribution showed that this overestimation was because of an overabundance of small trees (classes 6–22 cm), whereas the rest of the distribution corresponded quite well to the empirical distribution. This was also true for earlier years (Fig. 4).

In Hospental and Morissen, plentering was used in combination with thinning and as a consequence, the simulated basal areas did not match the empirical data quite as well as in St. Moritz (Fig. 3). All basal areas were underestimated, with the exception of *L. decidua* at Hospental, which was overestimated particularly from 1975 onwards. An avalanche destroyed parts of the stand in 1975, which is most likely the reason for this trend. Tree numbers and diameter distributions corresponded to the

empirical data much better. Nevertheless, the simulated main peaks lagged behind the empirical data by some diameter classes: the number of small and medium trees was overestimated, while very large trees were underestimated.

A quantitative description of model accuracy regarding basal area and stem numbers can be found in Appendix 3 of this chapter.

## Generic management

The overall shape of the diameter distribution simulated with the generic management setting in Aarburg (Fig. 5) was very similar to the one produced with the specific management setting and also to the measured one. The generic thinning setting was, however, in its intensity somewhat harsher and removed trees up to diameter class 42 cm, whereas the specific management setting only removed trees up to class 34. The loss of basal area via generic thinning was therefore unsurprising (Fig. 6a), although it did produce a greater number of stems overall (Fig. 6b).

Generic management in Zofingen yielded unsatisfactory results because the mean thinning intensity executed at mean intervals was obviously too severe, resulting in virtually no trees in the medium diameter classes (18–70 cm). The remaining overstorey trees grew too quickly in the simulation and the understorey trees (class 14) did not grow enough. Not surprisingly, the simulated basal area (Fig. 6a) and the number of stems (Fig. 6b) were therefore severely underestimated with the generic management setting.

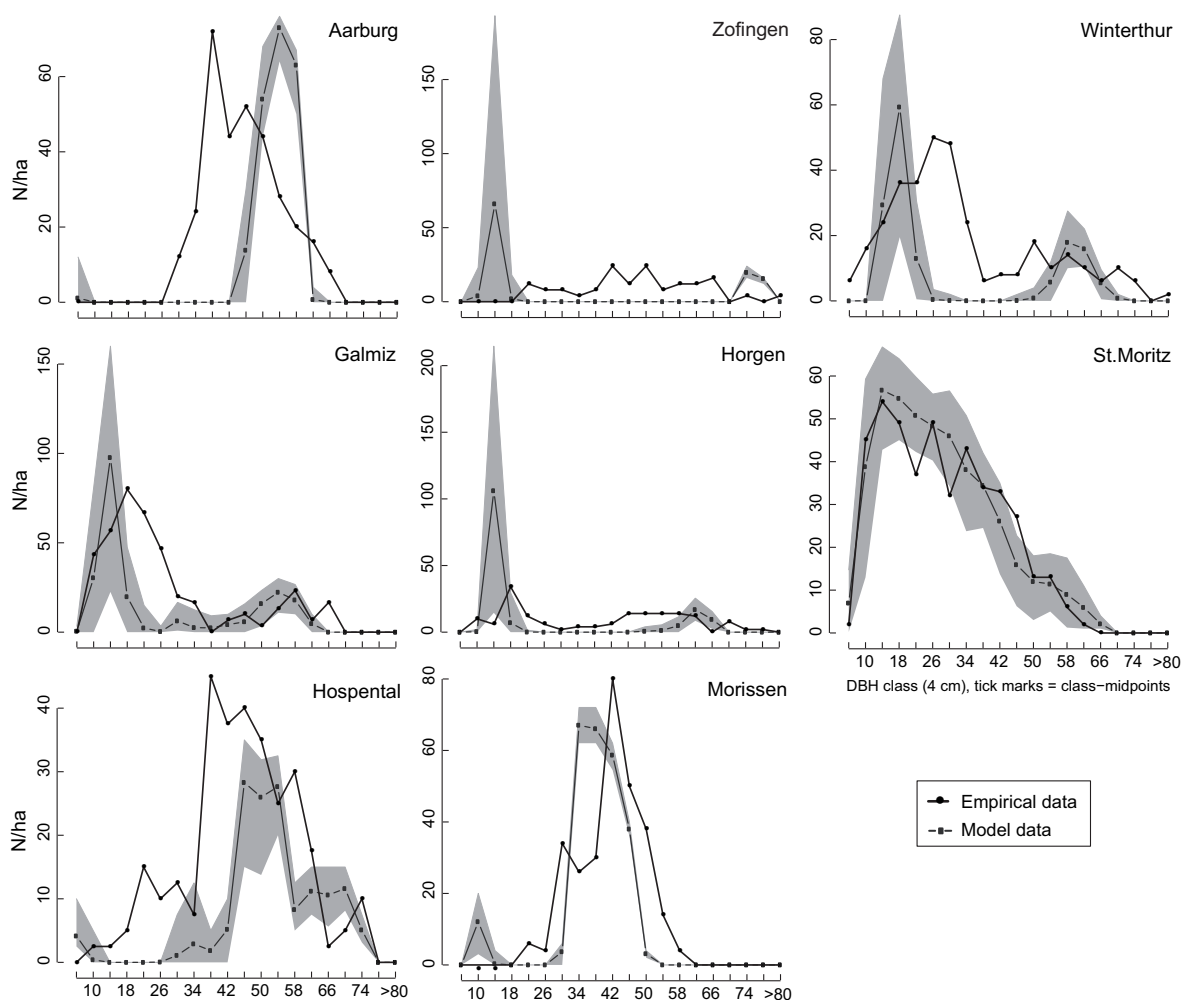
As with Aarburg, both simulated diameter distributions in Winterthur resembled each other closely (Fig. 5); although the simulated basal area and stem numbers were strongly underestimated under generic management (Fig. 6a, b). The same applied to Galmiz (Figs 5 and 6a, b).

In Horgen, the diameter distributions produced by the specific and generic thinning settings were very similar (Fig. 5), except for tree numbers in diameter class 14, where more trees were left behind under the specific management setting. Overall, the generic thinning setting underestimated basal area more than the specific one (Fig. 6a), whereas stem numbers were similar and reflected reality (Fig. 6b).

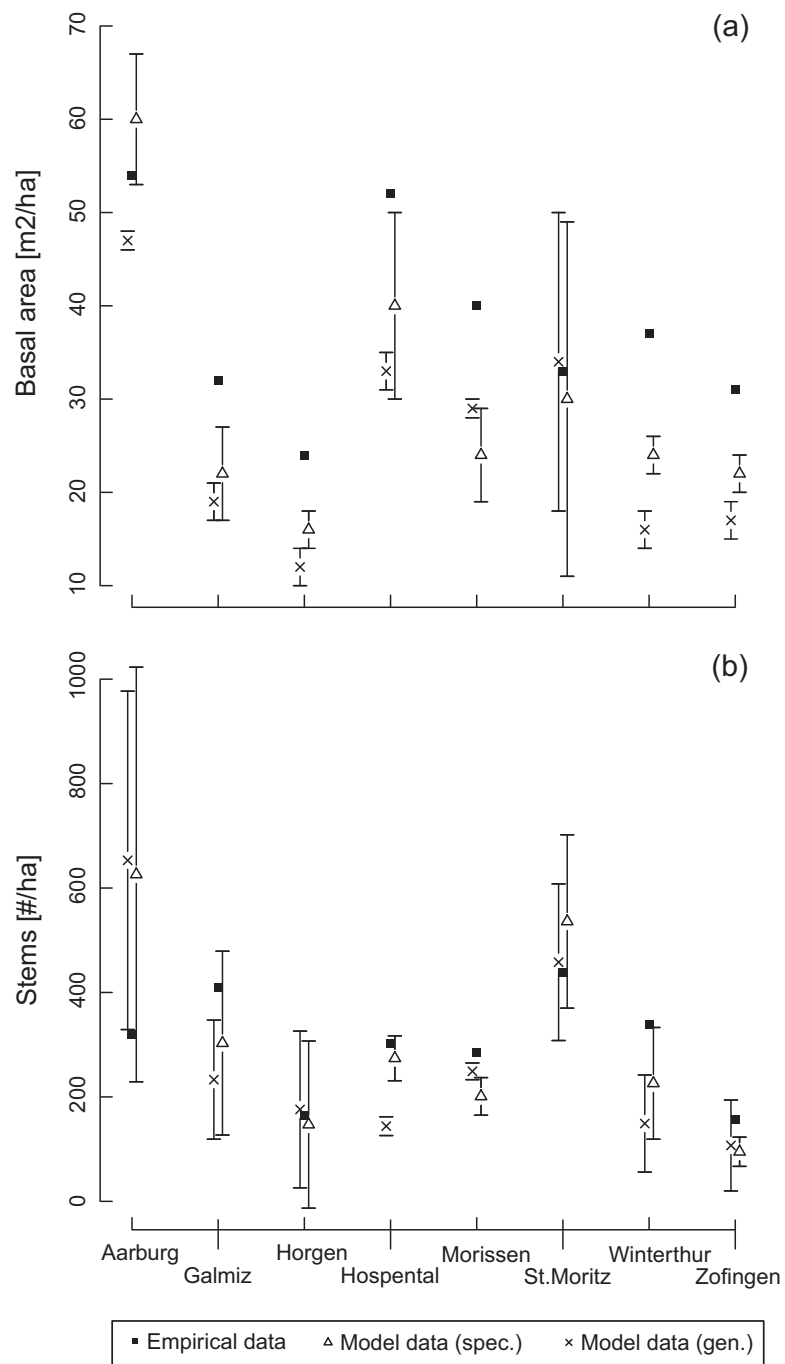
The generic management setting in St. Moritz yielded a diameter distribution that corresponded more closely to the empirical data than that obtained with the specific management setting, because tree numbers in the smaller diameter classes and

overall stem numbers were lower (Figs 5 and 6b). Basal area did not differ greatly, neither from empirical values nor from those generated with the specific management setting (Fig. 6a).

In Hospental and Morissen, the diameter distributions closely matched the shape of the empirical ones (Fig. 5), but it was obvious that the generic thinning setting targeted the medium diameter classes (Hospental: 18–42 cm, Morissen: 18–34 cm) far more strongly than the specific setting. Basal area and stem numbers were underestimated in both approaches (Fig. 6a, b).



**Fig. 5.** Diameter distribution in the final observation year for the eight study sites generated with the generic harvesting setting. Grey area: 2.5<sup>th</sup> and 97.5<sup>th</sup> percentile of simulated data.



**Fig. 6.** Comparison of simulated (specific/generic setting) and measured (a) basal area and (b) stem numbers for the eight study sites with standard deviation.

## Comparison of harvested stem numbers and basal area

There were no systematic differences between the generic and the specific harvesting setting in the sum of basal area and stem numbers removed (Table 3). Irrespective of the approach, on average, the total number of stems removed per observation period corresponded more closely to the empirical number of stems removed than that of basal area removed (stems were misjudged by  $\pm 14\%$  on average, basal areas by  $\pm 23\%$ ). In the conifer mountain forests, the harvested basal area was underestimated by 35% on average, whereas in the lowland *F. sylvatica* forests, it was overestimated by 39%. The number of trees harvested from the *Quercus* ssp. stands and from the mixed stand in the simulations reflected the empirical data quite accurately ( $\pm 6\%$ ).

## Statistical comparison of diameter distributions

Comparisons of the simulated and empirical cumulative diameter distributions under both management settings with a Kolmogorov–Smirnov test revealed no significant differences except at Horgen (P-values = 0.0141/0.0021 for specific and generic setting, respectively), Winterthur (P-values = 0.0063/0.0006) and Zofingen (P-value 0.0063, generic setting). None of the generically simulated diameter distributions differed significantly from the distributions simulated with the specific management setting. For details see Appendix 4 of this chapter.

**Table 3.** The sum of harvested stems (N) and harvested basal area (G) over the observation time for the yield research plots, the specific management, and the generic management setting. (%): Percentage of simulated in regards to the measured numbers.

Site	Measured		Specific management				Generic management			
	$\Sigma N$ (#/ha)	$\Sigma G$ (m <sup>2</sup> /ha)	$\Sigma N$ (#/ha)	%	$\Sigma G$ (m <sup>2</sup> /ha)	%	$\Sigma N$ (#/ha)	%	$\Sigma G$ (m <sup>2</sup> /ha)	%
Aarburg	2320	84.5	3103	134	109	129	2585	111	66.0	78
Galmiz	2141	51.2	2188	102	46.6	91	2246	105	48.7	95
Horgen	8328	68.1	6918	83	69.7	102	6934	83	71.6	105
Hospental	1165	65.9	1186	102	38.3	58	1318	113	45.3	69
Morissen	1328	70.0	1383	104	49.4	71	1347	101	45.1	64
St. Moritz	516	45.6	322	62	37.2	82	184	36	22.2	49
Winterthur	1894	57.7	1995	105	58.2	101	2001	106	58.9	102
Zofingen	5168	59.9	5209	101	86.9	145	5170	100	85.8	143

## Discussion

### Experimental setup

To our knowledge, this is the first time that a management submodel has been tested (i) against inventory data from so many different forest types along such a wide climatic gradient, (ii) for such long time periods, (iii) for both a specific and a generic setting, and (iv) without any site-specific calibration of species parameters. Growth models, for example, are usually tested for shorter periods (e.g. 15 years in Mette et al., 2009) or for mono-species stands (e.g. Matala et al., 2003) and need to be calibrated beforehand to the site conditions. Gap models that incorporate management options, e.g. LINKAGES, have been compared to inventory data from four Eucalyptus-dominated plots over a time period of 40 years in terms of biomass and basal area (Ranatunga et al., 2008); Seidl et al. (2005) used data from two long-term observation sites in Austria to compare simulated and observed growing stock and diameter distribution over a time span of 20 years; and Lasch et al. (2005) employed data from one *Pinus sylvestris* L. stand in Brandenburg (Germany) to evaluate model performance with regard to various measured properties over 61 years.

With eight multi-species sites at very different locations and simulation periods of 72–111 years, our testing regime was much more rigorous and extensive than has been undertaken previously, and it was not self-evident that FORCLIM would meet this challenge. The model performed well, tracking the development of measured basal area, stem numbers and diameter distribution closely in most cases. This has demonstrated (i) that FORCLIM adequately embodies the prescribed harvesting techniques, including plentering, and (ii) that dealing with widely different climatic conditions did not negatively influence model performance. Although we acknowledge that this does not prove the model's applicability under future climate scenarios, the capability of handling widely different current climates undisputedly is a prerequisite for such applications.

There are, however, some exceptions with regard to forest type. In *F. sylvatica*-dominated stands, the growth rate of the overstorey trees was overestimated at all three sites (Aarburg, Horgen, Zofingen). The trees in the understorey are heavily shaded and consequently inhibited in their growth; this happens in reality, but to a lesser extent than in the model. This is most probably caused by the way light

availability is simulated in FORCLIM, as in reality even in closed stands diffuse light reaches the forest floor from the side (Canham et al., 1990), whereas in FORCLIM, the leaf area of each tree is distributed homogeneously over the whole patch, not allowing any light from the side.

The overestimation of growth rates of overstorey trees also leads to an overestimation of basal area. Álvarez-González et al. (2010) showed that *F. sylvatica* trees in Switzerland experience enhanced growth in basal area after thinning, but the strong increase in *F. sylvatica* basal area after thinning from below in FORCLIM is unrealistic. It may, therefore, be advisable to reevaluate the parameterization of the growth rate of *F. sylvatica* (cf. Heiri, 2009). Another option would be to adapt the height growth function, since Lindner et al. (1997) reported an exaggerated diameter growth rate in simulations of *F. sylvatica*-dominated plots in Bavaria for the FORSKA model, which decreased to more realistic values after implementing a modified growth function.

On *Quercus*-dominated sites, the growth rate was under rather than overestimated, especially for *Quercus* ssp. itself. The empirical data on development at Winterthur indicated that the *Quercus* trees on this plot grew faster through the diameter classes than *F. sylvatica*. Schütz (1979) suggested that no foreign yield table was able to capture the growth rate of *Quercus* ssp. on richer sites in Switzerland and clearly FORCLIM experienced difficulties as well: the growth rate simulated for *Quercus* ssp. was similar to that for *F. sylvatica*, leading to a substantial underestimation of large *Quercus* trees in the later years. In Galmiz, this problem was not as clear, but the basal area of *F. sylvatica* was nevertheless underestimated, owing not to the growth rate, but to two other mechanisms: (i) *F. sylvatica* trees are found mainly in the understorey, leading to the shading problem mentioned previously, and (ii) the medium diameter classes they mainly occupy were selected for thinning most often in the simulation, thus unduly sparing the larger *Quercus* trees.

On the *P. abies*-dominated site at St. Moritz, the management submodel captured the nature of the uneven-aged forest management (cf. Zingg et al., 2009). In contrast to the *F. sylvatica*-dominated lowland forests, however, growth rates in these conifer mountain forests were underestimated by the model, leading to an underestimation of harvesting numbers. Seidl et al. (2005) suggested that precise soil and climate data are a prerequisite for accurately simulating *P. abies* growth rates, noting an underestimation of growth rates in simulations of a *P. abies*-dominated colline site in

Austria not present elsewhere. Thus, it may be that FORCLIM does not capture all the factors determining tree growth rates at these elevations. And even though the model considers the degree-day sum – the most influential factor concerning growth rates at these sites (Ott et al., 1997) – more subtle mechanisms like the formation of tree clusters, i.e. collectives of conifers that are clearly separated from their surroundings, narrowly spaced and commonly featuring a near-zero bole height, cannot be captured by FORCLIM because of the nonspatial nature of the model. This may lead to lower light availability than in reality and thus to lower growth rates.

### **Simplifying complex silvicultural interventions to generic ones**

The comparison between the two different simulation scenarios showed that it is possible to substitute variable intensities and intervals of thinning by mean intensities and average harvesting intervals. There is no significant difference between diameter distributions at the end of the fixed time-span and the deviations of simulated harvesting numbers from measured levels mostly occur within the same error margin. This suggests that when simulating forest dynamics into the future, one can be reasonably confident that a generic harvesting setting will yield results similar to a detailed one without introducing an additional source of uncertainty.

However, the generic management setting tends to underestimate basal area more than the specific setting. The reason for this is the way thinning intensities are defined, i.e. by removing a certain percentage of the growing stock at every intervention. If at any point in time, the average intensity defined in the generic setting is higher than the one that was used at this time in reality, basal area is permanently reduced, and the next percentage to be removed is calculated based on the overly decreased value. Another point of relevance is the mechanism underlying the thinning function: the Weibull distribution function draws the diameters of the trees to be removed based on parameters describing the actual diameter distribution. If the stand is altered because of differing thinning intensities, stand characteristics change as well and different diameter classes are selected for thinning, thus altering the characteristics even more.

## Conclusions

We conclude that the new management submodel in FORCLIM depicts real management scenarios adequately and that generic settings of the management function can replace detailed ones. Thinnings as well as plentering were executed in a way that reflects reality well. Basal area and stem numbers matched the empirical data reasonably well, and diameter distributions were also captured to a satisfying extent. In terms of removed basal area and stems, the simulation was acceptable for many sites, with some deviations of basal area in *F. sylvatica*- and *P. abies*-dominated stands. However, the simulations show that the model is quite sensitive to the thinning intensity employed, probably attaining better results with a cautious estimation of intensities.

Based on these encouraging results, we propose that FORCLIM v.2.9.8 can henceforth be used as a flexible tool to analyse future management scenarios under climate change and also that it may be not only a valuable tool for researchers but also for decision support in practical forestry.<sup>2</sup>

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<sup>2</sup> In Chapter II of this dissertation improvements to the FORCLIM model are presented. To test if the conclusion of this chapter was still valid after these changes, we redid the simulations done here with the new model version. For the results see Appendix III of the dissertation.

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## Appendix 1

This appendix contains a detailed description of the management submodel implemented in FORCLIM v2.9.8. The model is available upon request from one of the authors (H.B.). For the sourcecode see Appendix V of this dissertation.

### Selection forest (plentering) function

The plentering function calculates an ideal plenter equilibrium following Cancino and von Gadow (2002) for the whole stand (all patches). An optimal plenter equilibrium is reached when the ingrowth into each diameter class is equal to the outgrowth. The surplus ingrowth is harvested. The optimal number of trees ( $N$ ) in each diameter class  $i$  is given by

$$N_i = q^{i-1} N_1 \quad [\text{eqn 1}]$$

with  $q$  being the desired ratio of tree numbers between subsequent diameter classes, a parameter defined by the user that typically takes values between 1 and 1.6 (Cancino and von Gadow, 2002).  $N_1$  states the number of trees in the highest dbh class, and is defined by

$$N_1 = B / k_3 \quad [\text{eqn 2}]$$

with  $B$  denoting the desired residual basal area [ $\text{m}^2/\text{ha}$ , user defined] of the stand and  $k_3$  being a parameter, which is calculated as

$$k_3 = k_2 h^2 \left[ \frac{c^2}{1-q} - \frac{2cq}{(1-q)^2} + \frac{q(1+q)(1-q^c)}{(1-q)^3} \right] \quad [\text{eqn 3}]$$

where  $h$  is the width of the diameter class [cm],  $c$  the number of dbh classes, and  $k_2$  is defined as

$$k_2 = \pi / 40000 \quad [\text{eqn 4}]$$

The plenter function checks in user-defined intervals the numbers of trees in the diameter classes and removes those that exceed the optimal number or the specified target diameter. For a more detailed description of the derivation of the equations, see Cancino and von Gadow (2002).

### Thinning function

Following the example of the models FORSKA-M and 4C (Lasch et al., 2005; Lindner et al., 1997), we implemented thinning as a Weibull distribution-based stochastic

function (Gerold, 1991; Wenk and Gerold, 1996), which draws diameters of trees to be removed until a certain amount of basal area is reached (defined as a percentage of the original basal area on the patch). The equation is as follows:

$$i = b_{TH} (-\ln(1 - u))^{\frac{1}{c_{TH}}} + d_{min} \quad [\text{eqn 5}]$$

with  $i$  being the diameter at breast height (dbh) of the tree to be removed,  $b_{TH}$  and  $c_{TH}$  are parameters of the Weibull distribution function representing the diameters to be removed,  $d_{min}$  is the smallest diameter present on the patch, and  $u$  denotes a uniformly distributed random variable between [0,1). The scaling factor  $c_{TH}$  is defined by

$$c_{TH} = \frac{1.09719}{\ln\left(\frac{d_{95\%} - d_{min}}{d_{63\%} - d_{min}}\right)} \quad [\text{eqn 6}]$$

with  $d_{95\%}$  and  $d_{63\%}$  denoting the 95<sup>th</sup> and 63<sup>th</sup> percentile of the diameter distribution, respectively. The shape parameter  $b_{TH}$  is defined by

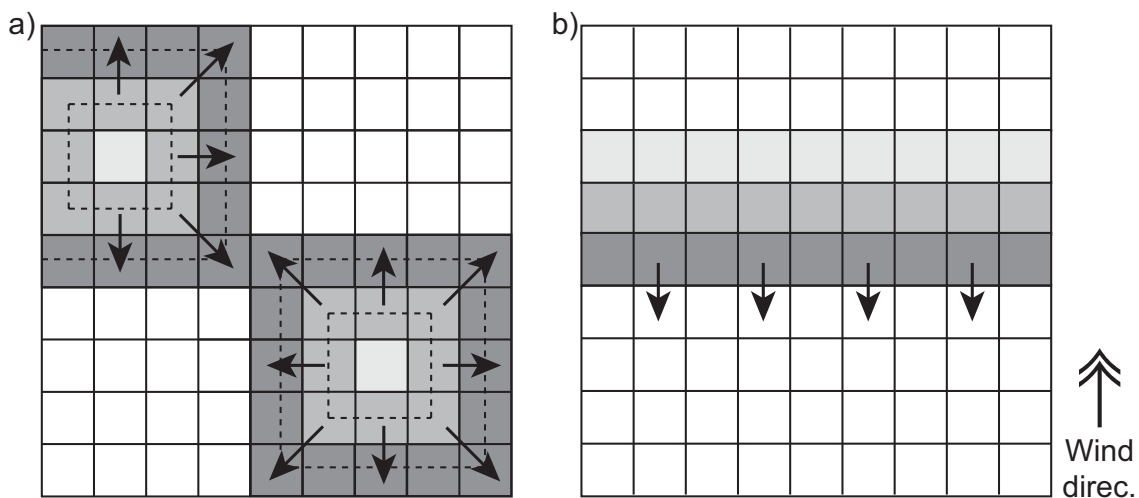
$$b_{TH} = b_{PT} / K_b \quad [\text{eqn 7}]$$

with  $b_{PT}$  being the shape parameter of the diameter distribution of the stand before thinning and  $K_b$  a constant controlling the type of thinning.  $K_b$  takes values of 2.5 for tending (light thinning from below), 1.8 for moderate thinning from below and 1.2 for moderate thinning from above (Lasch et al., 2005; Lindner et al., 1997). Lastly,  $b_{PT}$  is described by

$$b_{PT} = d_{63\%} - d_{min} \quad [\text{eqn 8}]$$

## Cutting function

The cuts are implemented in a straightforward way: In every year for which a *clear cut* is scheduled, all trees on all patches are removed. This can be modified to removing only certain species or harvesting only a certain number of patches. For a *target cut*, all trees on all patches are checked in user-stated intervals if the user-specified target diameter has been reached and are then removed. A *shelterwood felling* removes all trees on all patches except those that match certain height specifications stated by the user. This could be for example all trees with a height of 18 to 28 meters. The desired density of the sheltering trees can be specified, as well as of which species the sheltering trees should be.



**Fig. A1.** Spatial depiction of the cuts a) *group selection* and b) *strip felling* for a theoretical grid of 81 patches.

With *group selection*, a number of patches are chosen to represent the initial number of gaps, which are then cleared of all trees. Henceforth, each year an operation is scheduled, the “ring” around the centers is widened by the distance of half a patch (Fig. A1 a). As FORCLIM does not consider interactions between patches, the patches to be harvested are selected randomly, but are eligible for harvesting only once.

In the case of *strip felling*, in each year for which an operation is scheduled, a strip of the stand is cut (in case of FORCLIM a clear cut is performed on a certain number of patches representing the strip area) until the whole stand is rejuvenated (Fig. A1 b).

## Regeneration

It is either possible to allow for natural regeneration, or to plant saplings after the *clear cut*, *target cut* and *shelterwood felling* interventions. The user can state the number of saplings to be planted per hectare and also choose the desired species. Saplings are then initialized with a dbh of 1.27 cm, the default value used in FORCLIM.

## Limitations and possibilities

When simulating management, FORCLIM does not consider indirect effects as, for example, the increased risk of mortality that the remaining trees of a stand may face after a harvesting intervention through damages (Shugart et al., 1980). This may be a valuable addition in for future model applications. What could also be explored is the

usage of the MANAGEMENT submodel as a disturbance submodel, as some harvesting techniques that can be performed in our management regime closely resemble the zero-order effects of natural disturbances (cf. Doyle, 1981; O'Brien et al., 1992).

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## Appendix 2

This table contains further data on the settings used for the simulations on each site.

**Table A2.** Additional information on simulation settings: species allowed in the simulations, state of establishment and initial LAI values.

Site	Species simulated	Establishment		Init. LAI
		Spec.	Gen.	
Aarburg	<i>Acer pseudoplatanus</i> L., <i>Carpinus betulus</i> L., <i>F. sylvatica</i>	Yes	Yes	10
Galmiz	<i>P. abies</i> , <i>F. sylvatica</i> , <i>Fraxinus excelsior</i> L., <i>Q. ssp.</i> , <i>Ulmus glabra</i> Huds.	No	No	7
Horgen	<i>A. alba</i> , <i>P. abies</i> , <i>A. pseudoplatanus</i> , <i>Betula pendula</i> Roth, <i>F. sylvatica</i> , <i>F. excelsior</i> , <i>Populus tremula</i> L., <i>Sorbus aucuparia</i> L., <i>Tilia platyphyllos</i> Scop., <i>U. glabra</i>	No	No	6
Hospental	<i>L. decidua</i> , <i>P. abies</i> , <i>P. cembra</i> , <i>S. aucuparia</i>	No	No	7
Morissen	<i>P. abies</i> , <i>P. cembra</i>	No	No	8
St. Moritz	<i>L. decidua</i> , <i>P. abies</i> , <i>P. cembra</i>	<i>P. cem.</i>	No	7
Winterthur	<i>P. abies</i> , <i>F. sylvatica</i> , <i>Q. ssp.</i>	No	No	8
Zofingen	<i>B. pendula</i> , <i>F. sylvatica</i> , <i>Q. ssp.</i>	No	No	7

## Appendix 3

This appendix contains the description of the calculation and the values of the relative bias and the relative root mean square error (RMSE) of simulated basal area and stem numbers. Together they provide a good assessment of model accuracy.

The relative bias is calculated as follows:

$$\text{bias\%} = 100 * \frac{\sum(\text{pred} - \text{obs})/n}{\sum \text{obs}/n}$$

The relative RMSE is described by:

$$\text{RMSE\%} = 100 * \frac{\sqrt{\sum(\text{pred} - \text{obs})^2/(n - 1)}}{\sum \text{obs}/n}$$

with *pred* as the values predicted by the model, *obs* as the observed values and *n* as the number of observations.

**Table A3.** Relative bias and RMSE of simulated basal area (G) and stem numbers (N) with regard to observed values.

Site	Species	G		N	
		RMSE%	bias%	RMSE%	bias%
Aarburg	<i>F. sylvatica</i>	28	-23.6	10	-8.1
Galmiz	<i>Quercus sp.</i>	11	-8.5	29	-24.2
	<i>F. sylvatica</i>	147	111.1	57	50.5
Horgen	<i>F. sylvatica</i>	11	2.7	27	-2.3
	<i>P. abies</i>	31	19.3	34	-22.8
	<i>A. alba</i>	325	271.8	63	53.9
Hospental	<i>P. abies</i>	39	38.8	24	8.3
	<i>L. decidua</i>	38	-27.4	41	-32.5
	<i>P. cembra</i>	44	36.6	26	-13
Morissen	<i>P. abies</i>	25	19.9	10	-3.6
	<i>P. cembra</i>	49	40	13	-7.4
St. Moritz	<i>P. abies</i>	5	0.9	12	9
	<i>P. cembra</i>	10	-2.7	54	-37.1
	<i>L. decidua</i>	42	31.7	16	13
Winterthur	<i>Quercus sp.</i>	15	3.1	12	-7.8
	<i>F. sylvatica</i>	45	39.2	36	29.9
Zofingen	<i>F. sylvatica</i>	33	-21	17	13.8

## Appendix 4

This table contains the results of the Kolmogorov-Smirnov test for relative cumulated diameter frequencies.

**Table A4.** Statistics and  $p$ -values for measured (Meas.) and simulated (Sim.) cumulative diameter distributions. (s.): simulation with specific management, (g.): with generic management setting. Bold: Distributions differ significantly ( $\alpha = 5\%$ ).

Site	Meas. – Sim. (s.)		Meas. – Sim. (g.)		Sim. (s.) – Sim. (g.)	
	Statistic	$p$ -value	Statistic	$p$ -value	Statistic	$p$ -value
Aarburg	0.1429	0.9829	0.2381	0.5911	0.1905	0.8407
Galmiz	0.1905	0.8407	0.3333	0.1938	0.1905	0.8407
Horgen	0.4762	<b>0.0141</b>	0.5714	<b>0.0021</b>	0.1429	0.9829
Hospental	0.1429	0.9829	0.2857	0.3581	0.2857	0.3581
Morissen	0.1905	0.8407	0.2381	0.5911	0.1905	0.8407
St. Moritz	0.1905	0.8407	0.1429	0.9829	0.1429	0.9829
Winterthur	0.5238	<b>0.0063</b>	0.6191	<b>0.0006</b>	0.1429	0.9829
Zofingen	0.3333	0.1938	0.5238	<b>0.0063</b>	0.2857	0.3581

## Chapter II

# Enhancing gap model accuracy by modeling dynamic height growth and dynamic tree height

Livia Rasche, Lorenz Fahse, Andreas Zingg, and Harald Bugmann. 2012.

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**Abstract.** Gap models are flexible tools for the simulation of forest dynamics under different climatic conditions. An important area, however, has not yet received the attention it deserves: the formulation of height growth and maximum tree height. In most gap models, every tree approaches a fixed maximum height regardless of site conditions, and tree height as such is approximated via stem diameter. To address these issues, we converted maximum height from a parameter to a variable that depends on site-specific climatic conditions. We also established tree height as a separate state variable besides diameter, to allow for competition effects to influence the ratio between height and diameter growth. The new model formulations were tested against data from the Swiss National Forest Inventory (NFI) and from a forest growth and yield research plot. Lastly the new model version was applied to study productivity changes due to climate change along an environmental gradient.

The new model formulations increased the accuracy of simulations of stand characteristics without negatively influencing the general applicability of the model. The height/diameter relationship of a Douglas-fir stand in Switzerland simulated with the new model version resembled measurements closely, and biomass simulated along an environmental gradient agreed better with measurements (NFI) when using the new model version. Simulations with site-specific maximum height showed that the maximum heights of the dominant species on the gradient did not differ significantly from NFI data, whereas static maximum heights did.

The application of the old and new model versions to simulate productivity under climatic change along the same environmental gradient showed that the conversion of a static parameter such as maximum height to a site-specific variable is not only a desirable, but a crucial feature to incorporate, since climate-induced changes in productivity are simulated to be more pronounced with the new model formulation. We conclude that dynamic height growth and site-specific maximum tree height can significantly improve simulation results of forest succession models, especially with regard to forest management under climate change.

**Keywords.** *climate change, forest productivity, gap model, tree height growth, site quality, taper.*

## Introduction

With rapidly changing environmental conditions and the associated loss in the applicability of traditional yield tables and growth models (Pretzsch, 1992) the interest of forest scientists and stakeholders in more reliable methods to estimate the future growth of forests is rising. Gap models have proven to be flexible tools with regard to estimating the impact of climatic change on natural forest dynamics (e.g. Didion et al., in press; Huo et al., 2010), yet few have both the capacity to simulate forest management and the necessary accuracy in simulating forest stand structure to serve as decision support tools.

Key aspects of locally accurate forest models are the simulation of height and diameter growth, as they result from allocation priorities under varying environmental conditions (Waring and Schlesinger, 1985). The allocation of total growth into diameter vs. height growth and the absolute height that is achievable under given conditions have not received much attention to date in forest gap models (for an exception, see Lindner et al., 1997). Assmann (1970) emphasized that height rather than diameter growth should be used as an indicator of growth patterns, as it is less influenced by management. Many individual-tree growth models simulate height and diameter increment separately (Vospernik et al., 2010), yet most gap models treat height as a derived variable that depends solely on the current diameter of a tree (e.g. Kellomäki et al., 2008; Kienast, 1987; Pacala et al., 1996; Pastor and Post, 1985), where all growing trees approach an asymptotic value of maximum height, regardless of site conditions. Such models are unable to account for thinning effects that may occur after thinnings of a specified intensity and are marked by an increase in diameter increment, yet not in height growth (e.g. Crecente-Campo et al., 2009; Pothier and Margolis, 1991). They cannot mimic the growth behavior of shaded trees in the understory either, which may invest dramatically varying amounts of resources in height versus diameter growth with changing light conditions (e.g. Holbrook and Putz, 1989; Naidu et al., 1998).

There are several other factors that make a more reliable simulation of height and diameter growth an important feature: for instance, tree height to diameter ( $h/d$ ) ratio influences vulnerability to wind and snow breakage (Kimmins, 2003), it may allow to infer the fraction of belowground biomass (Delagrange et al., 2004), and it is also important in terms of the fate of a tree in the stand, since in reality small initial

differences in height tend to increase with age and allow for little change in rank in subsequent years (Ammer et al., 2008).

Besides a static  $h/d$  relationship, it is a strong simplification to assume that the maximum height that is being approached by the growth function is a site-independent constant (Albert and Schmidt, 2010). Foresters have long known that the “site” as a composite of climate, soil, topography, hydrology and other factors determines tree growth (Kimmins, 2003). (Kimmins, 2003). In forest growth models, this is routinely taken into account, e.g. by choosing different potential height growth curves depending on site conditions (e.g. Pretzsch, 2001). It is therefore important to find a way to relate maximum potential tree height to site characteristics. An accurate estimation of maximum height influences not only stand structure and stand growth dynamics, but also derived properties such as productivity and carbon storage. Simulating these features accurately is particularly important in times of environmental change, as there is evidence that site index (e.g. Albert and Schmidt, 2010; Boisvenue and Running, 2006; Bravo-Oviedo et al., 2010) and maximum stand height (e.g. Bontemps et al., 2009; Kahle et al., 2008) is changing.

The goal of this paper is hence to (i) show how the traditional growth equation used in gap models can be altered to account for a changing ratio in diameter to height growth, (ii) propose a way to convert a usually static growth-constraining parameter such as maximum tree height to a dynamically calculated variable, and (iii) explore if these model changes improved the overall results and also determine how sensitive simulations under climate change are with regard to these changes. Our model development focuses on FORCLIM, which showed promise of becoming a decision support tool based on the implementation of a versatile management submodel (Rasche et al., 2011). We validate the new model version against long-term growth-and-yield plot and National Forest Inventory (NFI) data. By ascertaining the reliable simulation of stand structural features in terms of height growth, we make another step on the way to improve a gap model to the level of a decision support tool.

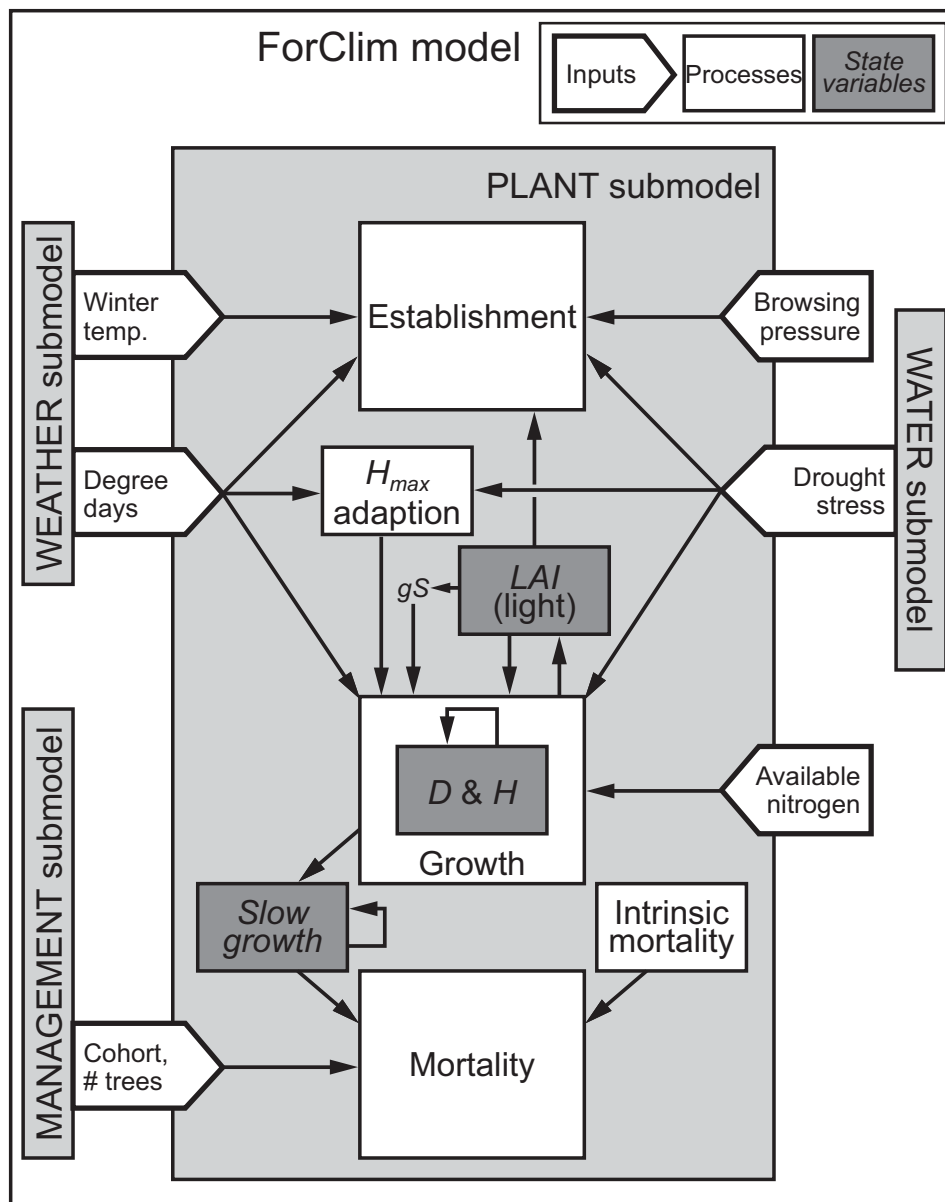
## Methods

### Model description

FORCLIM is a gap model that was developed with the premise to use as few parameters as possible and operate with the least amount of ecological assumptions (Figure 1). It simulates forest dynamics on independent small patches of land and is currently parameterized for 31 species in Europe. Tree development is primarily determined by light availability and climatic parameters; besides these, only nitrogen availability, soil water holding capacity and slope/aspect are used to characterize site properties. The submodels WEATHER and WATER provide values for soil moisture, minimum winter temperature and growing season temperature, based on the long-term weather data and soil water holding capacity of the site. Values are drawn from a probability distribution around the climate parameters – derived from the standard deviation calculated from the time series – separately for each of the patches.

The submodel PLANT simulates establishment, growth and mortality of single tree cohorts. *Growth* is modeled based on the carbon budget approach by Moore (1989), in which an optimal growth rate is calculated and then decreased according to environmental factors, which also determine tree *establishment* rates. These factors include light and nitrogen availability, growing season temperature, soil moisture and crown length. Tree *mortality* consists of an age-related and a stress-induced component. For silvicultural treatments, an extensive MANAGEMENT submodel can be activated, which presently comprises the methods thinning, clear cutting, strip felling, target cutting, group selection (“Swiss femel”), shelterwood felling, continuous cover forestry (“plentering”) and planting. A more detailed description of the original model can be found in Bugmann (1996). Changes to the original model are described in Bugmann and Solomon (2000), Risch et al. (2005), Didion et al. (2009) and Rasche et al. (2011, FORCLIM v2.9.8).

Mathematical symbols in FORCLIM follow the notation suggested by Swartzman and Kaluzny (1987), with the first letter denoting the type of the symbol: *u* for input/output variables, *k* for model parameters and *g* for auxiliary variables; state variables do not possess a prefix. Below, this notation is used throughout to avoid confusion, even in equations from other sources.



**Fig. 1.** Structure of the FORCLIM model with submodels PLANT, WEATHER, WATER and MANAGEMENT.

## Model improvement 1: Implementing a dynamic h/d relationship

### Description

In many gap models, diameter increment is calculated based on Moore's (1989) carbon budget approach:

$$\frac{dV}{dt} = \frac{\Delta(D^2 * H)}{\Delta t} = kG * D^2 \left(1 - \frac{H}{kH_{max}}\right) \quad (1)$$

where  $V$  denotes volume,  $D$  diameter,  $H$  height,  $kG$  growth rate and  $kH_{max}$  maximum tree height, with  $kG$  and  $kH_{max}$  being species-specific parameters. In FORCLIM, this equation was adjusted to calculate diameter instead of volume increment, and to allow for the continuation of diameter growth as maximum height is approached:

$$\frac{dD}{dt} = kG * D \frac{1 - \frac{H}{kH_{max}}}{2 * kH_{max} - kB * \exp^{kC * D} * (kC * D + 2)} \quad (2)$$

with  $kB = kH_{max} - 137$  cm (breast height), and  $kC = -gS / kB$  where  $gS$  denotes initial height growth relative to diameter growth (Risch et al., 2005). Tree height is approximated as a function of diameter:

$$H = 1.3 + kB * (1 - \exp^{kC * D}) \quad (3)$$

This formulation may be appropriate for unmanaged forests, but Lindner et al. (1997) argued that this is not the case for managed ones, as thinnings promote diameter growth through the elimination of competition, whereas height growth may even subside. For this reason, Lindner et al. (1997) took into account the effect of competition on the parameter  $gS$ , and made it dependent on the light available to the tree:

$$gS = kS_{min} + kE_1 (1/I_c - 1) \quad (4)$$

where  $kS_{min}$  and  $kE_1$  are species-specific parameters, and  $I_c$  is the relative intensity of incoming solar radiation at the center of the tree crown. Making the ratio of diameter to height increment variable entails that height can no longer be calculated from diameter, but must be followed separately as a state variable. This was accomplished by rewriting eq.(3) to a function  $f_h$  that distributes volume growth between diameter and height growth according to the competition-driven parameter  $gS$ :

$$f_h = gS * \left(1 - \frac{H - 1.3}{H_{max} - 1.3}\right) \quad (5)$$

Lindner et al. (1997) assumed that  $\Delta H$  and  $\Delta D$  have the relationship  $\Delta H = f_h * \Delta D$ , which yields, when substituted into the differential of eq. (1), a measure for annual diameter increment:

$$\Delta D = \frac{\Delta(D^2 * H)}{2 * H * D + f_h * D^2} \quad (6)$$

### Implementation

The variable  $gS$  has no upper limit in eq. (4), which we felt was unrealistic and therefore constrained to  $kS_{min} + kE_1$ :

$$gS = kS_{min} + kE_1 * (1 - AL_H) \quad (7)$$

where  $AL_H$  denotes relative light availability at the top of the tree crown.  $AL_H$  is calculated for each cohort based on the cohort's height  $H$ . Above the tallest cohort,  $AL_H = 1$ , whereas further down light availability diminishes through shading of higher cohorts and self-shading until it may approach 0 near the forest floor. Due to this mechanism, it is necessary that in the initialization of the simulation (e.g. when starting from measured inventory data), the height of each cohort in the stand is determined. This can be accomplished either directly as input (measured heights) from the inventory data, or with the help of eq. (3), in which  $gS$  is generically calculated as  $kS_{min} + 0.75 * kE_1$ . During the simulation,  $gS$  is then determined as a function of  $AL_H$  (eq. 7), and this value is used in eq. (5), which thus allows us to calculate the partitioning factor  $f_h$ . The latter is finally employed in a modified growth equation of FORCLIM, which results from combining eqs. (1) and (6) and taking into account the environmentally-induced reduction of growth ( $gGRF$ ):

$$\frac{\Delta D}{\Delta t} = kG * D * \frac{\left(1 - \frac{H}{kH_{max}}\right)}{2 * H + f_h * D} * gGRF \quad (8)$$

Then,  $\Delta H$  can simply be calculated as  $\Delta H = f_h * \Delta D$ .

Lindner et al. (1998; 1997) used data from several long-term observations of thinning trials in Germany to iteratively estimate the values of the parameters  $kS_{min}$  and  $kE_1$  (eq. 4) for *Fagus sylvatica*, *Picea abies*, *Pinus sylvestris* and *Quercus* sp. (cf. Table 2) through a series of simulations and subsequent visual comparisons of stand and simulation data. The authors then proceeded to estimate these parameters for ten other species, based on the species' ecological characteristics in relation to those of the four fitted species.

Lindner (1998) noted that the shade-intolerant pine trees in the under- and mid-storey behaved differently than trees of the three other species, as that they invested more into height than into diameter growth. A connection between shade

**Table 1.** Parameter values for  $kS_{min}$  and  $kE_1$  dependent on  $kLa$ , based on equations (9) and (10) and resulting  $kS_{max}$  value ( $kS_{min}+kE_1$ ). Depending on light conditions, the model parameter  $gS$  can take any value between  $kS_{min}$  and  $kS_{max}$ .

$kLa$	$kS_{min}$	$kE_1$	$kS_{max}$
1	41	27	68
2	42	41	83
3	43	55	98
4	45	69	114
5	46	83	129
6	47	97	144
7	49	111	160
8	50	125	175
9	51	139	190

intolerance and higher h/d ratios has been observed for other species as well (e.g. Beaudet and Messier, 1998; Delagrange et al., 2004; Messier et al., 1999; Williams et al., 1999), hence we assumed a correlation between the parameters  $kS_{min}$  and  $kE_1$  on the one hand and the species-specific shade tolerance ( $kLa$ ) on the other hand. Instead of separately deriving parameter values for each of the species parameterized in FORCLIM, we plotted Lindner's (1998)  $kS_{min}$  and  $kE_1$  values against the FORCLIM  $kLa$  values (nine classes from 1=shade-tolerant to 9=shade-intolerant) and calculated a linear regression for each parameter. Both regressions showed a significant correlation ( $p = 0.0028$  and  $0.0071$ , and  $R^2 = 0.446$  and  $0.373$  for  $kS_{min}$  and  $kE_1$ , respectively), and therefore for each species these parameters were calculated according to the species'  $kLa$  value (for resulting values see Table 1):

$$kS_{min} = 1.3 * kLa + 39.5 \quad (9)$$

$$kE_1 = 14 * kLa + 13 \quad (10)$$

### Validation

In order to properly assess the benefit of the new dynamic h/d relationship, we obtained data of a colline forest growth and yield research plot from the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL). The plot has an area of 0.44 ha, is located near Küsnacht, Switzerland (630 m a.s.l.), and was planted in 1884 with *Pseudotsuga menziesii*. The stand was thinned from above in low to medium intensities at 3- to 10-year intervals starting in 1924, with inventories

taking place just before treatments. In each inventory (15 in total), the species and diameter at breast height (DBH) of all trees were recorded, as well as the heights of a subset of trees, serving as tariff trees to estimate the height of the others. The latest inventory took place in 2001, providing a period of 77 years for the simulations. Data from the first inventory were used to initialize the model's state variables (dbh, height), and a detailed management plan for the MANAGEMENT submodel was set up based on site records, in essence recreating the management interventions that had taken place (for more details on the method see Rasche et al., 2011).

For climate, we used the database of the Landscape Dynamics Research Group at WSL, which comprises climate data spatially interpolated across all of Switzerland to a 100 m grid using DAYMET (Thornton et al., 1997). We chose data series from the grid cell covering the plot and additionally from the eight neighboring cells to derive long-term means of temperature and precipitation sums. The daily data from the nine grid cells were averaged, and from the resulting series we calculated means, standard deviations, and cross-correlations of monthly temperature and precipitation, thus reducing the potential bias associated with using data of a single grid cell (Daly et al., 2008; Didion et al., 2011). The other site-specific parameters in FORCLIM, i.e. soil water holding capacity ("bucket size") [cm] and available nitrogen [ $\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ ], were estimated from the site description as amounting to 12 and 80, respectively.

The stand was then simulated for 77 years, with a patch size of  $880 \text{ m}^2$  and 250 patches overall (250 patches represent 50 repeat simulations of the plot, to reduce stochastic noise; (cf. Wehrli et al., 2005)). As we included all trees marked as "removed" into the management plan, we assumed that no further natural mortality had taken place. The measured vs. simulated h/d relationship of the Küssnacht stand at the end of the simulation were compared to assess whether the new growth formulation had improved model accuracy.

## **Model improvement 2: Implementing a site-specific maximum height**

### **Description**

The maximum height a tree can reach depends on several factors, most notably available water (Friend, 1993; Koch et al., 2004; Ryan and Yoder, 1997), length of

the growing season (Ott, 1978) and nutrients (Tilman, 1988; Wilcke et al., 2008). Soil-bound nutrients are represented in FORCLIM by available nitrogen, a site-specific constant that does not change with climate or vegetation cover. Therefore we decided to forego the effect of nutrients on maximum tree height and to make it solely dependent on the two climatic variables. It has to be stressed at this point that this only concerns the adjustment of the maximum height variable to site conditions. The calculation of annual tree height increment is of course subject to nutrient availability.

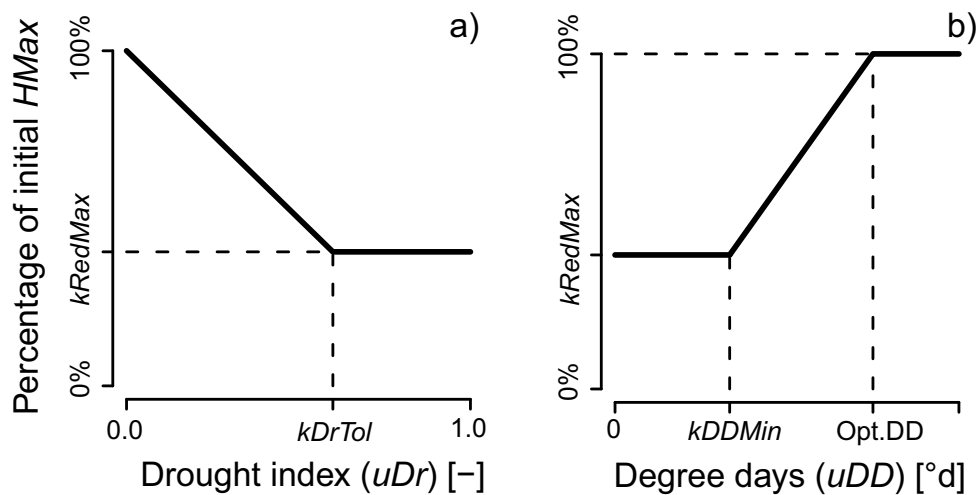
The FORCLIM drought index ( $uDr$ ) is appropriate for representing available water (Bugmann and Cramer, 1998), since it comprises not only water holding capacity of the soil, but also precipitation during the growing season. Growing season length and warmth are well represented by the number of annual degree-days ( $uDD$ ).

Under poor site conditions, stand-specific maximum height is thus reduced by unfavorable temperature ( $uDD$ ) or drought ( $uDr$ ) conditions. Hence, the task at hand was to introduce a dependency of the species-specific maximum height parameter ( $kHMax$ , parameterization see Bugmann, 1994) on  $uDr$  and  $uDD$ . In the case of  $uDr$  we assumed that there would be no reduction of  $kHMax$  when  $uDr = 0$  and a maximum reduction ( $kRedMax$ ) when  $uDr \geq kDrTol$  (the drought tolerance of the respective species, i.e. its dry distribution limit). We assumed a linear decline to  $kRedMax$  for intermediate  $uDr$  values (Figure 2a). We made a distinction between evergreen and deciduous species in using the seasonal drought index for the latter and the annual drought index for the former group (Bugmann and Solomon, 2000).

In the case of  $uDD$  we assumed that the reduction of  $kHMax$  is maximum ( $kRedMax$ ) when  $uDD \leq kDDMin$  (species' minimum degree day sum required for growth), using the annual sum of degree-days for evergreen and the seasonal sum for deciduous species. Next, the question arose at which degree-day sum the upper boundary should be placed. This could not be answered readily for all species, but Ott (1978) reported that in the Lötschental (Switzerland) the height growth of *P. abies* declines sharply at altitudes above 1900 m a.s.l., and Tschermak (1930) indicated a corresponding altitude of 1000 m a.s.l. for *F. sylvatica* in Vorarlberg (Austria). Based on this information, we employed long-term weather data from the climate stations Visp (640 m a.s.l.) and Montana (1508 m a.s.l.) for the Lötschental (time period 1931-1960) and the stations Feldkirch (440 m a.s.l.) and Galtür (1587 m a.s.l.) for Vorarlberg (time period 1900-1940) to calculate the average degree-day sums at

these locations, altitudes and time periods and used the resulting values as the upper boundary of height reduction (Figure 2b). For the other species, we calculated the difference between the  $kDDMin$  values of spruce and beech and the calculated degree-day sums from the Lötschental and Vorarlberg, and added the differences to the species-specific  $kDDMin$  values to obtain the value at which the reduction of  $kHMax$  becomes nil; this amounted to a difference of 353 °C·d from the Lötschental for evergreen and 471 °C·d from Vorarlberg for deciduous species.

For the estimation of the maximum reduction ( $kRedMax$ ) of  $kHMax$ , we used data from 52 yield tables downloaded from the European Yield Table Database (Teobaldelli et al., 2010), which were selected according to species, number of yield classes (more than two), and presence of data on dominant height ( $H_{dom}$ ). We then plotted the columns age and  $H_{dom}$  of each table against each other and proceeded to fit an asymptotic Chapman-Richards function to the lowest yield classes present, with  $H_{max}$  as the asymptotic value (Richards, 1959). Estimates of the model parameters were obtained by using the *stats* package of the open source statistics software *R* (R Development Core Team, 2010), enabling us to determine minimum  $H_{max}$  values ( $MinH_{max}$ ) for 18 of the species considered in FORCLIM and thus via the difference between  $kHMax$  and  $MinH_{max}$  a value for  $kRedMax$ . Values for the other species were estimated according to the similarity of their ecological characteristics to those of the species for which yield table data were available (Table 2).



**Fig. 2.** Site-specific reduction of  $kHMax$  based on a) drought and b) degree days. For the final reduction the lower value is used.

**Table 2.** Maximum reductions ( $kRedMax$ , expressed in %) of the species parameter  $kHMax$ , determined by the maximum height of the lowest yield class ( $MinH_{max}$ ) found for the species in the European Yield Table Database (Teobaldelli et al., 2010).

Species	$kHMax$ [m]	$MinH_{max}$ [m]	$kRedMax$ [%]
<i>Abies alba</i> Miller	60	26.4	44
<i>Acer campestre</i> L.	23	18.4	80
<i>Acer platanoides</i> L.	32	18.4	58
<i>Acer pseudoplatanus</i> L.	37	18.4	50
<i>Alnus glutinosa</i> (L.) Gaertn.	31	21.2	68
<i>Alnus incana</i> (L.) Moench	22	-	68
<i>Alnus viridis</i> (Chaix) DC.	4	-	68
<i>Betula pendula</i> Roth	29	18.4	63
<i>Carpinus betulus</i> L.	27	15.2	56
<i>Castanea sativa</i> Mill.	33	13.2	40
<i>Corylus avellana</i> L.	10	-	68
<i>Fagus sylvatica</i> L.	45	19.2	43
<i>Fraxinus excelsior</i> L.	42	16.9	40
<i>Larix decidua</i> Miller	52	19.6	38
<i>Picea abies</i> (L.) H.Karst.	58	19.6	34
<i>Pinus cembra</i> L.	26	-	38
<i>Pinus montana</i> Miller	23	-	38
<i>Pinus sylvestris</i> L.	45	17.1	38
<i>Populus nigra</i> L.	36	28.2	78
<i>Populus tremula</i> L.	30	21.5	72
<i>Pseudotsuga menziesii</i> (Mirbel) Franco	54	26.3	49
<i>Quercus petraea</i> (Mattuschka) Liebl.	45	19.2	43
<i>Quercus pubescens</i> Willd.	25	-	42
<i>Quercus robur</i> L.	52	21.7	42
<i>Salix alba</i> L.	27	-	68
<i>Sorbus aria</i> (L.) Crantz	22	-	68
<i>Sorbus aucuparia</i> L.	19	-	68
<i>Taxus baccata</i> L.	22	-	38
<i>Tilia cordata</i> Miller	30	-	40
<i>Tilia platyphyllos</i> Scop.	39	-	40
<i>Ulmus glabra</i> Huds.	43	-	40

### Implementation

During the initialization process for a simulation and subsequently every year the submodels WATER and WEATHER calculate  $uDr$  and  $uDD$  separately for every patch based on a probability distribution of the monthly weather data. Averaging those values over all patches thus assures a balanced estimation of site conditions without the danger of distortion due to climatically extreme years.  $uDr$  and  $uDD$  are then separately used to determine the reduction of  $kHMax$  for each species, and subsequently the lower value of both is employed (minimum approach). Other, more complicated approaches for deriving the final percentage of reduction, such as the multiplication, the geometric mean or the cubic root used to combine several growth factors in JABOWA and FORCLIM (cf. Botkin et al., 1972; Bugmann, 1996), were deemed unnecessary, as tree growth is usually either limited by degree-days or drought, but rarely by both.

It is reasonable to assume that the growth potential at a site – here represented by  $kHMax$  - stays constant as long as environmental conditions stay roughly the same. We therefore implemented that  $kHMax$  of every species is calculated once based on site conditions during the initialization stage of the model (i.e., under current climate), and thus stays constant. Only during the simulation of climate change scenarios is the value adjusted again; once every 10 years as long as the change continues (usually 100 years, as climate change scenarios beyond the year 2100 are not available, but simulations do not necessarily stop there). For the adjustment we use the mean  $uDr$  and  $uDD$  values in the current year, just like in the beginning of the simulation. The decadal time step is arbitrary, but it allows for a smoother transition of  $kHMax$  values instead of changing the value abruptly at the end of the simulation of climate change, which might cause relicts in the simulation results.

### Validation

Maximum tree height depends on climatic factors in the new model version, and thus these changes need to be tested against data from a range of environmentally different locations. For this we chose 9 sites from a previously utilized environmental gradient (e.g., Bugmann and Solomon, 2000; Didion et al., 2009), which comprises a variety of elevations (i.e., temperature regimes) and drought conditions in Europe (Table 3). We obtained data from the first Swiss National Forest Inventory (NFI1, Bachofen et al., 1988) for the 16 NFI plots that were nearest to each site. The NFI1 plots are located at every forested intersection of a 1 km grid mapped over

Switzerland, from which a 200 m<sup>2</sup> and a 500 m<sup>2</sup> circle are drawn. In the smaller circle, every tree with a DBH larger than 12 cm is measured, in the bigger one every tree larger than 36 cm. Additionally, the height of every tree with an azimuth smaller than 151° is recorded. Using these data, we estimated maximum heights for the most abundant species at each of the 9 sites by again fitting an asymptotic Chapman-Richards function to the measurements.

For climate, we used the same data that had been employed in previous studies, i.e. long-term daily temperature and precipitation data from climate stations at the 9 locations converted to monthly means of temperatures and precipitation sums. Available nitrogen and bucket size for each stand were also adopted from previous studies (e.g. Bugmann, 1994) and set as stated in Table 3. With these data we calculated the temperature- and drought-related reduction factors of *kHMax* as described above, took the minimum and adjusted species-specific maximum height separately at each of the 9 locations. We then compared for each location the adjusted *kHMax* values of the species to the potential maximum heights of the same species that we had calculated from the NFI data to assess the performance of our approach.

## General validation of new model version

After assessing the performance of the two model improvements, we also wanted to test whether the general applicability of the new model version, FORCLIM v3.0, was still maintained. To this end, we applied both the new and the old model versions at the 9 sites of the environmental gradient mentioned in section 2.3.3 to analyze the impact of the two changes (separate height growth and flexible maximum tree height) on simulated total biomass, species composition and forest productivity.

Climate data were taken from the respective weather stations at the locations (for other site-specific parameters see Table 3), and the duration of the simulations was set to 3000 years, with 1500 years under current climate, then 100 years of climatic change, and a further 1400 years under a scenario of future climate., for which we used data from the ENSEMBLES project (Hewitt and Griggs, 2004) of the Institute for Atmospheric and Climate Science, ETH Zürich, which focuses on the A1B scenario of the IPCC AR4 (IPCC, 2007) that was regionalized to a 10 km grid. For each of the 9 locations, data from the grid cell covering the location and its eight neighbors were

**Table 3.** Sites along a broad drought and elevation gradient used in the present study, the long-term annual mean temperature (Temp.) and precipitation sums (Prec.), their observation period, bucket size (BS) and available nitrogen (AvN) as used as input parameters in ForCLIM, and dominating tree species of the potential natural vegetation (PNV) according to Ellenberg and Klötzli (UNEP, 2011), Krausch (e.g. Bont, 2011) and Ellenberg and Leuschner (Anonymous, 2011).

Site	Lat. (°N)	Long. (°E)	Elevation (m a.s.l.)	Temp. (°C)	Prec. (mm)	Observation period	BS (cm)	AvN (kg·ha <sup>-1</sup> ·yr <sup>-1</sup> )	PNV
Bever	46.6	9.9	1712	1.5	841	Jan. 1901 – Dec. 1982	10	60	<i>Pinus cembra</i> , <i>P. montana</i> , <i>Larix decidua</i>
Grande Dixence	46.1	7.4	2166	1.2	1016	Jan. 1965 – Dec. 1984	10	60	<i>Pinus cembra</i> , <i>Picea abies</i> , <i>Larix decidua</i>
Davos	46.8	9.8	1590	3.0	1007	Jan. 1867 – Dec. 2003	10	60	<i>Picea abies</i> , <i>Larix decidua</i>
Adelboden	46.5	7.6	1325	5.5	1351	Jan. 1959 – Dec. 2005	15	80	<i>Picea abies</i> , <i>Fagus sylvatica</i> , <i>Abies alba</i>
Huttwil	47.1	7.8	638	8.1	1290	Jan. 1972 – Dec. 1995	20	100	<i>Picea abies</i> , <i>Fagus sylvatica</i> , ( <i>Abies alba</i> )
Bern	46.9	7.4	570	8.4	1006	Jan. 1864 – Dec. 2003	20	100	<i>Fagus sylvatica</i> , ( <i>Picea abies</i> )
Schaffhausen	47.7	8.6	400	8.6	882	Jan. 1880 – Dec. 2003	15	80	<i>Fagus sylvatica</i> , ( <i>Quercus ssp.</i> )
Basel	47.5	7.6	317	9.2	784	Jan. 1864 – Dec. 2003	15	80	<i>Fagus sylvatica</i> , ( <i>Quercus ssp.</i> )
Sion	46.2	7.4	542	9.7	597	Jan. 1864 – Dec. 2003	15	60	<i>Pinus sylvestris</i> , <i>Quercus ssp.</i>

employed, with the periods 1961-90 as baseline and 2075-99 as representative years for a hypothetical “future climate”. Seasonal temperature and precipitation anomalies as well as anomalies of the monthly cross-correlations were derived based on the mean monthly temperatures and precipitation sums of the two periods and applied to modify the current climate. For the simulations we assumed that the climate changed linearly between the baseline and the future climate scenario (for more details on the process see Didion et al., in press).

The first evaluation focused on the results from the simulation year 1500. When starting simulations from bare ground with FORCLIM, this time span ensures that the stand is in equilibrium with the current climate. We compared the simulated total biomass in this year with biomass estimates from the NFI for these locations. We further compared the simulated species composition in this year with the potential natural vegetation of these locations (Table 3). These analyses were made to ensure that the improvement of local accuracy had no detrimental effect on the general applicability of the model.

The second evaluation compared the two model versions in terms of simulated changes in forest productivity from the simulation years 1500 to 3000. The results from this last year represent unmanaged stands in equilibrium with the future climate. This was done to assess what effects the model improvements had on simulations under climate change.

## Results

### **Model improvement 1: Stand structure on a forest growth and yield research plot**

A visual comparison of simulated vs. measured h/d data (Figure 3) showed that the new formulation of the diameter growth equation with height being a new, independent state variable is a clear improvement: instead of simulating a static relationship between height and diameter that is independent of stand structure or age (FORCLIM v2.9.8), in v3.0 it was possible to generate a more differentiated picture with trees of the same species that had the same diameter but different heights, or vice versa. Uncoupling tree height from diameter has the additional advantage that the model can be initialized with tree height measurements, improving the starting

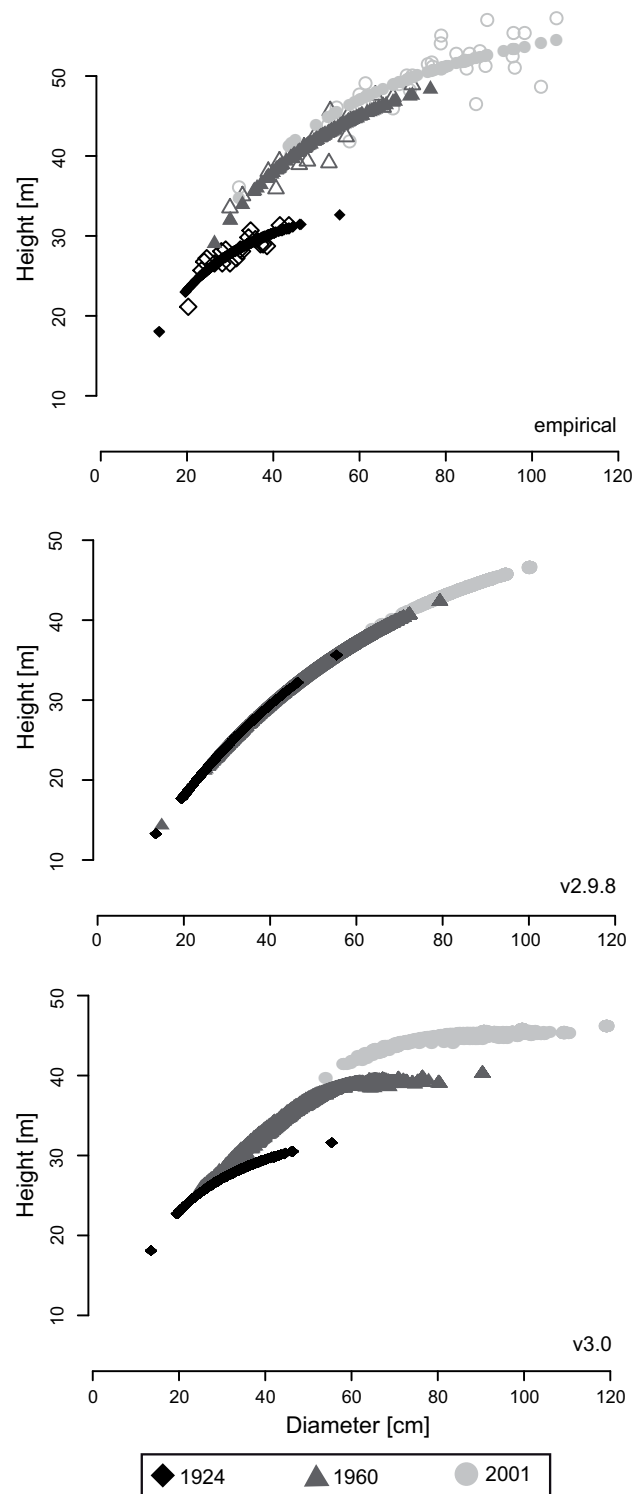
conditions of simulations and thus of the stand structure depiction in the early years (Fig. 3, year 1924 in first and last panel). In later years, simulations with v3.0 overestimated diameter increments slightly but underestimated height increments, whereas v.2.9.8 underestimated both. The trend of the  $h/d$  ratios in the simulated (v.3.0) results was slightly different from the measured ones, though, with the measured values steadily increasing and the simulated ones apparently approaching an asymptotic value, indicating that  $kHMax$  is somewhat larger in reality than estimated for this stand by the new model formulation.

## Model improvement 2: Potential maximum height along an environmental gradient

Table 4 shows the results of the simulations regarding maximum height of the dominant species on the NFI sample plots at the 9 locations of the gradient. The maximum heights calculated by FORCLIM v3.0 did not differ significantly from the NFI estimations ( $p = 0.72$ , Wilcoxon Mann-Whitney test), whereas those of v2.9.8 differed significantly from the NFI data ( $p = 0.03$ ). However, the reduction still does not mimic reality perfectly, as shown by the values for spruce and fir in the lower subalpine and montane sites Davos, Adalboden and Huttwil. At these sites, FORCLIM v3.0 did not compute any or only a slight reduction of  $kHMax$ , whereas NFI estimations yielded maximum heights that are about 10 m lower. Overall, however, the distribution of maximum heights of the NFI and FORCLIM v3.0 along the gradient is what one would expect both qualitatively as well as quantitatively, with the highest values in center of the gradient, and the lowest at the extreme ends.

## General validation of FORCLIM v3.0

In terms of total biomass, results from FORCLIM v3.0 agreed closely with NFI estimates along the whole gradient, whereas the earlier model version showed differences particularly at the sites Bever and Grande Dixence (Figure 4). The lower simulated biomasses of v3.0 at both the sub-montane and dry colline end of the gradient were most likely due to the substantial reductions in maximum height, which gave rise not only to lower simulated tree volumes but also to diminished growth rates, capturing growth conditions at least at sub-montane sites more accurately. In Sion, simulated biomass was even lower with v3.0 than with v2.9.8 and far lower than the NFI data. This probably results from the fact that the weather station (which was used to drive the model) is located in the very dry bottom of the



**Fig. 3.** Tree height versus diameter for three points in time in a *Pseudotsuga menziesii* stand in Küssnacht (CH). Measured (top) and simulated data (middle: v2.9.8, bottom: v3.0). In the first panel blank symbols represent the tariff trees, solid ones the estimated heights of the remaining trees.

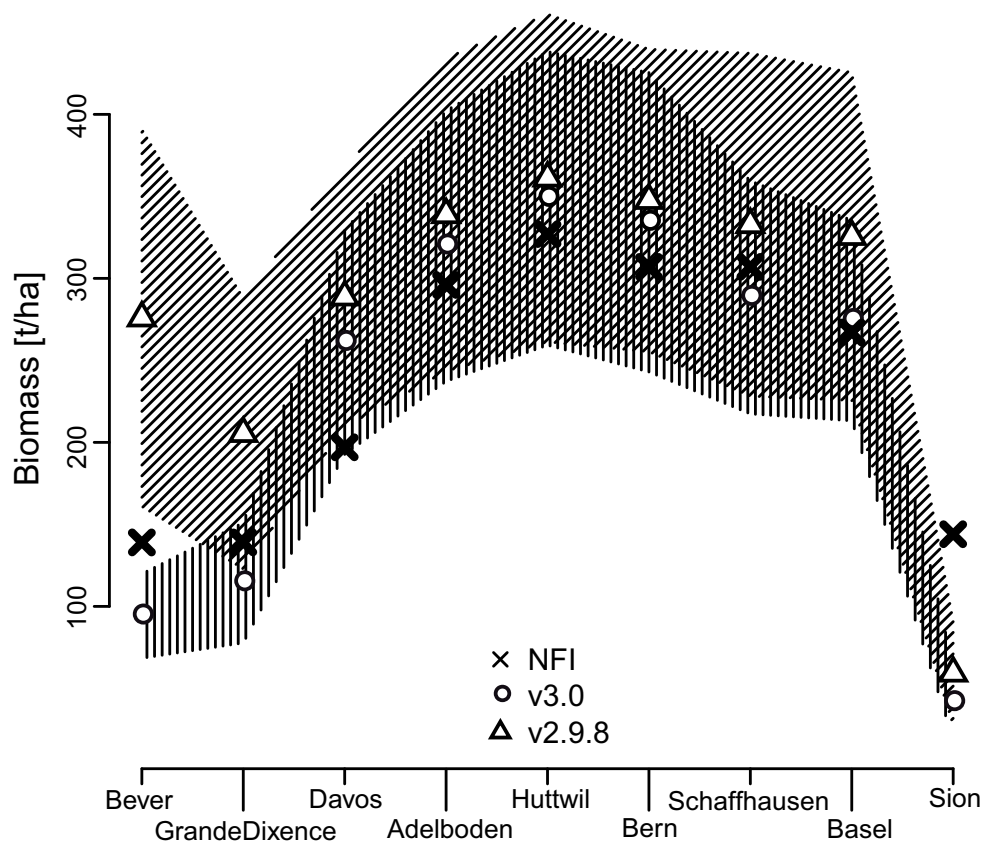
Rhône valley, whereas forested NFI sample plots are only found higher up on the adjacent slopes, where climatic conditions are more favorable for tree growth.

As several authors have analyzed in great detail the simulated potential natural vegetation (PNV) along the gradient (Bugmann and Cramer, 1998; Bugmann and Solomon, 2000; Didion et al., 2009), we will not do so again but focus on the differences between the model versions 2.9.8 and 3.0 (Figure 5). The most notable difference was found in the amount of biomass each species contributed to the simulated equilibrium forests.

In Bever and Grande Dixence, *Pinus cembra* experienced the greatest reduction in v3.0, and *Larix decidua* disappeared almost completely. In Adelboden, *Populus nigra* appeared which had also been the case in older model versions, but not in v2.9.8. In Huttwil and Bern, changes were not substantial, although the biomass of *Castanea sativa* and *Acer pseudoplatanus* declined slightly, and *Abies alba* biomass increased in Bern. In Schaffhausen and Basel, *C. sativa* was still simulated as a co-dominant species, but had lost a considerable portion of its biomass in v3.0, whereas *Ulmus glabra* and *Tilia platyphyllos* increased theirs and joined *C. sativa* as co-dominant species. In case of *T. platyphyllos*, this appears realistic, as analyses of the NFIs show a substantial fraction of lime stem numbers; however, *U. glabra* tree numbers keep decreasing in Switzerland due to the Dutch elm disease, a factor not considered in FORCLIM. In Sion little changed, except for the disappearance of *Pinus montana*.

**Table 4.** Maximum tree heights ( $H_{max}$ ) on an environmental gradient; comparison between national forest inventory (NFI) and simulation data (FORCLIM versions 3.0 and 2.9.8) for the dominant species (dom. sp.) present the NFI sample plots at the specific sites, with N as the number of height-measured trees.

Site	Dom. sp. (N)	$H_{max}$ NFI [m]	$H_{max}$ v3.0 [m]	$H_{max}$ v.2.9.8 [m]
Bever	<i>Pinus cembra</i> (32)	28 ± 13.3	20	26
Grande Dixence	<i>Picea abies</i> (22)	36 ± 5.9	37	58
Davos	<i>Picea abies</i> (50)	48 ± 5.6	58	58
Adelboden	<i>Picea abies</i> (83)	45 ± 6.8	58	58
Huttwil	<i>Abies alba</i> (17)	50 ± 6.4	59	60
Bern	<i>Fagus sylvatica</i> (22)	43 ± 5.1	44	45
Schaffhausen	<i>Fagus sylvatica</i> (15)	35 ± 3.4	38	45
Basel	<i>Fagus sylvatica</i> (20)	42 ± 4.9	36	45
Sion	<i>Picea abies</i> (16)	28 ± 5.1	20	58



**Fig. 4.** Total biomass along an environmental gradient in Europe, measured (crosses), and simulated values. Shaded areas: standard deviation of simulation results (vertical stripes: v.3.0, diagonal stripes: v2.9.8).

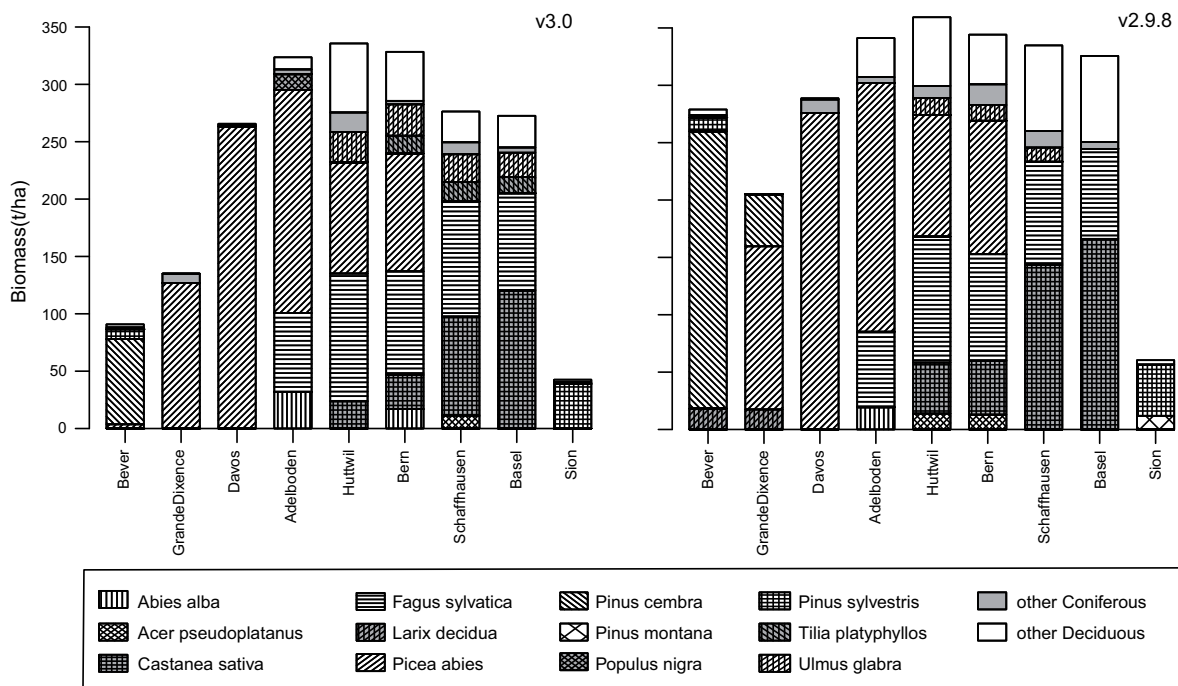
## Model behavior under a changed climate

Productivity changed noticeably from current climate to a scenario of future climatic conditions (Figure 6). It rose at the subalpine and montane sites, gently declined in the warm-moist center of the environmental gradient, and sharply declined at the colline sites to a degree where conditions became unsuitable for forest growth in Sion – at least for the species currently parameterized in FORCLIM. Both model versions agreed on this general pattern, but the magnitude of change was portrayed differently, especially at either end of the gradient.

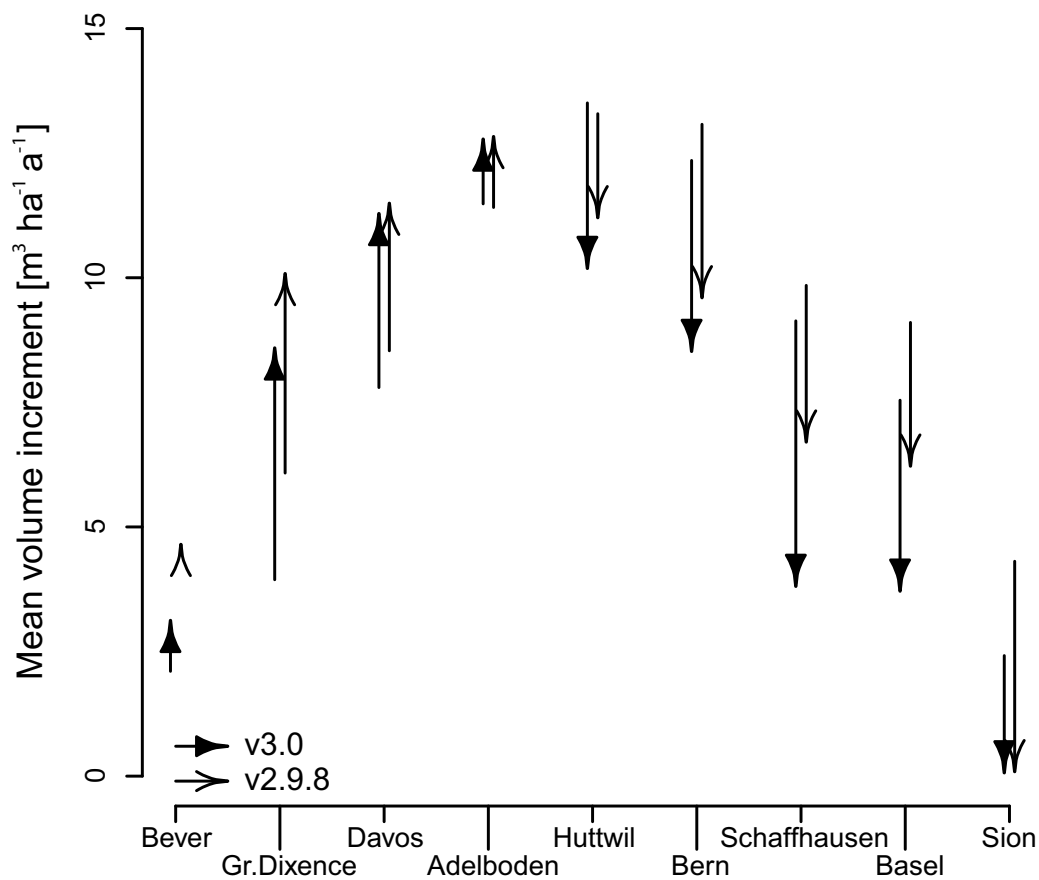
In Bever, the earlier model version showed nearly no change in productivity, whereas v3.0 indicated a clear increase, yet not to the overall level of the old model version. Analyses of the diameter distributions (data not shown here) indicated that this was due to the numbers of trees with large diameters, which slightly declined in

v2.9.8 but rose in v3.0. By comparison, at Grande Dixence (and to some extent also at Davos), where temperatures are comparable to Bever but precipitation is more abundant, the pattern was closer to what one would expect: Productivity in v3.0 started at a lower level due to temperature-constrained maximum heights, but rose to approximately the same values as simulated with v2.9.8 when this reduction was gradually diminished with a warmer, yet not overly dry climate.

In the warm-moist center of the gradient (Adelboden, Huttwil, Bern), the two model versions produced nearly identical growth rates, as neither temperature nor drought warranted an adjustment of  $kHMax$ . At Schaffhausen, both model versions agreed on the productivity level for the current climate, but the new model version estimated noticeably larger losses in productivity under future climatic conditions. In Basel and Sion, due to the new mechanism of reduced maximum height caused by dry conditions, v3.0 simulated a lower productivity under current climate conditions than v2.9.8. Both model versions, however, agreed on the magnitude of change in Basel, and that conditions become unsuitable for tree growth in Sion under climate change.



**Fig. 5.** Simulations of species composition along an environmental gradient in Europe using FORCLIM versions 3.0 (left) and 2.9.8 (right). Species grouped into the “other” categories failed to contribute at least 5% to total biomass, respectively.



**Fig. 6.** Simulations of productivity change along an environmental gradient in Europe.  
a) Start of arrow: productivity at equilibrium under current climate; arrowhead: productivity at equilibrium under future climate

## Discussion

In this study we developed, validated and applied a new version of the forest succession model FORCLIM that features a dynamic relationship of height to diameter increment and a climatically sensitive modification of maximum tree height. These changes clearly increased the local accuracy of the model, as the h/d relationship over time was simulated much more realistically, in quality comparable to the results achieved with individual-tree growth models (Vospernik et al., 2010), while not negatively influencing the model's general applicability. On the contrary, the new model version depicted biomass and maximum tree heights along an environmental gradient very close to NFI estimations, and certainly better than the old one.

## Model improvements

In their growth equations, gap models – and many other types of forest models – require one or several parameters constraining growth. By definition, parameters are constants and thus cannot be affected by environmental influences. Using the example of maximum height, we showed that converting such a parameter to a variable had a non-negligible influence and highly positive effect on the simulation results, especially when considering scenarios of climatic change.

One could, of course, argue that instead of further refining a simple growth equation, a more sophisticated approach should have been taken that would entirely abolish the need for parameters like maximum height. In the model 4C, for example, maximum tree height and other tree state variables are determined by the allocation of NPP, which itself is influenced by environmental conditions (Bugmann et al., 1998). An even more “realistic” approach would be to incorporate e.g. the findings of Koch et al. (2004) and explicitly model maximum height as limited by leaf water stress due to gravity and path length resistance. For a variety of reasons, we do not believe that taking such a route would be more promising and more successful than the approach we adopted here, as explained below.

Besides the fact that a more detailed, highly mechanistic approach would by far exceed the frame of a gap model, we feel that our work is congruent with the principle of parsimony (“Ockham’s razor”). The new parameters that we introduced are either derived from existing ones, eliminating the need for elaborate parameterization, or are easily calculated from readily available data such as yield tables, and as such make it straightforward to add new species should the need arise. Another possibility would have been to follow the example of Kellomäki et al. (2008) and not adjust the growth-constraining factor to site conditions, but the height/diameter relationship based on the temperature sum at the location. This would have been a valid approach if we had stayed within the concept of a fixed relationship between  $d$  and  $h$ , but not with our new, light-dependent allocation of volume growth to diameter and height growth.

Concerning the parameterization of the maximum reduction of  $kHMax$  with the help of yield tables, the approach may be debatable since yield tables are usually only available for commercially interesting species and sites where a commercially rewarding yield is to be expected. We also acknowledge that there are many different types of yield tables, usually constructed for one location, one species and

one silvicultural regime, which ordinarily should not be mixed. But we feel that we can safely disregard these limitations, as we only wanted to get an idea of the average height growth of the least productive classes of one species. The large number of yield tables we considered made sure that we actually captured a wide range of yield classes in Europe, most likely including very poor conditions (irrespective of the exact stand conditions and silvicultural regimes), as they were derived for climatically very different parts of Europe ranging, for example, from Hungary to Great Britain.

Another matter is the parameterization of the value of the optimal degree days (Figure 2b, section 2.3.1), marking the point below which  $kHMax$  is becoming lower. We assumed that all deciduous and all evergreen species followed the patterns set by the available data for *F. sylvatica* and *P. abies*, respectively, mostly because, as mentioned above, this parameter could not readily be derived for other species. Ott (1978), however, in his study not only measured *P. abies*, but also *L. decidua* and noticed that they indeed followed the same pattern and started to have lower asymptotic heights at roughly the same altitude. We therefore feel comfortable with having the species follow these two height-reduction patterns, even though it would of course be desirable to discriminate further. At least we can distinguish deciduous (via *F. sylvatica*) from evergreen (via *P. abies*) species in our approach.

Another aspect that could further improve the simulation results is the inclusion of soil nutrients into the estimation of maximum height. For example, Albert and Schmidt (2010) and Bravo-Oviedo et al. (2010) identified this factor as being significant for the explanation of site productivity. However, as mentioned in section 2.3.1, this would only be warranted if soil nutrient availability varied over time, which is not the case in the current version of FORCLIM.

## Model validation

The h/d ratios simulated with FORCLIM version 3.0 show a slightly different trend than the measured ones (Figure 3). Additionally, height growth is slightly underestimated in Küssnacht and diameter growth slightly overestimated as compared to the measured data. It should be kept in mind, however, that this result, which we view as being highly promising, was achieved without any calibration of species parameters. By doing so, we ensure the general applicability of the model, while simultaneously yielding less-than-perfect, but quite satisfactory results in terms of

local accuracy. The goal of implementing the variable height to diameter growth function was to enable FORCLIM to render realistic patterns of h/d relationships, which clearly was achieved, even down to a slight scattering of values with the new model version.

Concerning the validation study for the reduction of maximum height (section 3.2, Table 4), one should keep in mind that comparisons of simulated data with NFI data are not always straightforward. For example, it is uncertain how accurate our estimation of these (asymptotic) values of tree height from the NFI dataset is. Spruce stands, for instance, are on average a little younger than beech stands in Switzerland, and even though there are many old stands on unproductive locations, there are also quite a number of young ones (Brändli, 2010), which makes it possible that some estimations of their maximum height could be too low. Therefore, the differences between “observed” and simulated maximum heights at the sites Davos, Adelboden and Huttwil, for example, could be smaller than currently shown.

Furthermore, the estimation of biomass from the NFI raises some questions as well (Figure 4). It is not clear if it would be more desirable to have a systematic overestimation of biomass by the model, as the model results show an unmanaged forest in an equilibrium state, whereas most of the NFI plots represent managed stands that are typically 80-120 years old. This may apply to Grande Dixence, for example, but we believe that the total biomass simulated at Bever with v2.9.8, which reached nearly the same level as the one at the submontane site Adelboden, is strongly overestimated and approximated more accurately with v3.0.

## Simulation of productivity under climate change

This simulation was undertaken to assess the impact of the model improvements on simulated forest properties under scenarios of climate change. The results clearly showed that it is important to implement a site-specific growth constraint (*kHMax* in our case) into the model, since it has a strong and beneficial influence on the results. Not only is simulated productivity under current climate markedly different, especially at the two ends of the gradient, but also the changes of forest productivity under climate change are simulated to be much more severe in the new model version.

The overall results, a simulated rise in productivity levels in the subalpine and upper montane zone, and a fall in the lower montane and colline zone, are consistent with

earlier studies by Prentice et al. (1993), Lasch et al. (2002b) and Albert and Schmidt (2010), who found that future productivity is likely to decrease at sites that are currently subject to drought, and also with estimations by Lindner et al. (2010), who suggested that productivity on sites currently limited by low temperature may rise with climatic change. The latter authors also stress that temperature and precipitation trends for mountain regions are highly uncertain, and that dry valleys may show a different trend, which may explain the surprisingly minor changes in productivity simulated in Bever.

The simulation results provided here should be considered with caution, however, as there are some variables that may influence forest productivity in the future that FORCLIM does not consider, such as rising CO<sub>2</sub> values, pests, insect damage and a higher frequency of disturbances. It should also be considered that choosing a different climate change scenario may result in different findings (Lasch et al., 2002a), although a test with a scenario that was not as harsh as the one we selected at the sites Grande Dixence, Huttwil and Basel showed that while changes in productivity were not as severe, the overall trends stayed the same. Hence we are confident that the patterns we found are robust.

## Conclusions

In this paper we showed (i) that the traditional growth equation used in many forest gap models can be altered to account for a dynamic  $h/d$  ratio, thereby improving the simulation of stand structure in FORCLIM, and (ii) that it is possible to convert a growth-constraining parameter (maximum tree height) to a site-dependent and temporally flexible variable without strongly complicating model structure, thus enhancing model reliability under changing climatic conditions. We further showed that (iii) these changes to the model improved overall model performance in terms of biomass, basal area and species composition of strongly different forest types.

Moreover, the study on productivity under climatic change suggests that a flexible height-diameter relationship and a climatically sensitive growth constraint are not only desirable, but crucial features to incorporate, since climate-induced changes in productivity are simulated to be more severe with the new model formulations.

Taking these changes into account, we propose that our work is an important step on the way towards using gap models in decision support for adaptive forest management.

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## Chapter III

# Key factors affecting the future provision of tree-based forest ecosystem goods and services

Livia Rasche, Lorenz Fahse, and Harald Bugmann

In revision with *Climatic Change*

**Abstract.** The continuous provisioning of forest ecosystem goods and services (EGS) is of considerable interest to society. Yet it is unclear how much the provision will change with a changing climate, and which factors will be influencing the change the most.

Thus we simulated forest stands on six climatically different sites in Central Europe under several scenarios of species diversity, management, and climatic change and evaluated whether one of the factors influenced the provision of tree-based EGS – represented by harvested basal area, total biomass, stand diversity and productivity – more strongly than others.

The most influential factor was species diversity: diverse stands showed lower sensitivity to climate change than monocultures. Biomass was more influenced by management, with the most intensively treated stands retaining more of their original biomass than others. Despite climate change being the driver of change, the choice of climate change scenario was arbitrary.

The results show that (i) only few stands – represented by their combination of characteristics – may do significantly worse than others, (ii) diversity aspects are important for adaptive management measures, (iii) dependent on the indicator management might be more important, (iv) at locations subject to increasing drought, the provision of EGS may suffer in future regardless of stand characteristics.

This quantitative evaluation of the influence of different factors on changes in the provision of forest EGS under climate change represents an important step towards the design of more focused adaptation strategies and highlights factors that should be considered carefully in simulation studies under climate change.

**Keywords.** *adaptive management, climate change, forest ecosystem goods and services, sensitivity, species diversity.*

## Introduction

Forests present an important source of ecosystem goods and services (EGS). They contain ~50% of the world's terrestrial carbon stock, provide habitat for more than 50% of the world's known terrestrial plant and animal species, deliver timber, and

more than 75% of the world's fresh water comes from forested catchments (Shvidenko et al. 2005). There is a strong interest to preserve the provision of forest EGS, and to ensure that future generations may benefit from them, too. However, studies suggest that a changing climate may exert considerable influence on ecological processes (e.g. Bonan, 2008; Dale et al., 2010; Kirschbaum et al., 1996; Root et al., 2003), and at the local scale lead to changes in stand diversity (Hansen et al. 2001), forest composition and forest productivity (Shugart et al. 2003), stand characteristics the provision of EGS is intimately tied to and dependent on (Shvidenko et al. 2005).

Thus to evaluate the potential change in forest EGS provision, knowledge about the sensitivity of forest stands to effects of climate change is required. This sensitivity is influenced by certain stand characteristics, such as the “functional response diversity” (e.g. Elmqvist et al. 2003; Hooper et al. 2005), a heterogeneous structure (Bodin & Wiman 2007), a natural (unmanaged) status (Thompson et al. 2009), or forest management with a reduced intensity (Noss 2001). The importance scientists attribute to each of these factors varies and seems to depend on the goal to be reached: The preservation of the protective capability of mountain forests (Cordonnier et al., 2008) e.g. is supported by other characteristics than a maximization of net value of timber production (Nuutinen et al., 2006), or C-storage (Lasch et al., 2005).

This is where our study sets in. There are numerous publications concerned with effects of climate change on forest ecosystems (e.g. Dale et al., 2010; Huo et al., 2010; Lindner, 2000), and also with suggestions on how to adapt to these changes (e.g. Badeck et al., 2005; Kellomäki et al., 2008; Noss, 2001). Yet most studies, like the ones cited above, were focused on specific EGS, often in a specific region, and aimed to provide practical suggestions for adaptation. They tried to answer the question of *how* climate change will affect forest ecosystems. We want to take a slightly different approach and tackle the question of *how much* climate change will influence the provision of EGS, and if the magnitude of change is statistically significant. Furthermore, we want to determine which factor – species diversity or management alternative – influences the magnitude of change most, and if there are differences in decisive factor when different indicators are considered. We also wanted to assess how much influence the choice of one specific scenario of climate change has on simulation results.

To answer these questions, we conduct a simulation experiment in which we vary the factors species diversity and management intensity at climatically different sites and under different scenarios of climate change to be able to quantify their influence on the provision of selected tree-based EGS.

Though we only consider a subset off all possible EGS, we think that this study nevertheless forms an important step towards the design of reliable adaptation strategies, as it aims to identify factors that should primarily be targeted, and highlights factors that should be handled carefully when projecting the development of forest EGS under climate change.

## Material and Methods

### The model

There is no obvious choice of model for a study like this. To assess EGS like water purification and regulation, a process-based model is required. These models are complex and require many data, so that most are only parameterized for commercially interesting, well studied species. Forest succession models as mechanistic models require fewer data and can consider more species, but often lack the detail necessary for results beyond the tree level. The most appropriate choice of model thus depends on the study's objective. We wanted to consider a variety of tree species diversities; and could show previously that the forest succession model FORCLIM (Bugmann, 1996) performed robustly under climate change (Rasche et al., 2012), so that we chose this model for the study.

FORCLIM simulates forest dynamics on small (800 m<sup>2</sup>) patches of land, usually 200 to determine ecosystem properties at the stand scale. It consists of four submodels: *weather*, *water*, *plant* and *management*. The first two provide values for minimum winter temperature, growing season temperature and soil moisture based on long-term monthly climate data and soil water holding capacity. In the submodel *plant*, these variables and light availability determine the establishment probabilities of new cohorts. A modification of Moore's (1989) carbon budget approach is used to model tree growth: an optimal growth rate is reduced based on environmental factors (light, available nitrogen, growing season temperature, soil moisture) and crown length. The resulting volume growth is allocated dynamically to height and

diameter growth based on available light and the shade tolerance of the species. Tree mortality is triggered by an age-related and a stress-induced component. In the management submodel (Rasche et al., 2011) several silvicultural treatments are available, including thinning, cutting and a continuous cover forestry method (“plentering”). In the plentering function the surplus ingrowth per diameter class is harvested based on an equilibrium equation (shaped by values for the desired constant stand basal area, maximum diameter, and quotient between diameter classes, see Appendix 1 Chapter I). Plentering results in uneven-aged stands with a reversed J-shaped diameter distribution.

For a more detailed description of the model see Bugmann (1996) and Didion et al. (2009); for the latest model version used here see Rasche et al. (2012).

### **Study locations**

We chose six European locations from a previously utilized environmental gradient (e.g. Bugmann and Solomon, 2000; Didion et al., 2009; Rasche et al., 2012), comprising a variety of elevations and drought conditions in Europe (subalpine to colline). In FORCLIM sites are characterized by long-term monthly climate data, soil water holding capacity and available nitrogen (Table 1). Climate data were obtained from the Landscape Dynamics Unit at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), who used the DAYMET model (Thornton et al., 1997) to interpolate daily climate data to a resolution of 1 ha for 1930-2006. From this grid we chose data from the nine cells covering and surrounding each of the six sites and averaged the data over the cells, thus avoiding the potential bias associated with using data from just a single cell. From the resulting single time series we calculated the mean temperature and precipitation sum for each month, the standard deviations, and the cross-correlations between them; receiving five values for each month. In the model-internal weather generator the values are used to construct distributions from which weather variables are drawn. The other two site-specific parameters were adopted from the previous studies.

### **Management and species diversity scenarios**

Three management alternatives were used: no management (NO); plentering (PL), and age-class forestry (AC). Treatments were conducted in 10-year intervals. For the AC method, thinning intensity was set to 10% and clear-cuts performed at stand age 120. The detailed settings of PL can be found in Table A1 (appendix of this chapter).

**Table 1.** Sites along an environmental gradient used in the study, their location, elevation, and altitudinal zone, their long-term mean temperature (Temp.) and precipitation sums (Prec.) and their bucket size (BS) and available nitrogen (AvN) as used as FORCLIM input.

Site	Lat. [°N]	Lon. [°E]	Elevation [m a.s.l.]	Altitudinal zone	Temp. [°C]	Prec. [mm]	BS [cm]	AvN [kg·ha <sup>-1</sup> ]
Bever	46.6	9.9	~1710	Subalpine	2.3	838	10	60
Davos	46.8	9.8	~1590	Subalpine	3.0	1030	10	60
Adelboden	46.5	7.6	~1320	Altimontane	4.9	1260	15	80
Bern	46.9	7.4	~570	Submontane	8.4	951	20	100
Cottbus	51.8	14.3	~80	Planar	8.5	535	24	60
Basel	47.5	7.6	~320	Colline	9.3	740	15	80

A spin-up of 1500 years was conducted for NO and PL simulations to ensure stands were mature and in equilibrium with current climate. For AC simulations, the model was spun up for 80 years to allow stands to grow to the age typical of current Swiss forests. The prescribed management was also used in the spin-ups.

For species diversity three alternatives were chosen: stands where all 30 species parameterized for Europe in FORCLIM were eligible for establishment (ALL); stands consisting of only the 2-4 dominant species of the current potential natural vegetation (PNV); and monocultures (MONO) of the species currently most abundant at these locations (Table 2). Regeneration was allowed to occur naturally, but was restricted to the species of the respective diversity scenario.

**Table 2.** List of tree species used in the monoculture and potential natural vegetation (PNV) simulations. For monocultures the currently dominant species (Bachofen et al., 1988) at the sites was chosen. PNV is according to Ellenberg and Klötzli (1972) and Krausch (1992).

Site	Monoculture	PNV
Bever	<i>Pinus cembra</i>	<i>Larix decidua</i> , <i>P. cembra</i> , <i>Pinus montana</i>
Davos	<i>Picea abies</i>	<i>L. decidua</i> , <i>P. abies</i>
Adelboden	<i>P. abies</i>	<i>Abies alba</i> , <i>F. sylvatica</i> , <i>P. abies</i>
Bern	<i>Fagus sylvatica</i>	<i>F. sylvatica</i> , <i>P. abies</i>
Basel	<i>F. sylvatica</i>	<i>F. sylvatica</i> , <i>Quercus</i> sp.
Cottbus	<i>Pinus sylvestris</i>	<i>F. sylvatica</i> , <i>P. sylvestris</i> , <i>Quercus</i> sp.

**Table 3.** List of climate change scenarios used: The institutions that produced them, the abbreviation used in the simulations, mean anticipated temperature ( $T_m$ ) and precipitation ( $P_m$ ) changes from year 2000-2100, and changes anticipated only for summers (June-August).

Institution	Abb.	RCM	$\Delta T_m$	$\Delta P_m$	$\Delta T_s$	$\Delta P_s$
Royal Netherlands Meteorological Institute	KNMI	RACMO2	+3.5°C	+5%	+4.3°C	-12%
Swedish Meteorological and Hydrological Inst.	SMHI	RCA30	+4.0°C	-	+3.8°C	-14%
Max-Planck-Institute for Meteorology	MPI	CLM	+4.3°C	+2%	+4.7°C	-9%

## Climate change scenarios

To represent the anticipated change in climate, we used spatially interpolated data from the Landscape Dynamics Unit at WSL. For this dataset (resolution 1 km), three different Regional Climate Models nested in the General Circulation Model ECHAM5 were used to derive climate data based on the IPCC (2007) AR4 scenario A1B (Table 3).

We chose the nine cells covering and surrounding our six locations and proceeded as described in section 2.2. To derive anomalies, we used the periods 1950-2000 for KNMI, 1961-2000 for SMHI and 1960-2000 for MPI (see Table 3 for acronyms) from the WorldClim dataset (Hijmans et al., 2005) as baseline periods (as prescribed by the models) and the period 2075-2100 as representative for future conditions. We then calculated the absolute (temperature) and relative (precipitation) seasonal changes between the two periods. We assumed that the changes proceed linearly over a period of 100 years from 2001 to 2100 and that climate would stay constant thereafter until the end of the simulation in 2300.

## Indicators of ecosystem goods and services

The Millennium Ecosystem Assessment report mentions four categories of EGS: provisioning, regulating, cultural and supporting services (Hassan et al., 2005). From each of these categories we chose one indicator that could be assessed with FORCLIM, deliberately narrowing the choice to those that could reliably be estimated by the model. The small number also ensured that we could assess each indicator individually without having to aggregate results and thus maybe miss a signal.

For the provisioning services we chose total basal area harvested per hectare ( $\text{m}^2 \cdot \text{ha}^{-1} \cdot \text{a}^{-1}$ ). For regulating services we chose biomass per hectare ( $\text{t} \cdot \text{ha}^{-1} \cdot \text{a}^{-1}$ ) to assess the potential for carbon sequestration and thus climate regulation. For cultural services we chose a stand diversity index (SDI), representing the fact that diverse forests are usually perceived to be more aesthetically pleasing than even-aged stands (e.g. Carvalho-Ribeiro and Lovett, 2011). SDI was calculated following a suggestion by C. Elkin (personal communication, modification of an index by Jaehne and Dohrenbusch (1996)). It was designed to facilitate the comparison of forest stand heterogeneity with easily measurable data and considers species, age-class (cohorts), and height diversity in a stand:

$$\text{SDI} = \# \text{species} \cdot \# \text{cohorts per species} \cdot \text{StDev}(\text{height}) \quad (1)$$

Lastly, for supporting services necessary for the production of all other ecosystem services we chose productivity in terms of volume growth ( $\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{a}^{-1}$ ).

### Simulation studies and statistical analyses of results

To quantify the magnitude of change in the provision of our chosen EGS we used a modified version of Whittaker's (1952) similarity index. It was used to calculate the difference between the climate change and the corresponding non-climate change simulation of each scenario. In our version of the index ("relative semblance"), changes for the better (e.g. a higher productivity) result in positive values up to 1, changes to the worse in negative values down to -1, and no change equals 0:

$$\text{Relative semblance} = \left( 1 - \frac{\sum_{i=1}^n (x_i - y_i)}{\sum_{i=1}^n (x_i + y_i)} \right) - 1 \quad (2)$$

With  $n$  = number of observations (31, see below),  $x$  = observations from simulation with climate change,  $y$  = observations without climate change. Observations were taken at a decadal time step, so that the relative semblance was based on 31 values (years 2000-2300). With three management alternatives (NO, PL, AC), three species diversity alternatives (ALL, PNV, MONO), three climate change alternatives (KNMI, SMHI, MPI), and four indicators, a total of 108 relative semblance values per site were calculated.

To compare the scenarios (= unique combination of alternatives, e.g. ALL-NO-KNMI), we grouped the values first based on the management alternative used, then on the species, and lastly on the climate change scenario used. The subgroups were then

compared using a Kolmogorov-Smirnov test to assess whether one alternative yielded significantly different relative semblance values than another, and whether they significantly diverged from the value 0 (= no change).

Other approaches to statistically analyze the results, such as fitting linear models of generalized least squares directly to the time series of the indicators, were rejected, as sigmoidally shaped and other non-linear trends could not be accounted for, and because it would not have been possible to compare the different scenarios to a reference state.

In a last step, we calculated correlation coefficients between the relative semblance values of all 162 simulations (6 sites, 27 scenarios per site) for each indicator and the simulated bioclimatic variables influencing tree growth in ForCLIM (minimum winter temperature, annual/seasonal degree days and annual/seasonal drought index) to evaluate possible general patterns underlying the trends in relative semblance.

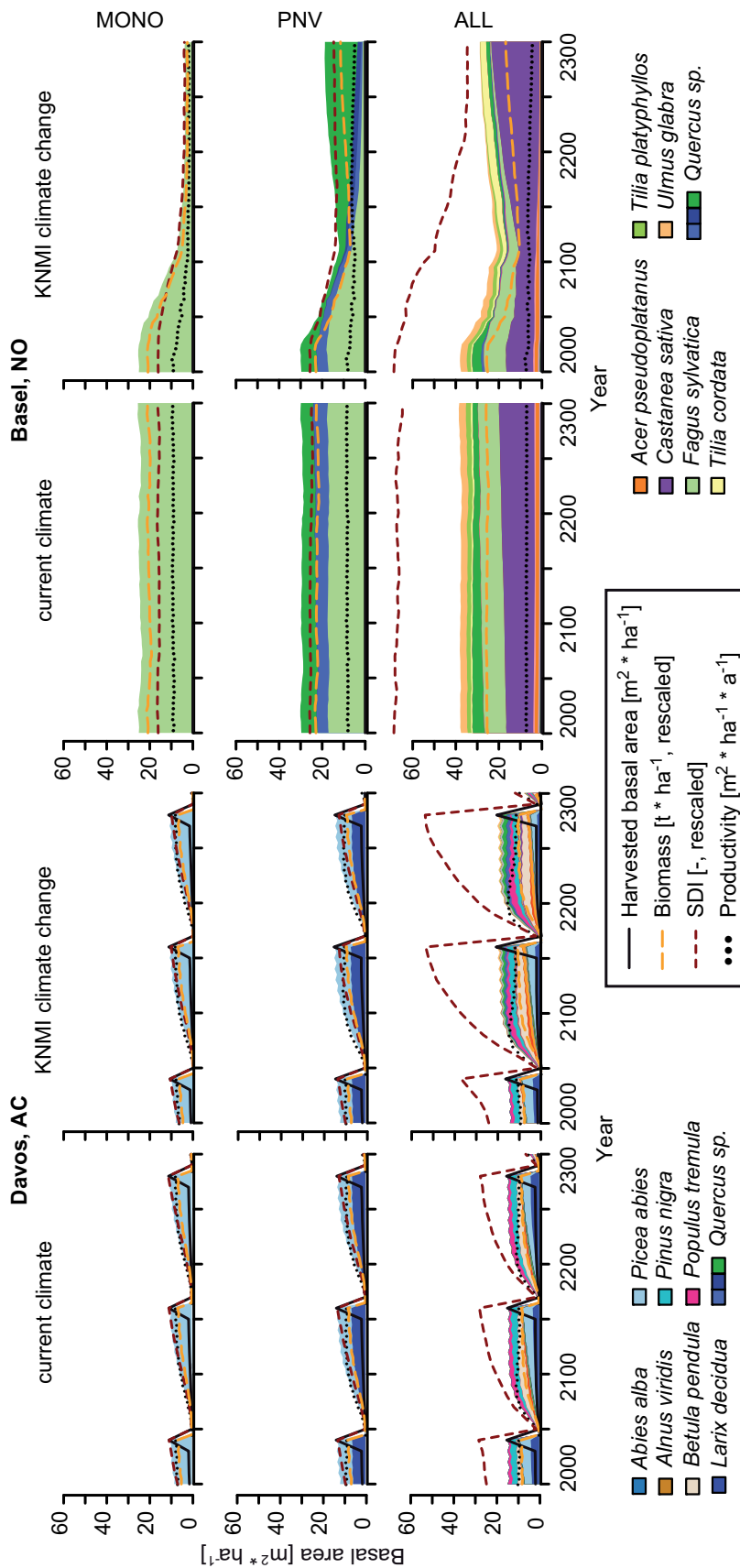
## **Adaptive management scenarios**

At sites where a scenario performed significantly worse than other scenarios (relative semblance significantly below 0 and below other scenarios) we created adaptive management measures targeting the responsible factor. On three sites this concerned the factor species diversity with the alternative MONO, on two sites management with the alternative PL, and on one the alternative AC. Monocultures were treated by replacing the original species with a species more suitable for the changed climate (here the dominant species in the ALL simulations under climate change) which was introduced after the first clear-cutting in AC scenarios, and gradually after the year 2000 in NO and PL scenarios. On sites where management was the decisive factor, thinning intensity was increased (see Table A2, appendix of this chapter, for detailed settings). Results of the adaptive management simulations were evaluated as described in section 2.6.

# **Results**

## **Example of unprocessed results**

To facilitate the understanding of the aggregated results reported below, two examples of the underlying unprocessed data are provided (Fig. 1).



**Fig. 1.** Examples of the underlying data used for the calculation of relative semblance. Left: development of species basal area, harvested basal area, biomass, stand diversity and productivity at Davos (management: age class forestry), right: Basel (unmanaged). Top panels: monocultures; center panels: dominant species of the PNV; bottom panels: all 30 species. The values of the indicators correspond to the y-axis scale, yet with different units (see legend). The units of biomass and SDI were rescaled to fit the axis (biomass/10; SDI/1000000).

The figure shows the development of species-specific basal area and the four chosen indicators in Davos and Basel. Each indicator clearly responded to the effects of climate change, some more pronounced than others, and some markedly influenced by the scenario considered. In Davos e.g., the climatically induced changes in SDI were much larger in ALL stands than in monocultures, resulting in relative semblance values of  $>0$  for the ALL, and near 0 for the MONO scenario.

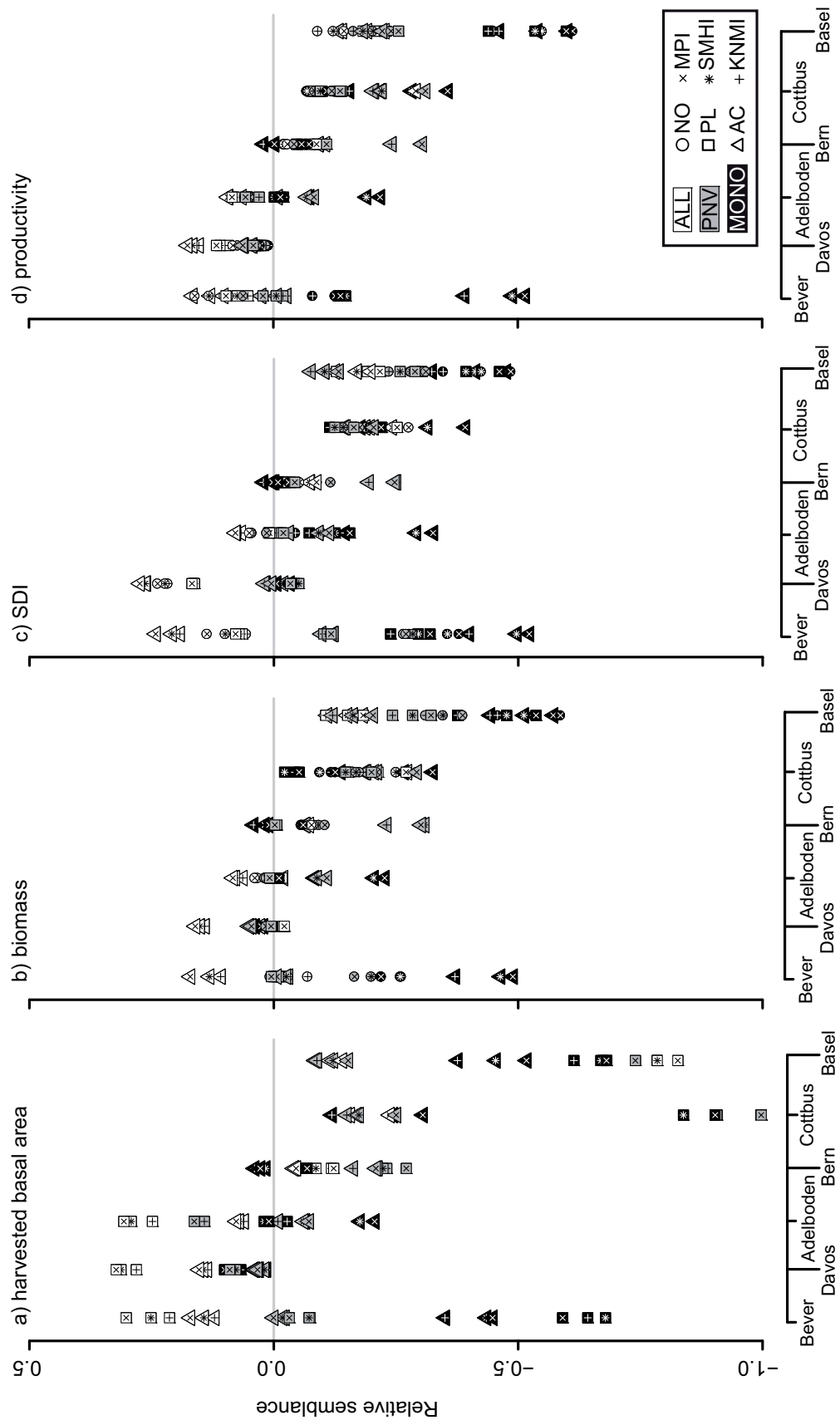
For an overview of the results described below see Table 4.

### Harvested basal area

Total harvested basal area increased for most scenarios in Bever, Davos and Adelboden, and decreased for most in Bern, Cottbus and Basel (Fig. 2a). In Bever, especially scenarios with monocultures suffered losses, and both monocultures and PNV stands declined in their harvest numbers below levels of 2000. In Davos all scenarios rose above their levels of 2000, with very diverse stands (ALL) rising significantly higher than those with fewer species numbers. In Adelboden only ALL stands rose above the harvest levels of 2000, whereas the other scenarios did not change significantly from their 2000 levels. In Bern only monocultures retained the level of 2000, whereas stands with more than one species declined significantly in their harvested basal area. Lastly, both in Cottbus and Basel all scenarios showed a significant decline in harvested basal area, yet scenarios with the plentering (PL) management alternative were doing significantly worse than others.

**Next page: Fig. 2.** Relative semblance values of each simulated scenario at six different sites for the four indicators harvested basal area (a), biomass (b), SDI (c), and wood productivity (d). Relative semblance was calculated between the indicator value in the simulation without climate change, and the simulation with a climate change scenario (as shown in Fig. 1). Scenarios can be identified by their symbol: a black triangle with a star e.g. would be the scenario monoculture managed with age-class forestry under the climate change scenario SMHI. Thick grey line: level of 2000, corresponding to “no change”.

The most obvious pattern in this graph is that black symbols (monocultures) are usually found at lower relative semblance values than grey (PNV) and white ones (ALL).



### **Biomass**

Only in Davos did the relative semblance of biomass stay near 0 or rise to positive values for all scenarios (Fig. 2b). On all other sites in most scenarios biomass declined relative to the levels of 2000. In Bever only very diverse (ALL) and also age-class managed stands did not fall below the level of 2000, whereas all other scenarios yielded negative relative semblance values. In Adelboden unmanaged stands rose significantly above the level of 2000, whereas other factor alternatives had no significant effect. In Bern all scenarios besides those with either age-class forestry or the monoculture alternative fell below 0. In Cottbus and Basel all scenarios performed worse than in 2000, with monocultures performing better than diverse stands in Cottbus, and worse than diverse stands in Basel.

### **SDI**

Stand diversity increased only for a few scenarios in Bever, Davos and Adelboden, and decreased for all others (Fig. 2c). In Bever and Adelboden highly diverse stands (ALL) experienced a rise in SDI, whereas PNV stands experienced a slight, and monocultures a strong decline. In Davos, ALL stands experienced a significant rise in SDI compared to stands with a lower diversity, and were the only ones to rise significantly above the level of 2000. In Bern the trend was reversed: only monocultures did not differ significantly from their level in 2000, whereas the more diverse stands were below this mark and also performed significantly worse than monocultures. In Cottbus all scenarios declined below the level of 2000, but did not differ strongly among each other. In Basel stands with more than one species experienced a slight decline compared to the levels of 2000, monocultures a significantly stronger one. SDI was neither influenced significantly by management nor climate change scenario alternative.

### **Productivity**

Productivity declined under climate change on most sites. In Bever and Adelboden ALL stands developed to be significantly above, monocultures significantly below the levels of 2000 (Fig. 2d). ALL stands also had significantly higher relative semblance values than PNV stands, which themselves had significantly higher values than monocultures.

In Davos, productivity uniformly rose significantly above the level of 2000, with very diverse stands showing the highest values. In Bern and Cottbus all scenarios

decreased significantly below the level of 2000, but did not differ between themselves in Bern. In Cottbus AC-managed stands performed significantly worse than the others. In Basel there was a uniform decline below the level of 2000, yet ALL and PNV stands had significantly higher relative semblance values than monocultures.

**Table 4.** Results of the Kolmogorov-Smirnov test comparing simulations of one scenario to another for each of the four indicators. + better than; - worse than; x no significant differences; NC: level of indicators in year 2000 (→ relative semblance of 0, **no change**). Shaded cells indicate those scenarios for which an adaptive management scenario was devised.

	Management			Species diversity			Climate change		
	NO	PL	AC	ALL	PNV	MONO	KNMI	SMHI	MPI
<b>Harvested BA</b>									
Bever		x	x	+NC +PNV +MONO	-NC -ALL +MONO	-NC -ALL -PNV	x	x	x
Davos		+NC	+NC	+NC +PNV +MONO	+NC -ALL	+NC -ALL	+NC	+NC	+NC
Adelb.		+NC	x	+NC +MONO	x	-ALL	x	x	x
Bern		-NC	x	-NC	-NC -MONO	+PNV	-NC	-NC	-NC
Cottbus		-NC -AC	-NC +PL	-NC	-NC	-NC	-NC	-NC	-NC
Basel		-NC -AC	-NC +PL	-NC	-NC	-NC	-NC	-NC	-NC
<b>Biomass</b>									
Bever	-NC - PL	-NC +ALL	x	x	-NC	-NC	-NC	-NC	x
Davos	+NC +PL -AC	-NO -AC	+NC +NO +PL	x	+NC	+NC	+NC	+NC	+NC
Adelb.	+NC	x	x	x	x	x	x	x	x
Bern	-NC -PL	+NO	x	-NC	-NC	x	-NC	-	-NC
Cottbus	-NC	-NC	-NC	-NC -MONO	-NC -MONO	-NC +ALL +PNV	-NC	-NC	-NC
Basel	-NC	-NC	-NC	-NC +MONO	-NC +MONO	-NC -ALL -PNV	-NC	-NC	-NC

Table 4. cont.

	Management			Species diversity			Climate change		
	NO	PL	AC	ALL	PNV	MONO	KNMI	SMHI	MPI
<b>SDI</b>									
Bever	x	x	x	+NC +PNV +MONO	-NC -ALL +MONO	-NC -ALL -PNV	x	x	x
Davos	x	x	x	+NC +PNV +MONO	-NC -ALL +MONO	-NC -ALL	x	x	x
Adelb.	x	x	x	+NC +PNV +MONO	-ALL +MONO	-NC -ALL -PNV	x	x	x
Bern	-NC	-NC		-NC	-NC -MONO	+PNV	-NC	-NC	-NC
Cottbus	-NC	-NC	-NC	-NC -PNV	-NC +ALL	-NC	-NC	-NC	-NC
Basel	-NC	-NC	-NC	-NC +MONO	-NC +MONO	-NC -ALL -PNV	-NC	-NC	-NC
<b>Productivity</b>									
Bever	x	x	x	+NC +PNV +MONO	-ALL +MONO	-NC -ALL -PNV	x	x	x
Davos	+NC	+NC	+NC	+NC +PNV +MONO	+NC -ALL	+NC -ALL	+NC	+NC	+NC
Adelb.	x	x	x	+NC +PNV +MONO	-ALL	-NC -ALL	x	x	x
Bern	-NC	-NC	-NC	-NC	-NC	-NC	-NC	-NC	-NC
Cottbus	-NC +AC	-NC +AC	-NC -NO -PL	-NC	-NC	-NC	-NC	-NC	-NC
Basel	-NC	-NC	-NC	-NC +MONO	-NC +MONO	-NC -ALL -PNV	-NC	-NC	-NC

## Adaptive management scenarios

The factors that were identified as responsible for the worst results were singled out and adaptive management strategies devised (see section 2.7). For the indicator harvested basal area this concerned monocultures in Bever and PL-managed stands in Cottbus and Basel, for the indicator biomass monocultures in Basel, for the

indicator SDI monocultures in Bever, Adelboden and Basel and for the indicator productivity monocultures in Bever and Basel and AC-managed stands in Cottbus.

Fig. 3 shows that most simulation results were positively influenced by the adaptive management measures. In Bever relative semblance of harvested basal area in monocultures rose significantly above the level of 2000 and did not differ significantly from the more diverse stands anymore (Fig. 3a). In Cottbus and Basel relative semblance values of harvested basal area rose with an increase in management intensity, yet not to the level of AC-managed stands.

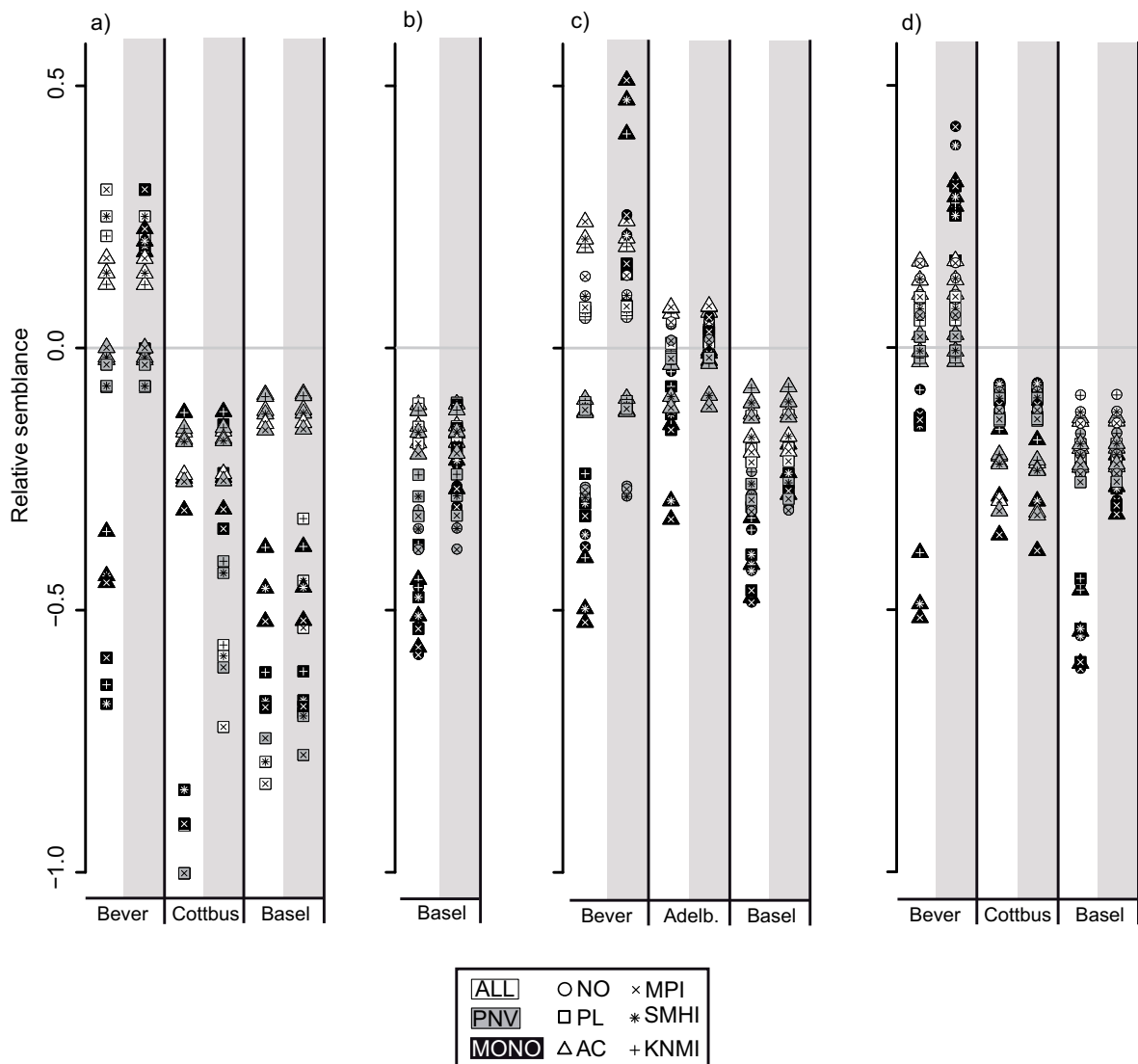
The relative semblance of biomass in Basel (Fig. 3b) could be increased to the levels of the more diverse stands, which also applied to the indicator SDI (Fig. 3c). In Bever and Adelboden relative semblance values of SDI rose significantly above the level of 2000. Values for productivity could also be improved: In Bever monocultures now outperformed the more diverse stands, whereas in Basel monocultures rose to the level of the more diverse stands. In Cottbus, however, where adaptive management measures targeted the management intensity, there was no improvement (Fig. 3d).

### **Correlation of relative semblance to climate parameters**

The change in seasonal drought index from current to future climate was significantly correlated with the relative semblance values of all indicators and consistently reached the highest values of adjusted  $R^2$ . The change in annual degree days and annual drought index showed significant correlations for the values of all indicators except harvested basal area, whereas the change in seasonal degree days only showed a significant correlation with that indicator. There was no significant correlation with minimum winter temperature (Fig A1, appendix of this chapter).

## **Discussion**

The aim of this study was to systematically vary combinations of different management, climate change and species diversity alternatives to create enough data to statistically quantify the influence of each factor group. Two pervasive patterns emerged: Firstly, at subalpine and montane sites (Bever, Davos, Adelboden), the relative semblance tended to rise, whereas at lower montane and colline sites (Bern, Cottbus, Basel) it tended to fall; a result in agreement with e.g. the simulation studies by Nabuurs et al. (2002), Loustau et al. (2005), Lexer and Seidl



**Fig. 3.** Relative semblance values of the four indicators harvested basal area (a), biomass (b), SDI (c), and wood productivity (d) simulated with the original scenario setting (left, not shaded), and an adaptive management setting (right, shaded). Symbols as in Fig. 2.

(2009) and Seidl et al. (2011). This pattern was linked to the magnitude of future drought, which is in agreement with earlier studies (Ciais et al., 2005).

Secondly, the drier the location, the bigger the variance in relative semblance values tended to be, meaning that under optimal conditions – approached in Davos under climate change – the scenario was unimportant. Under non-optimal conditions, sensitivity to climate change differed between scenarios, with the most influential factor mainly being species diversity.

## Key factors determining future EGS provision

### Species diversity

Species diversity significantly influenced SDI on all, harvested basal area and productivity on four, and biomass on two of six sites. This result is in agreement with e.g. Díaz et al. (2005), who wrote that carbon sequestration and productivity among others are frequently affected by biodiversity. Field studies typically showed that productivity increased with biodiversity, often leveling off at high levels (Cardinale et al., 2007; Hooper et al., 2005). Also demonstrated was a positive relationship between tree species richness and timber yield in tropical forests (Potvin and Gotelli, 2008).

Loreau and Hector (2001) attributed these facts to two types of effects: The “complementary effect” (inter-specific interactions or niche partitioning lead to a more efficient use of resources and thus to enhanced ecosystem functioning), and the “selection effect” (the higher the species number, the higher the probability that the most productive species is present). Morin et al. (2011) in a virtual experiment identified the complementarity effect as most influential: Gaps in forests were filled faster with a higher diversity in shade tolerance and growth ability present. The study did not consider climate change, but it is postulated that these species traits together with drought resistance will also determine the sensitivity of ecosystems in a changing climate (Díaz et al., 2005; e.g. Drever et al., 2006; Elmqvist et al., 2003; Hooper et al., 2005; Peterson et al., 1998).

Considering this it is almost surprising that of the overall 16 cases where species diversity was the decisive factor in our study, monocultures performed significantly worse than more diverse stands only in 7 cases. Yet e.g. Cardinale et al. (2007), Jacob et al. (2010), and Morin et al. (2011) also report that monocultures formed by the “right” species (most productive species under the specific environmental conditions) can outperform diverse stands. We saw this effect in Bever, when we replaced *Pinus cembra* with *Fagus sylvatica* in the adaptive management setting and improved the relative semblance of productivity beyond the level of more diverse stands.

We conclude that for the indicators harvested basal area, SDI and productivity species diversity is the most influential factor regarding sensitivity to climate change.

And even though stands with more than one species on average retain higher levels of EGS, this is not always the case.

### **Choice of management alternative**

Management significantly influenced the amount of harvested basal area retained under climate change at the warmer and drier sites of our climatic gradient (Cottbus, Basel): Age-class managed forests retained higher values of their former harvesting numbers than PL managed ones, even though both management alternatives could not avert a decline under the levels of the year 2000. The different results were most likely due to the implementation of the plentering routine: harvesting actions are only executed as long as the actual basal area is higher than the desired one. With a decreased growing stock (in this case due to drought) steady harvesting numbers can no longer be produced. In the adaptive management setting we thus reduced the desired residual basal area, gaining a rise in relative semblance values; yet it stays to reason if this is a desirable course of action, as timber is usually of secondary importance to a stable stand structure in plenter forests, which often serve as protection forests against gravitational hazards (Ott et al., 1997).

Concerning biomass, the choice of management was of importance mainly at the colder and wetter sites (Bever, Davos, Bern). In all three cases age-class managed stands retained more or increased their biomass more than unmanaged or PL-managed stands. In PL-managed stands, the reason for this was most likely again the objective of the management: to keep the growing stock stable at all times. Unmanaged stands, on the other hand, were not subjected to regular disturbances to promote regeneration and growth and thus most likely could not match AC-stands in this regard. The result suggests that management is of primary importance when carbon sequestration in biomass is a goal.

It is unexpected that SDI was not influenced more strongly by management. Even though the number of species was not controlled by management in our setting, the distribution of tree heights should have been influenced: In FORCLIM, changing light conditions lead to a change in allocation of volume growth to diameter and height growth, yet it seems that climate change did not lead to big changes in the light profile of stands.

Overall, in comparison to other simulation studies, like those of Eggers et al. (2008), Köhl et al. (2010) and Lindner (2000), with the exception of biomass the influence of

management in our study was rather small and we cannot attribute the highest influence to it. The authors of the cited studies, however, also looked at things like changes in species composition, an indicator we did not use but which would have shown marked differences between AC- and PL-managed stands in the ALL scenario. It should also not be forgotten that usually management is the factor controlling species composition in a managed forest stand, which would automatically make management the most influential factor (see e.g. Badeck et al., 2005; Lindner, 2000).

### **Choice of climate change scenario**

One factor that did not exert any significant influence on the change in EGS provision (represented by our four indicators) was the choice of climate change scenario. It may be that the only slight differences in temperature anomalies between the models were responsible for this, as Eggers et al. (2008) for example report noticeable differences in net annual increment between scenarios A1 and B1. However, the differences they produced with scenarios A1, A2 and B2 were much smaller; and Köhl et al. (2010) also reported little influence of either the A1B or the B1 scenario on timber volume and other stand characteristics in German forests; they concluded that management had a far greater impact on forest development than the climate scenario. Kardol et al. (2010) in their field study come to a similar conclusion, although the authors stress the importance of stand type in contrast to climate variability as the main driver of change.

We are aware that both the magnitude as well as the effects of climate change on climate variability and extremes are very uncertain (Schär et al., 2004; Vidale et al., 2007), but based on our results and those of others we conclude that with the climate change scenarios available to modelers right now, the choice of a specific scenario presents a minor source of uncertainty when simulating into the future.

### **Adaptive forest management**

We devised simple adaptive management strategies at four sites, targeting the factor with the most negative influence on the retention of EGS. In three cases the factor was species diversity, i.e. monocultures, where we chose more appropriate species to replace the original ones, and found that doing so enhanced monoculture relative semblance to the level of more diverse stands. Badeck et al. (2005) and Kellomäki et al. (2008) recommend similar treatments for the retention of suitable levels of productivity. Another possibility would have been to introduce additional

species, yet we felt this was inappropriate: Monocultures will most likely form part of mitigation strategies in the future (as carbon sinks and convenient producers of renewable materials and fuels; FOREST EUROPE, 2011) and should therefore be retained as such.

When management (AC, PL) was the factor with the most negative influence, the best measure was not as straightforward. An increase in thinning intensity did lead to better results concerning harvested basal area, yet productivity could not be improved. In the latter case we conclude that a conversion of these even-aged stands to uneven-aged ones (PL) would be the best solution.

We emphasize that we only ‘treated’ stands that performed significantly worse than others at the same location. This means that in Basel, for example, MONO stands retained relative semblance values in the same range as ALL stands, yet both MONO and ALL stands performed worse under climate change than they did under the current climate. To retain EGS levels of today, other measure would have to be taken, e.g. introducing Mediterranean tree species.

## Methodological aspects

A study that is based on simulations depends heavily on the reliability of the model. FORCLIM is well-established and has been tested and validated many times over the last 15 years (e.g. Bugmann and Solomon, 2000; Didion et al., 2009; Rasche et al., 2011). However, CO<sub>2</sub> is not considered explicitly in the model, and any fertilizing effect it may have in future (e.g. Körner, 2006) is thus ignored. The effects of pests and other disturbances are implicit in the age-related background mortality (Bugmann, 1996), a function not changing with climate. However, the PICUS model, equipped with a bark-beetle submodel, delivered the same basic patterns as ours in a study conducted in the Eastern Alps (Lexer and Seidl, 2009; Seidl et al., 2011), giving us confidence in this regard.

For the statistical analysis of the results we chose to primarily rely on visual evaluations and a simple statistical test. The reasons for this were explained in section 2; but we want to emphasize that results produced with more sophisticated methods agreed with those of the simple method we finally chose.

Lastly, if non-tree based EGS had been considered, results may look very different, but those were beyond the scope of this exercise. We can only caution that our indicators, even though they cover all four categories of EGS detailed in the

Millennium Ecosystem Assessment, do not cover the whole range of responses that may be relevant in an applied context.

## Conclusions

We found that sensitivity generally changed from nearly non-existent at subalpine-montane, to high at colline sites, mainly depending on the increase in seasonal drought. The most influential factor in this was species diversity, with monocultures usually being most sensitive to impacts of climate change. Their performance increased significantly when the species was switched to a more suitable one early on. The change in biomass was more influenced by management alternative than species diversity, with age-class managed stands retaining or increasing their biomass significantly more under climate change than others. The choice of climate change scenario was unimportant at all six locations of the climatic gradient.

These findings are relevant for the planning of adaptive management measures, as they show that (i) for projections the choice of climate change scenario is almost arbitrary; (ii) diversity aspects deserve the emphasis put upon them; (iii) there are cases where other factors are more important; thus planning needs to be targeted; and (iv) at locations subject to increasing drought, the provision of EGS may suffer in the future regardless of stand characteristics.

This quantitative evaluation of the influence of different factors on changes in the provision of forest EGS under climate change represents an important step towards the design of more focused adaptation strategies and highlights factors that should be considered carefully in simulation studies under climate change.

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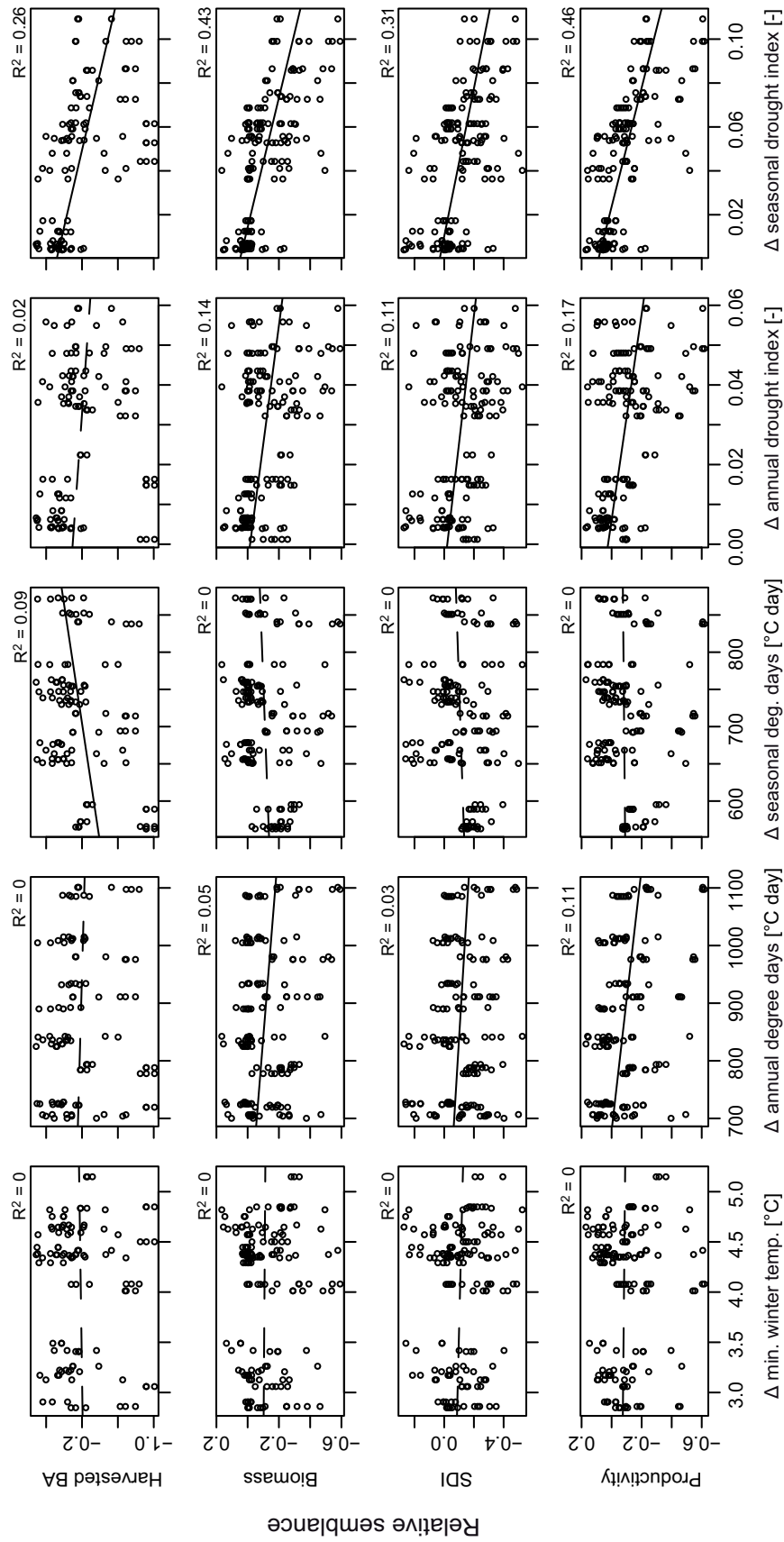
## Appendix

**Table A1.** List of parameters used in the PL (“plentering”) management alternative. The quotient between diameter classes ( $kQ$ ) and the desired maximum diameter in the stand ( $kTargetDBH$ ) were kept constant for all sites at default values. The parameter  $kResBA$  (desired basal area of stand which should be kept constant throughout) was set to 75% of the basal area reached when no management was applied.

Site	$kResBA$ [m <sup>2</sup> /ha]	$kQ$ [-]	$kTargetDBH$ [cm]
Bever	11	1.3	80
Davos	26	1.3	80
Adelboden	32	1.3	80
Bern	34	1.3	80
Cottbus	20	1.3	80
Basel	30	1.3	80

**Table A2.** Adaptive management scenarios developed after the evaluation of causes for negative trends in relative semblance

Site	Factor	Original setting	Adaptive management setting
Bever	MONO	<i>P. cembra</i>	<i>F. sylvatica</i>
Adelboden	MONO	<i>P. abies</i>	<i>F. sylvatica</i>
Cottbus	AC	Removal of 10%	Removal of 15%
	PL	$kResBA$ 20 m <sup>2</sup> /ha	$kResBA$ 13 m <sup>2</sup> /ha
Basel	MONO	<i>F. sylvatica</i>	<i>C. sativa</i>
	PL	$kResBA$ 30 m <sup>2</sup> /ha	$kResBA$ 20 m <sup>2</sup> /ha



**Fig. A1.** Relationship between relative semblance of harvested basal area, biomass, SDI and productivity and the change (current climate - future climate) in the five bioclimatic variables influencing tree population dynamics in FORCLIM (minimum winter temperature, annual/seasonal degree day sums, annual/seasonal drought index). Points: Relative semblance values of all scenarios on all sites; Lines: Results of correlation analysis, dashed: not significant, solid: significant. Correlation with the highest value of adjusted  $R^2$  was with  $\Delta DrSe$  for all indicators.

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# Synthesis

In this dissertation I aimed to develop a gap model into a tool suitable for dealing with questions concerning forest management under the influence of climate change, and to enable it to complement other tools to achieve the best possible decision support for stakeholder groups in the future. I wanted to assess if gap models are principally eligible for this kind of task and if they meet the expectations placed on hybrid models: to overcome the weaknesses of process-based and empirical models while combining their strengths to yield good results (Kimmins et al., 2010; Mäkelä, 2009). “Good” in this context meaning that the projection of yield and stand structure satisfies the demands of practitioners for accuracy.

For this task I used the gap model FORCLIM. I improved one of the core functions of the model, implemented an extensive submodel capable of simulating forest management and finally applied it to a problem pertaining to adaptive management planning in forestry in times of climate change.

## General evaluation of the results

Lindner (1998) concluded in his dissertation that gap models applied to simulate managed stands showed reasonable, yet not accurate enough results to be used in forest management. In his opinion they could be used to assess risks related to climate change, but still needed to be improved further, preferably by using long-term data from forest yield trial sites.

Since then some progress has been made in the development of gap models towards practical tools (e.g. Seidl et al., 2008), yet most gap models are still developed and used for the assessment of dynamics in natural forests. Thus, a decade after Lindner’s work with the FORSKA model, I started to follow in his footsteps and commenced with implementing forest management and with improving the depiction of management-related aspects of tree growth in another gap model, FORCLIM.

In Chapter I the nature and formulations of the management submodel were described, and also how it was tested against data from eight long-term growth and yield research plots. The focus of the tests was not only to reliably reproduce the values of species-specific basal area and stand density over time, but also to

accurately depict stand structure and timber yield. By doing so, I went beyond the common applications of gap models and ventured into territory usually reserved for empirical models.

In comparison to results usually achieved with site-calibrated empirical models the ones achieved with FORCLIM were underwhelming: Simulated basal area development between inventories usually followed the actual trend, yet it did not come very close to the absolute values of the measurements. The same applied to the simulated diameter distributions. In short-term tactical decision support, especially the latter poses a problem, since knowing the exact distribution of the trees over the diameter classes is of considerable economic interest, and a mismatch of one or two classes results in different return expectations.

And yet, the outcome presented in Chapter I was astonishingly good in the context that the model yielded the same quality of results for each of the eight research plots, despite FORCLIM not being calibrated to site conditions and the sites being located in climatically very different areas. This fact is a good indicator that FORCLIM is likely able to produce results of a similarly high quality in simulations under climate change. Furthermore, if the limitations discussed at length in Chapter I are kept in mind when evaluating these results, nothing truly prevents the utilization of FORCLIM for long-term strategical planning in forestry.

The model improvements that have been presented in Chapter II further encourage this view. Here, the formerly static relationship between diameter and height growth was abandoned in favour of a variable one depending on competition for light; and maximum height was converted from a parameter to a site-dependent variable. The tests and validations of the new model components showed that growth patterns could be depicted more realistically, while the model still retained its general applicability.

However, despite rendering more realistic results, the changes also highlighted an inherent problem in the calculation of tree growth in FORCLIM: The potential volume growth calculated with the FORCLIM growth equation is often estimated inaccurately. This was not as apparent when the distribution of volume growth to diameter and height growth still followed a fixed relationship, such as done in Chapter I. In these applications, only the diameter distributions were compared, whereas simulated tree heights were mostly ignored. The tests presented in Chapter II showed that

when both simulated tree diameter and height are compared to measured data, one of the variables usually ends up short. It thus seems that the changes described in Chapter II improved the simulation of growth trends and stand structure, yet revealed an area where more work has to be done (see recommendations at the end of this chapter).

In Chapter III, finally, the new, improved version of FORCLIM was applied to a problem that is characteristic of those that will need to be addressed by tools used in forest management planning in the near future. I examined which forest types are likely to be most sensitive to changes brought about by climate change, and thus will be in need of adaptive management interventions. I also evaluated how such successful adaptive strategies could look like. As indicators for sensitivity the change in harvested basal area, biomass, stand diversity and forest productivity were chosen. It was thus shown that FORCLIM, or gap models at large, are able to provide information on very different aspects of forests, a prerequisite for tools used in forest management planning. The chapter also showed that it is possible to use gap models to provide support concerning long-term strategical planning in forestry, and this again at climatically very different sites.

## Methodological aspects

### Choice of model

In the introduction it was explained in some detail why FORCLIM was chosen for this study. The question arises if another gap model might have yielded significantly different results, and thus influenced the conclusion of this dissertation, that gap models are suitable tools for long-term strategical planning in forestry. I do not think that this is the case. Marcus Lindner, for example, came to much the same conclusion in his dissertation regarding FORSKA (Lindner, 1998); and the ability to simulate managed forests could also be demonstrated for example for 4C (Lasch et al., 2005) and other models mentioned in the Introduction of Chapter I. This is hardly surprising, as silvicultural interventions mainly influence the light regime of a forest stand, and thus the most important resource driving competition - and in extension forest dynamics - in most gap models.

The other question is if another model type altogether could have yielded better results. In my opinion this entirely depends on the question asked. If the goal of the user is to assess the yield of a stand over the next 5 to 15 years, a time span where the changes in climate are most likely going to be negligible in comparison to today, then a forest growth model will yield the most accurate results. These models are parameterized to each site specifically and based on a large amount of data to accurately predict reactions of stands to management under a constant climate. If the time span is longer, the introduction of different species is a possibility, and the aim is to get a feeling for the most appropriate course of action over the next century, then a climate sensitive model not limited to its parameterization database, such as a gap model, will yield the better results. Lastly, if the question remains the same, but only few species are considered and many parameters of the site in question are well known, then a process model may yield the best results, as effects of CO<sub>2</sub>-fertilization, for example, can be explicitly considered.

### **Choice of simulation experiments**

New model formulations and components need to be thoroughly tested, either against data from other models or against empirical data. It does not suffice in this context to merely test them for local accuracy; they should always also be tested for their general applicability. Some changes to model formulations yield very good results in one aspect, yet reveal severe disadvantages in the other. Models that claim practical application qualities should be able to produce good results on both levels.

In the simulation experiments described in this work, I therefore tried to keep both levels in mind and validated the model against long-term data from forest growth and yield research plots, national forest inventory data and estimations of the potential natural vegetation. All three data sources were of great help and complemented each other in their utility for the study.

### **Forest management**

The goal of developing a model capable of providing decision support in forestry requires the inclusion of management options. Before I started the implementation of this submodel I researched the most commonly employed silvicultural treatments in Switzerland and the surrounding countries, so as to be able to potentially offer decision support to any forest stand there.

Most of these treatments could be transferred in a straightforward manner into model equations and computer code, yet others proved to be more complicated or not possible to implement at all due to the nature of FORCLIM. The “crop tree” method (“Z-Baum-Methode”) is one of these examples. This is a rather widely used treatment in Switzerland, where in the pole stage of a stand promising crop trees are marked, keeping a certain minimum distance between individual crop trees; their crowns are then repeatedly released in the following years, thus eliminating competition for light and favouring their growth.

Such a method heavily depends on the spatial context; FORCLIM as a model where the position of trees on the patches is not known thus does not commend itself for the simulation of the crop tree method. Also, testing against long-term empirical data would have been impossible, as coordinates of trees were only recorded after 1970.

Two other methods where the spatial context plays an important role are the cutting methods “group selection” and “strip felling”. The goal when using one of these methods is to remove a number of adult trees in a constricted area in order to let light into the stand and thus facilitate regeneration. In FORCLIM, a number of patches are cleared of trees when using one of these methods, which does facilitate establishment on those patches, but not in the “surrounding” area. For this to happen, a grid would have to be implemented in FORCLIM where patches may interact with each other, particularly regarding the light regime (see e.g. Garman et al., 1992; Köhler and Huth, 1998).

Thinning is another treatment that in the current state of the model was not straightforward to implement. The technique of using a Weibull distribution-based stochastic function to select trees is based on the assumption that the diameter distribution of the stand in consideration portrays reality accurately at any time. This condition has to be met because the distribution used to select the trees to be thinned is “attached” to the lower end of the total diameter distribution. FORCLIM, however, operates on the assumption of unlimited seed supply and thus allows many more species and tree cohorts to establish than can actually thrive on the patch. These trees die very quickly of stress, yet their mere presence distorts the selection of trees to be thinned. The problem has been solved by ignoring trees below a certain callipering limit, yet it would still be good if the entire diameter distribution simulated with FORCLIM actually corresponded to “realistic” values.

## Evaluation of model output

Models in forestry are often measured by their compliance with empirical data. It is, however, often not easy to conclusively determine if simulated data comply with measured ones. Statistical tests can be very helpful in this context, yet their conditions are not always met, and the often present autocorrelation in the data further complicates matters.

One method to deal with this issue is to visually assess the results and subjectively decide if a fit is adequate or not. A modeler concerned with projecting the yield of a specific stand over five years with a model especially fitted to this stand may consider the results of a gap model to be wholly inadequate. Others may be amazed at how good results can be using a model that is not fitted in any way to the location and therefore is able to yield much the same quality of results for a number of different locations.

In essence, even though I tried to assess model results objectively using appropriate tests, I am still of the opinion that everyone should judge for themselves if the results meet their standards. Test results in this context might serve as decision support, but nothing more.

## Recommendations for further research

Some recommendations have already been given elsewhere in the thesis, but for clarity's sake they will be summarized here.

1. The results of Chapter I and Appendix III and IV suggest that growth rates for some species and some locations are not realistic and that the source of this problem is most likely located either in the parameterization of the growth rate or in the reduction of optimum growth due to environmental constraints. I would therefore suggest analyzing this problem more closely and testing possible solutions either against data from forest reserves<sup>3</sup> or from growth and yield research plots located in the subalpine zone, as the problems are most pronounced there.

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<sup>3</sup> For a preliminary simulation study with forest reserve data see Appendix IV of this dissertation.

2. The assumption of unlimited seed supply poses a problem in situations where it is important to have realistic tree numbers in the lowest diameter classes; this assumption should therefore be reconsidered (see e.g. Wehrli et al., 2007, for suggestions).
3. It would be advantageous to implement a soil submodel (see e.g. Bugmann, 1994), so as to explicitly consider nitrogen dynamics. It is unrealistic that the amount of available nitrogen should stay constant over time, and it would have the added benefit that the reduction of the variable *gHMax* could also be linked to nitrogen availability (as a proxy of soil fertility) at a site.
4. The inclusion of pests and other disturbances that may change in intensity with a changing climate would improve the acceptance of the model as a tool. The background mortality as a 'blanket' function to cover all these agents does not seem satisfactory under the assumption of a changing climate.
5. Muys et al. (2010) state that a good visualization of simulation results is key to reaching stakeholders and that good decision support models should in this context be customized to the needs of the end-users. The development of a graphical user interface for FORCLIM that has been begun about a year ago (simulation software "ForSim") is a good step in this direction and should be pursued further, hopefully with input from possible end-users.
6. Kimmins et al. (2010) mention that decision support models should not only be focused on forest management, but also be able to consider economic and social issues. So it may be beneficial to some time in the future include an economic submodel into FORCLIM that automatically estimates costs and benefits of certain strategies.

## Conclusion

This work has shown that the potential of forest succession models is by no means fully realized and that it is still possible to significantly improve their performance through simple means. Furthermore, it was demonstrated that the models even at the current development stage are a useful complement to the range of decision support tools available in forestry today, and that they contribute to providing information for the alleviation of risks associated with climate change.

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# Appendix I

## Swiss forest growth and yield research plots

The network was established with the goal of monitoring tree and stand growth under various silvicultural treatments and site conditions over long periods of time. The first plots were founded in 1886 by Flury, and many others were added over time. The network is maintained by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL). It covers the whole of Switzerland from latitudes 45.51° to 47.44° N, longitudes 06.00° to 10.15° E and altitudes from 208 to 2150 m a.s.l.

The network consists of ca. 400 plots with areas from 0.05 to 10 ha and irregular shape. Their distribution over the country does not follow a systematic grid, rather plots were established to represent different forest types and also where land was available. The major land cover types thus sampled are broad-leaved, coniferous and mixed forests. Activities on the plots are supported by long-term management plans and the respective land owners.

Each plot is inventoried in intervals of 4 to 12 years, dependent on site quality and thus the expected speed of forest growth. The single tree data collected at every inventory include tree species, diameter [cm], status (alive, dead, harvested, etc.), tree coordinates (after 1970), compact wood [m<sup>3</sup>] and social position. Total height [dm] and height of crown base [dm] are recorded for a small fraction of so-called "sample trees".

For the model testing described in Chapter I we wanted data from forest stands with various species compositions, under various silvicultural treatments, and with early establishment dates (1930 and earlier). Thus we received data from 40 plots, from which eight were chosen according to the criteria mentioned in Chapter I.

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## Appendix II

### Initializing FORCLIM with single tree data

#### Initializing FORCLIM with simulated stand data

There are two ways FORCLIM can be initialized with existing single tree data. The first method is straightforward and simple: At the end of a simulation the relevant cohort data for each patch are written to an xml file. This comprises the species of the cohort, the age (*Start*), the number of trees (*Trs*), the diameter at breast height (*D*), the last diameter increment (*DInc*), the height (*H*), a factor relevant for the calculation of the crown-length ( $A_1$ ) and the number of years the cohort has been stressed (*SGr*). At the beginning of a second simulation, these data can be read in again to continue simulating with the same forest state as before.

#### Initializing FORCLIM with measured stand data

The second method is more complicated, as not model-produced tree data are used for initialization, but measured data from forest inventories. This distinction is relevant for two reasons: In the case of simulated stand data all cohort-specific parameters for all cohorts are known and can be passed on, thus facilitating an exact transfer of stand characteristics. This is not the case with inventory data, where in most cases only species and diameter of a tree are recorded – and sometimes its height – and not every tree is measured; only those above a certain callipering limit. The consequence is that firstly the other relevant cohort variables need to be estimated, thus prohibiting an exact transfer of stand characteristics, and secondly that establishment rates may not be simulated correctly due to the missing data on small trees below the callipering limit.

#### Distributing trees onto patches

Simulated stand data have a record of the patch number of every cohort, thus making sure that during an initialization every tree is assigned to the same patch it formerly grew on. This practice assures that the distribution in space follows ecologically sound principles, as it is unlikely that many small trees will grow on the same patch as one or a few very large and dominating trees. Inventory data, however, often miss spatial information, which is especially true for the early

inventories taken more than 40 years ago (cf. Appendix I). Unfortunately, these are the inventories that are most interesting for model initialization purposes, giving rise to the need of 'intelligent' methods for transferring inventory data into patch-vegetation data.

The first to encounter this problem with FORCLIM were Risch et al. (2005), who solved it by employing the structure generator STRUGEN of the forest growth model SILVA (Pretzsch et al., 2002). This tool can be used to read in inventory data, and from this stand data are generated while considering spatial interactions between trees based on expert knowledge that is built into STRUGEN. The synthetic stand generated by STRUGEN (typically 1 ha) that contains the exact coordinates of each tree can then be cut into smaller cells, each representing a patch with its vegetation. For reaching the desired repetition of runs needed in FORCLIM to reduce stochastic noise, a repetition of these steps is typically in order. This method is quite time-consuming, yet Heiri (2009), who employed this method in her study, stressed that this was a necessary step for correctly initializing FORCLIM with data from forest reserves, as these stands are very diverse and structurally complex.

In contrast to this, Wehrli et al. (2007; 2005) and Didion et al. (2009) in their studies assumed that their stands were spatially rather homogeneous, and they therefore perceived no need for an elaborate tool like STRUGEN to correctly initialize FORCLIM. Instead, with the help of the free statistical software R (R Development Core Team, 2010), they randomly distributed trees from the inventory data onto a certain number of patches, whose summed area amounted to the size of the sample plot. Subsequently, they copied these patches until 50 units (patches) were acquired.

For my work I used the latter method, knowing that the stands I used were rather poor in species diversity and more or less homogeneous, but with one slight difference: I did not simulate with only 50 runs, but with 50 copies of the original number of patches that once represent the sample plot area. In the paper Rasche et al. (2011) we felt that this was necessary to correctly compare simulation results to the inventory data, since we also assessed the results in terms of these evaluation units.

Concerning the initialization for diverse and complex stands, I am not convinced that STRUGEN is really needed. In Appendix IV of this work I initialized FORCLIM (using the random method) with forest reserve data – some the same that Heiri used – and the

diameter distributions at least were transferred correctly from the data into the model. The problems I encountered with the simulation results themselves – exaggerated mortality rates mainly – were the same that Heiri also noted, and they did not seem to be influenced by the manner of initialization. Hence I advise other users of FORCLIM to first test the far simpler method of random distribution of trees before employing STRUGEN, as the latter is a far more time-consuming method.

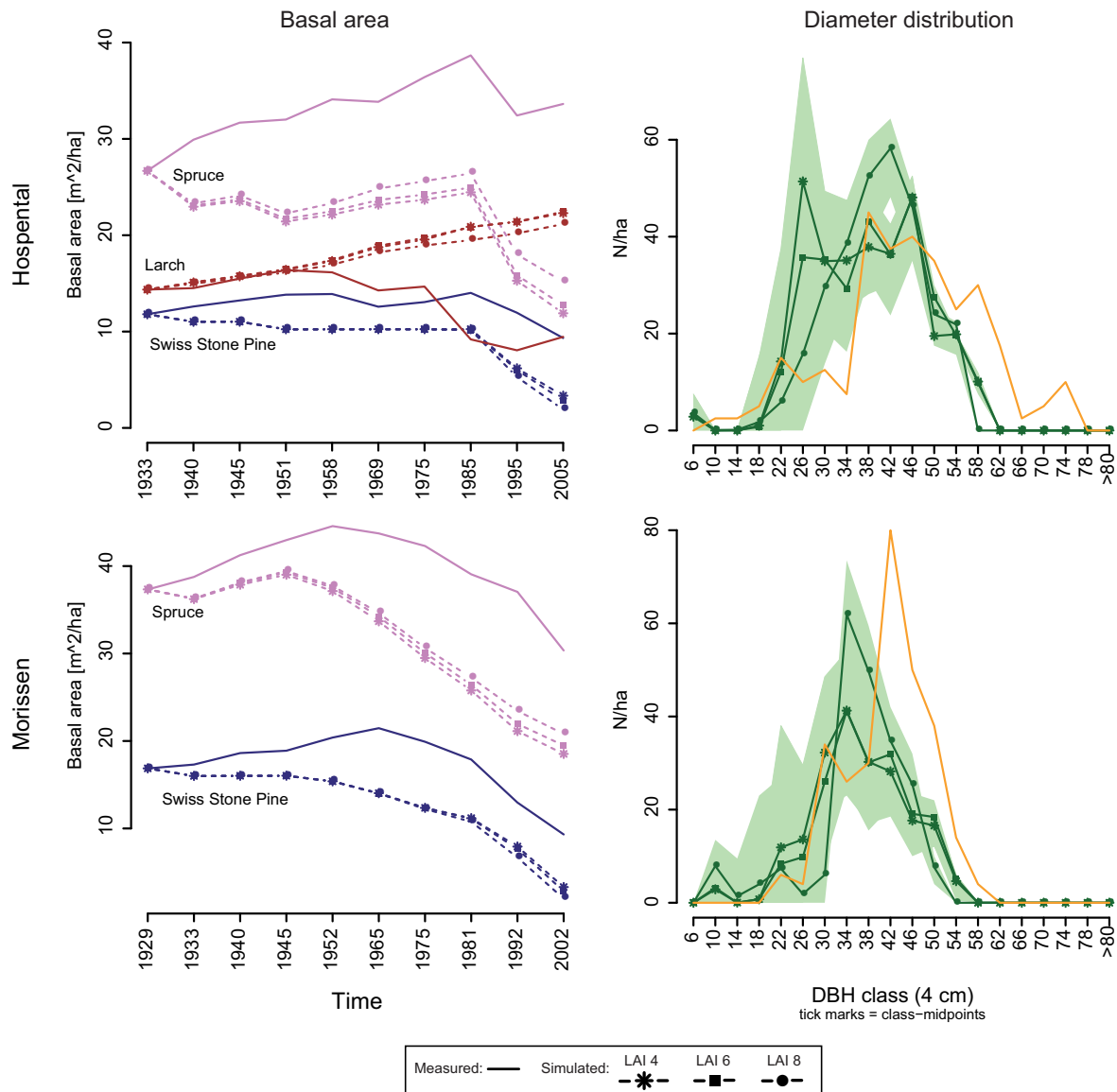
### **Estimating values for initial leaf area index (LAI)**

As mentioned above, it is necessary to estimate certain parameters when initializing FORCLIM with measured data. The most important of these is LAI, as it is required for calculating the variable  $A_1$  relating diameter to foliage area. Some stands are very sensitive to the estimated initial values of LAI (Fig. All-1). The most sensitive stands seem to be the ones dominated or co-dominated by beech (Fig. All-1, Aarburg, Zofingen, Winterthur, Galmiz, Horgen). This sensitivity not only pertains to the first few years, but is persistent through the whole simulation time, both for the development of basal area and the diameter distribution. Stands without beech (Fig. All-1, St. Moritz, Hospental, Morissen) are less sensitive concerning their basal area, but may be sensitive in their diameter distributions (Fig. All-1, Hospental, Morissen).

The reason for this is a problem in the initialization of the allometry between diameter and leaf area, which can be interpreted as a proxy of crown length, as implemented by Didion et al. (2009). At the beginning of a simulation the parameter  $A_1$  is set based on the estimated LAI of the cohort and other parameters. This parameter determines the transparency of the disc of leaves that is located – in the model – at the top of the tree), which can be reduced further during the simulation, but not be increased again. A reduced crown length reduces diameter growth (via *gCLGF*), and simultaneously increases the amount of light that is reaching the forest floor. Thus, if for example Aarburg is initialized with LAI 6, the tallest trees grow fast due to their long crown, whereas the growth of the small ones stagnates due to the poor light conditions. With time, the lower canopy trees grow even worse due to the ever more dominating few tall trees, and thus basal area stays relatively low. If initialized with LAI 10, however, the tall trees grow more slowly, the small ones better due to better light conditions in the lower canopy, and basal area rises.

This is not an optimal state of affairs. The underlying problem is that the assumed LAI does not need to agree with the calculated LAI once the allometries per cohort are initialized. It would be better to implement this as an iteration problem, i.e.

adjusting the allometries until calculated LAI converges to the prescribed LAI. A remaining problem, however, is that actual LAI values for any inventory are not known and need to be guessed. This is not very desirable given the sensitivity of model projections to this variable. However, so far only beech seems to be extremely sensitive to the matter.



**Fig. AII-1.** Species-specific basal areas (left panels) and overall diameter distributions in the final observation year (right panels) for three different settings of initial LAI. Green area in right panel: 2.5<sup>th</sup> and 97.5<sup>th</sup> percentile of simulated data.

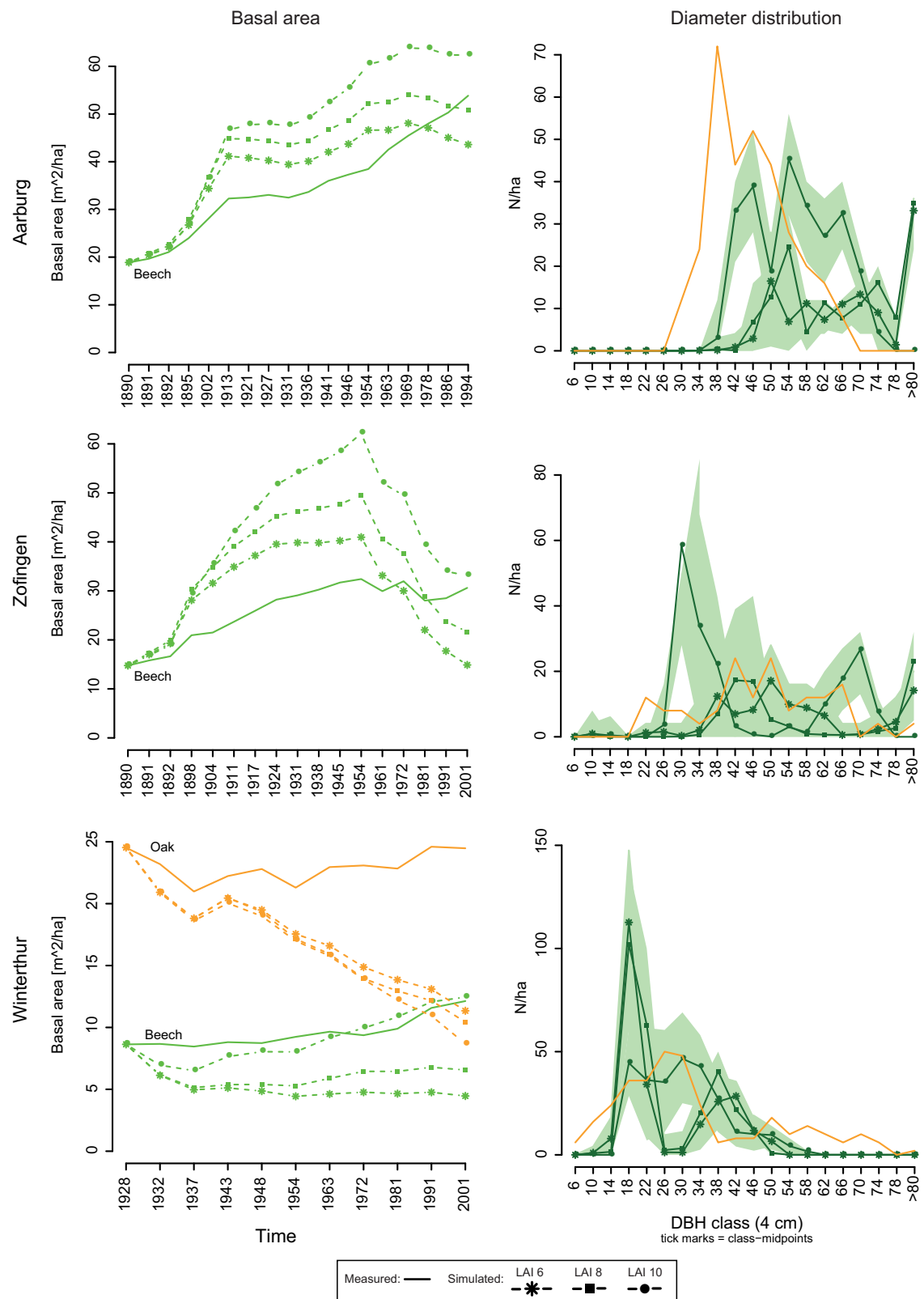


Fig. AII-1 continued

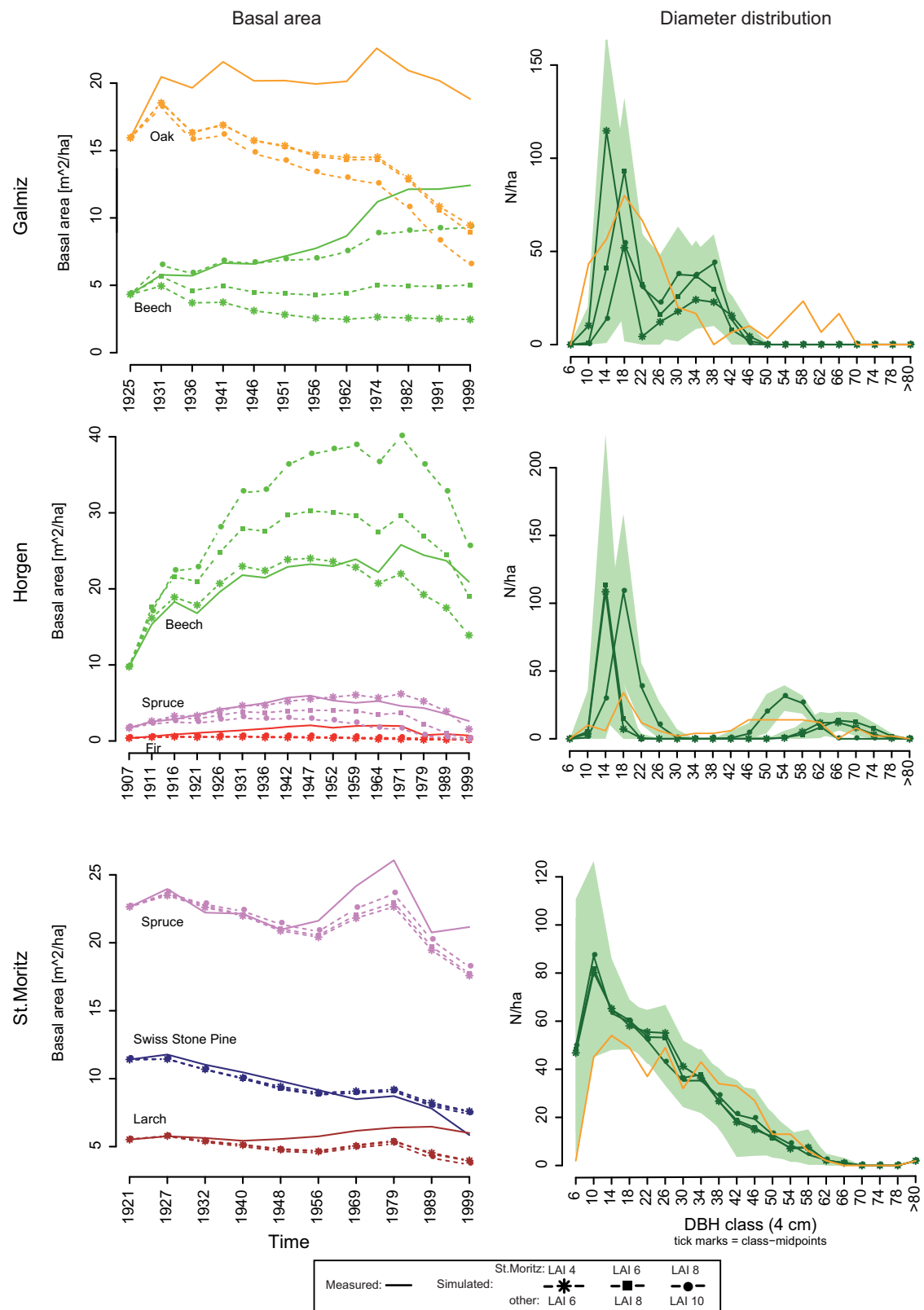


Fig. AII-1 continued

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## Appendix III

### Resimulating the development of the forest growth and yield research plots of paper 1 with FORCLIM v3.0

#### Introduction

Due to the uncertainty of how long it would take to develop a management submodel for FORCLIM, this part of the dissertation was done before any other model improvements. For this reason the validation study presented in Rasche et al. (2011b), while still valid concerning the evaluation of the general silvicultural treatments, is outdated concerning the evaluation of stand characteristics, as the changes introduced by Rasche et al. (2012) have a non-negligible impact on them. It was therefore uncertain how the results presented in the first part of this dissertation would change when produced with the new model version v3.0. Hence this appendix.

#### Material and Methods

The study was conducted in the exact same manner as described in Rasche et al. (2011b), on the same sites, using the same stand input data and applying the same harvesting scenarios and settings. The only change was that version 3.0 of FORCLIM was used instead of version 2.9.8, and that therefore an extended species file was employed, containing the species-specific parameter *kRedMax* for the climatically driven reduction of the tree maximum height. For the adjusted values of *kHmax* (i.e., now *gHmax*) at the eight sites, see Table AIII-1.

The second feature of FORCLIM v3.0 discerning it from v2.9.8 is that the parameter *kS* was turned into a variable that is light-dependent, i.e. *gS*, also taking into account the species-specific shade tolerance. Thus the values for this variable may now differ from the original fixed parameter (Fig. AIII-1).

**Table AIII-1.** Original (*kHmax*, in brackets) and reduced maximum heights (*gHmax*) of the species present on the 8 growth and yield research plots used in Paper I. SSP: Swiss Stone Pine.

	<b>Beech (45)</b>	<b>Fir (60)</b>	<b>Larch (52)</b>	<b>Oak (52)</b>	<b>Spruce (58)</b>	<b>SSP (26)</b>
Aarburg	42	-	-	-	-	-
Zofingen	42	-	-	-	-	-
Winterthur	43	-	-	50	-	-
Galmiz	37	-	-	45	-	-
Horgen	44	58	-	-	39	-
St. Moritz	-	-	52	-	58	26
Hospental	-	-	52	-	55	26
Morissen	-	-	-	-	57	26

## Results

Since the results were discussed in detail in Rasche et al. (2011b), I will focus on the major changes between the two model versions in the following.

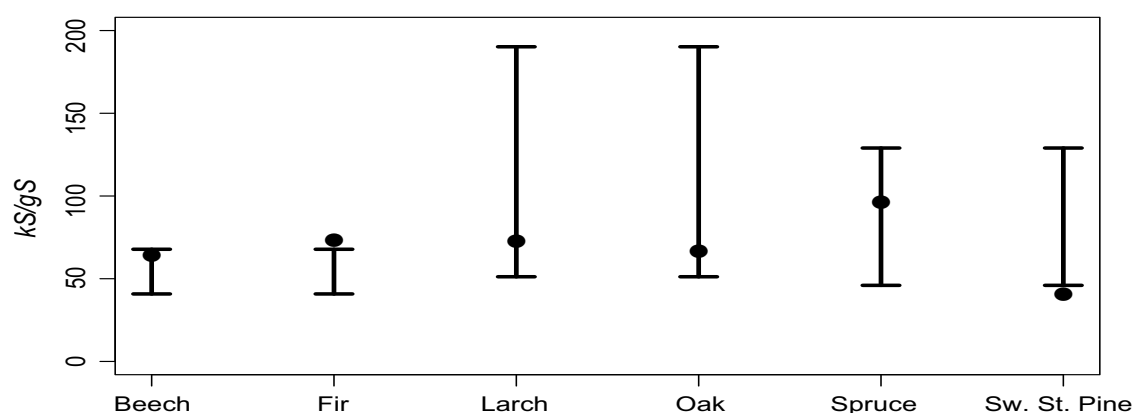
### Development of basal area

The development of simulated total basal area of each species on the stands was nearly interchangeable between v3.0 and v2.9.8. The only drastic difference was in the simulated basal area of oak in the stands Winterthur and Galmiz (Fig. AIII-2, panel 1). Version 2.9.8 simulated basal area close to inventory data, whereas basal area simulated with v3.0 was close to measurements only until the year 1948 in Winterthur and 1931 in Galmiz, after which the values decreased strongly and steadily.

### Diameter distribution

The differences between the diameter distributions as simulated with v3.0 and v2.9.8 were the same for both the generic and the specific setting of the management submodel (Fig. AIII-2, panel 2-3). In the beech stands Aarburg and Zofingen the taller trees grew faster through the diameter classes in v3.0 than in v2.9.8, whereas the trees in the understory seemed to be slightly inhibited by this. The fit of the simulated and measured distributions was therefore slightly inferior for v3.0.

In the oak-beech stands Winterthur and Galmiz the oak trees grew noticeably slower through the diameter classes in the new model version than in the old, resulting in a difference of approximately 20 cm dbh in the end.



**Fig. AIII-1.** Original, fixed  $kS$ -values (points) and new parameter space in which  $gS$  can vary dependent on available light (black lines) for the species present on the eight growth and yield research plots.

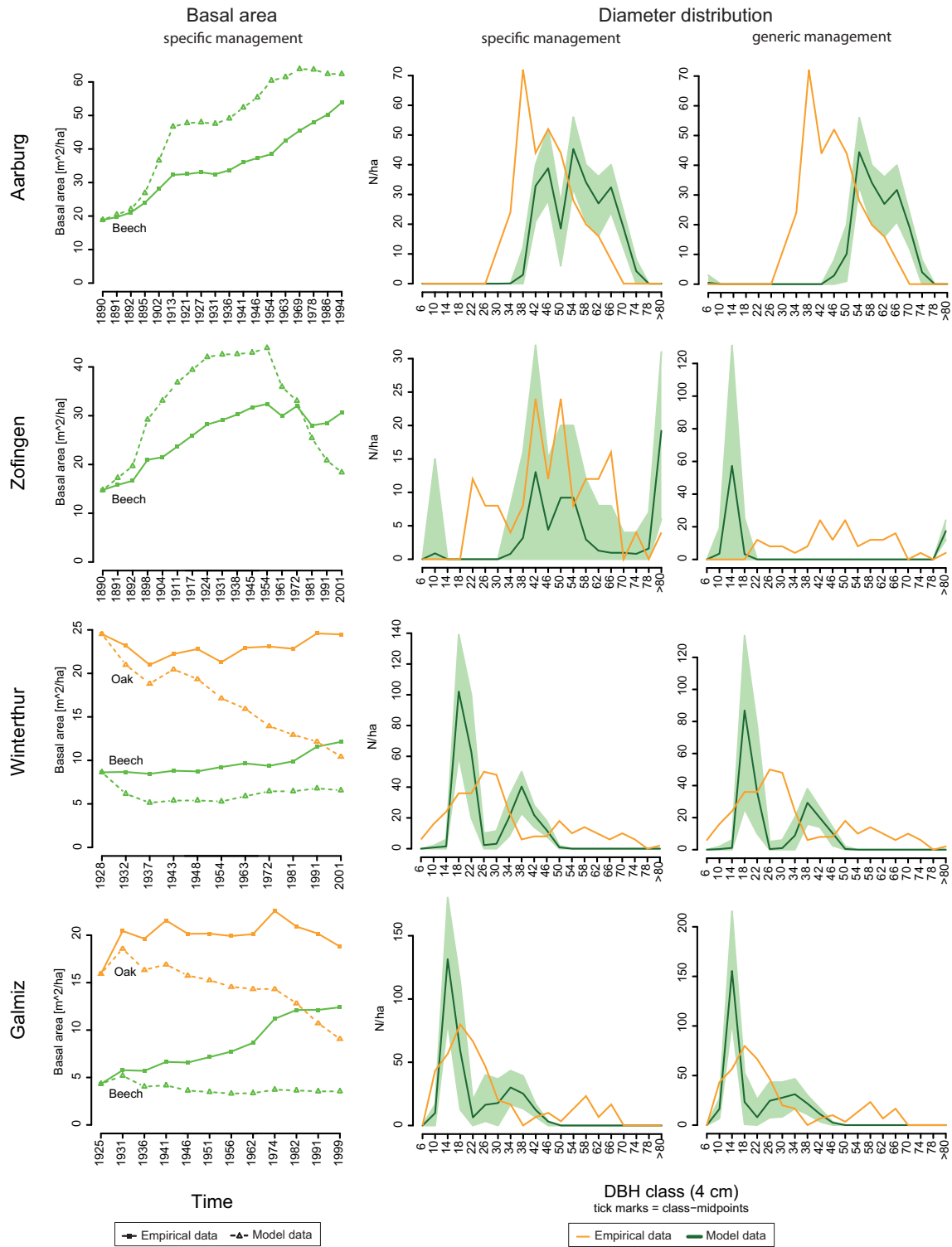
The beech trees in the stands, on the other hand, grew the same in both model versions, resulting in a slightly worse fit with the new model version.

In Horgen, St. Moritz and Morissen the results were nearly interchangeable, whereas in Hospental v3.0 simulated an overall slower growth of trees. The biggest diameter simulated occupied class 58 cm in v3.0 and class 74 cm in v2.9.8, resulting in a better model fit for the new model version.

A comparison of the simulated and measured cumulated diameter distributions with a Kolmogorov-Smirnov-test (Table AIII-2) revealed that there remained a significant difference between simulated and measured diameter distributions in Horgen, Winterthur and Zofingen, and that additionally the distributions in Aarburg now differed significantly as well.

### Harvesting numbers

The new harvesting numbers and the comparison to the measured data are shown in Table AIII-3. There was nearly no difference between the results of the two model versions concerning the number of harvested stems. There was, however, a difference when looking at the harvested basal area.



**Fig. AIII-2.** Species-specific basal area (left panels) and overall diameter distribution in the final observation year for the specific and generic management setting (middle and right panel, respectively). Green area in right panel: 2.5<sup>th</sup> and 97.5<sup>th</sup> percentile of simulated data.

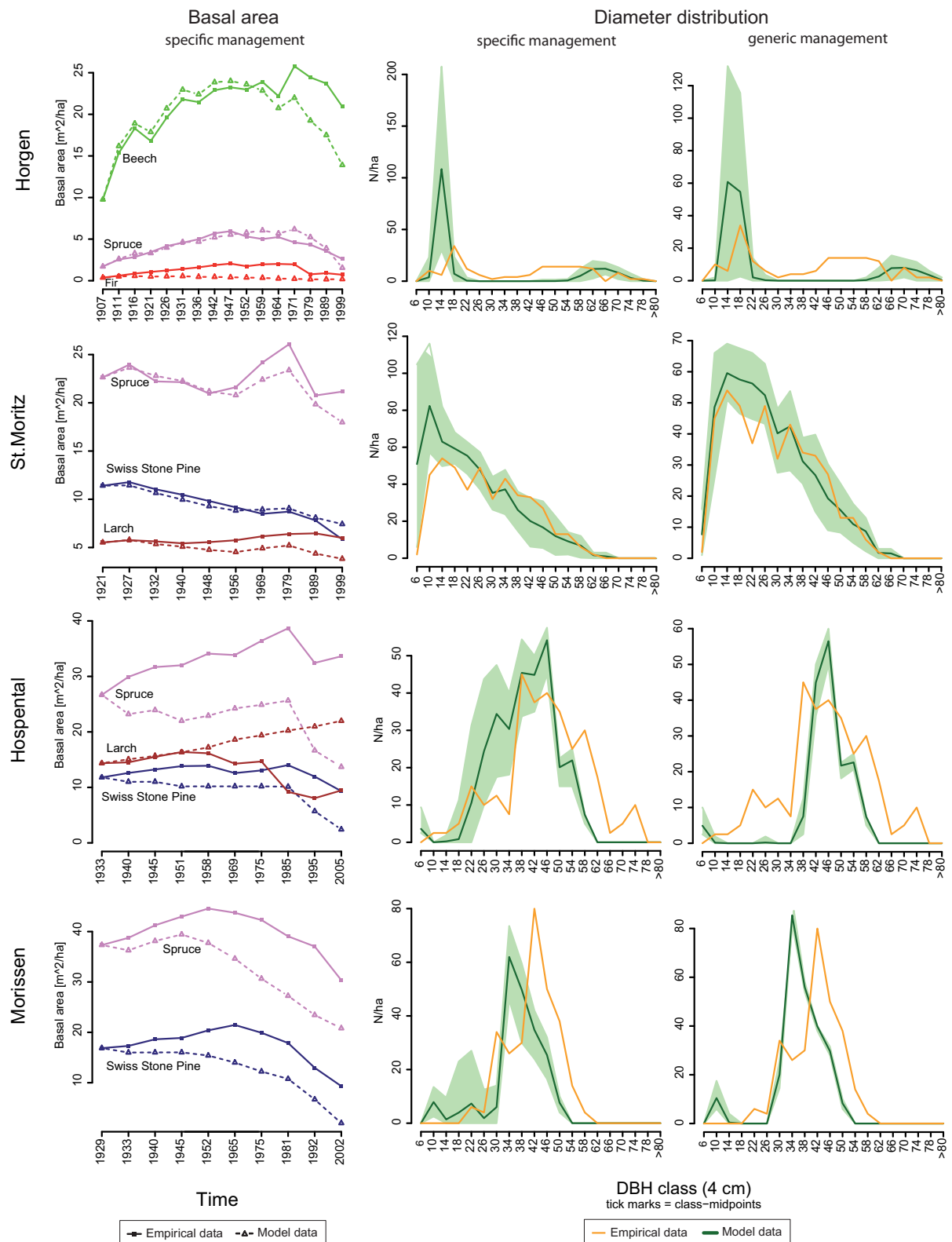


Fig. AIII-2 continued

**Table AIII-2.** Statistics and p values for measured (Meas.) and simulated (Sim.) cumulative diameter distributions. (spec.): simulation with specific management, (gen.): with generic management setting. Bold: Distributions differ significantly ( $\alpha = 5\%$ ).

	<b>Meas. – Sim. (spec.)</b>		<b>Meas. – Sim. (gen.)</b>	
	<i>p</i> -value	Statistic	<i>p</i> -value	Statistic
Aarburg	<b>0.00</b>	0.57	<b>0.00</b>	0.57
Galmiz	0.28	0.29	0.28	0.29
Horgen	<b>0.01</b>	0.48	<b>0.01</b>	0.48
Hospental	0.53	0.24	0.50	0.24
Morissen	0.46	0.24	0.43	0.24
St. Moritz	0.31	0.29	1.00	0.05
Winterthur	<b>0.03</b>	0.43	<b>0.03</b>	0.43
Zofingen	0.30	0.29	<b>0.01</b>	0.52

Here, the new model version underestimated the values in comparison to the old model version in Galmiz, Hospental and Winterthur for both management settings and in St. Moritz only for the specific management setting. In Zofingen the generic setting resulted in an intensified overestimation of harvested basal area. These differences were especially pronounced in the oak-dominated stands Winterthur and Galmiz, where v2.9.8 simulated very good results of 90-100% of measured data, whereas v3.0 simulated harvesting numbers of 70-80% of measured data.

## Discussion

This short study highlighted several things about the new model version. The first was that even though the results were not as good as the ones achieved with v2.9.8, they were not bad, either. Development of simulated stem numbers, basal area and diameter distribution followed the measured one adequately to good in many cases. In one case the new model version even yielded better results.

It was obvious, however, that either the light-dependent allocation of volume growth to height and diameter growth in v3.0 is not optimally parameterized for some of the species, or the formulation of growth in itself – the carbon budget approach by Moore (1989) and the reduction of growth based on several environmental factors (Bugmann, 1996) – may not be accurate enough.

**Table AIII-3.** The sum of harvested stems (N) and harvested basal area (G) over the observation time for the growth and yield research plots, using the the specific and the generic management setting. (%): Percentage of simulated relative to measured numbers.

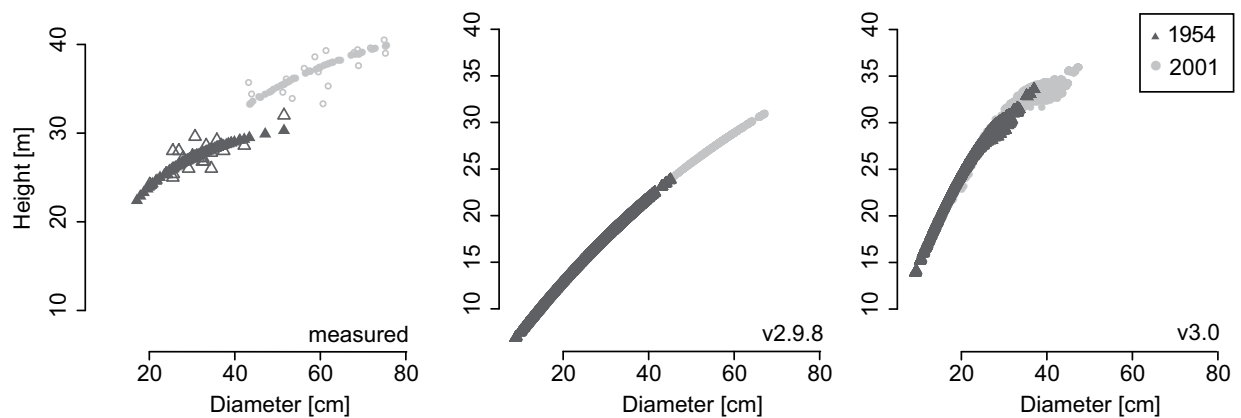
Site	Measured		Specific setting				Generic setting			
	$\Sigma N$ (#/ha)	$\Sigma G$ (m <sup>2</sup> /ha)	$\Sigma N$ (#/ha)	%	$\Sigma G$ (m <sup>2</sup> /ha)	%	$\Sigma N$ (#/ha)	%	$\Sigma G$ (m <sup>2</sup> /ha)	%
Aarburg	2320	84.5	3082	133	113.4	134	2636	114	68.3	81
Galmiz	2141	51.2	2185	102	35.8	70	2160	101	36.2	71
Horgen	8328	68.1	6939	83	71.5	105	6956	84	73.8	108
Hospental	1165	65.9	1164	100	32.3	49	1295	111	41.5	63
Morissen	1328	70	1387	104	48.6	69	1346	101	44.2	63
St. Moritz	516	45.6	288	56	33.9	74	165	32	19.9	44
Winterthur	1894	57.7	1964	104	45	78	1962	104	45.6	79
Zofingen	5168	59.9	5237	101	89.5	149	5200	101	92.7	155

In Winterthur, for example, even in the old model version oak trees did not grow as fast as they did in reality. In v3.0, the potential of growth was almost the same (only very slightly reduced due to the adjustment of *gHMax*), yet due to the new formulation of growth even less was invested in diameter growth, and instead more in height growth (Fig. AIII-3). The result was that in v3.0 tree heights were closer to reality, yet tree diameters were further off. This fact not only explained the discrepancies in basal areas, but also in harvested basal area. It also suggested that the problem really is potential volume growth, and that it should be higher, especially for oak trees.

In Aarburg and Zofingen, on the other hand, the beech trees did not seem limited in their growth potential, and thus trees in the upper canopy grew even faster in diameter (and less in height) in the new model version, whereas trees in the lower canopy invested more in height than in diameter growth due to shading (see Fig. AIII-2, Zofingen).

Based on this study I conclude that the changes implemented in ForCLIM v3.0 highlight already existing problems in the model that should be addressed sometime in the future.

Lastly, it should be noted that the paper by Rasche et al. (2011a) was produced with model version 3.0.



**Fig. AIII-3.** H/D ratio at the stand Winterthur for two different years as measured and as simulated with FORCLIM v2.9.8 and v.3.0.

## References

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## Appendix IV

### Simulating Swiss forest reserves – problems and attempts to deal with them

#### Introduction

In the last part of her dissertation, Heiri (2009) simulated the dynamics of near-natural forest stands using FORCLIM v2.9.6. The model was initialized with inventory data gathered at several Swiss Forest Reserves located all over Switzerland. Heiri noticed that trees in the understory of dense stands started to die abundantly in the simulations after two years, a clear indicator of the stress mortality being at work. In FORCLIM, the probability of a tree dying increases strongly after two consecutive years of near-zero growth, which in this case was caused by very low light availability.

Heiri therefore developed a new formulation of the background mortality, where trees no longer die due to getting closer to their maximum age, but to their maximum diameter. It was thus assured that trees did not grow as thick as before, and that consequently more light could reach the forest floor. Unfortunately, while working well for the relatively short time spans of the reserve simulations, the new mortality had detrimental effects on the general applicability of the model. The potential natural vegetation and total basal area on 11 sites along an environmental gradient could not be replicated satisfactorily (Rasche, unpublished), and the resulting model version v2.9.7 was thus abandoned.

This study was conducted to assess whether the new model version v3.0 of FORCLIM would yield better results at simulating forest reserves than v2.9.6, and if not, whether minor changes to the model structure would improve the performance.

#### Material and Methods

##### Site data

In this study I used a selection of the reserves that Heiri had also used in her study. The reserves are divided into several compartments, each of which is homogeneous

in its characteristics, and on which a full cruise is conducted regularly. For every reserve I chose one of those compartments (Table AIV-1), usually the one that was established first and had an area of 0.25 - 1 ha, as this size was tested in Rasche et al. (2011) for the initialization of FORCLIM and deemed appropriate. The initial LAI was estimated based on Breuer et al. (2003). For a description on how the model was initialized, see Rasche et al. (2011) and Appendix II.

### Simulation experiments

First I conducted simulations with the new model version v3.0 without any changes to the model structure. I initialized the model with inventory data from the first inventory of each compartment, and ran the model with the same climate and soil data that Heiri (2009) had used in her simulations for the duration of years from first to last inventory. Subsequently I compared the simulated and measured total basal area [ $\text{m}^2/\text{ha}$ ] of the stands.

After it was obvious that the changes from v2.9.6 to v3.0 had not touched upon the problem of understory trees dying in dense stands, I implemented some changes to FORCLIM v.3.0 with the hope of ameliorating the problem.

**Table AIV-1.** Name of reserve, number of compartment used (DF=Dauerfläche), area of the compartment, time span from first to last inventory conducted there and main forest associations. Number of patches (Items) that together represent the compartment area once, overall number of runs in simulation (Runs=50\*Items), patch size (PS=Area/Items), initial LAI of cohorts.

Site	DF	Area (ha)	Time span	Association	Items	Runs	PS ( $\text{m}^2$ )	LAI
Adenberg	1	0.45	1970-2002	<i>Galio odorati Fagetum</i>	6	300	750	8
Derborence	2	0.25	1955-1991	<i>Adenostylo-alliariae-Abieti-Piceetum typicum</i>	3	150	833	6
Fürstenhalde	1	0.35	1971-1994	<i>Cardamino-Fagetum tilietosum</i>	4	200	875	7
Tariche HC	1	0.72	1973-1999	<i>Cardamino-Fagetum (Abieti-Fagetum)</i>	9	450	800	8
Weidwald	1	0.78	1976-1998	<i>Aceri-Tilietum, Cardamino-Fagetum (Seslerio-Fagetum)</i>	10	500	780	7

### New mortality formulation

Small trees die in dense stands in FORCLIM as well as in reality because they do not get enough light and thus in the model are subjected to the stress mortality. One possibility to tackle this problem is to let more light come through the canopy. Didion et al. (2009) already attempted this with their self-pruning routine in FORCLIM v2.9.6, which almost certainly improved the conditions in the simulations of forest reserves, but obviously not enough.

The other possibility is to change the formulation of the stress mortality. Laarmann et al. (2009) present mortality probabilities based on the relative diameter ( $rD = \text{dbh of tree} / \text{mean dbh of stand}$ ) of a tree. They analyzed mortality patterns in managed and semi-natural forests in Estonia and found that the mortality risk increased for trees with an  $rD < 1$  due to competition and also for those with  $rD > 1$  due to vulnerability to wind damage.

They also analyzed other sources of stress (game, fungi, insects, others), but these two were the most extreme, so I decided to focus on them. I implemented the mortality as described by Laarmann et al. (2009) and ran a test for the reserve Derborence. It was determined that the formulation was too extreme for FORCLIM and it was therefore recalibrated to more mellow values to only stress the comparatively small and very big trees (Fig. AI-V 1).

The mortality risk based on  $rD$  ( $gPReID$ ) was thus formulated as:

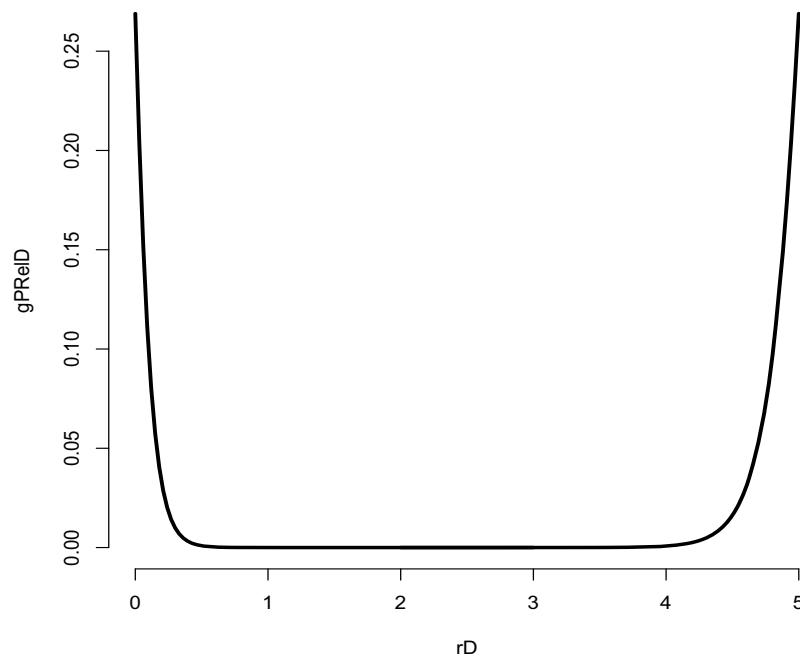
$$gPReID = \text{MAX} \left[ \frac{1}{1 + \exp^{-6.2 * rD + 33}} , \frac{1}{1 + \exp^{12 * rD + 1}} \right]$$

and replaced the “standard” stress mortality in FORCLIM v3.0.

### Other attempts to solve the problem

Besides implementing a new stress mortality I also tried to work with the current one and changed other model settings to improve simulation results. As a test site I used the reserve Derborence, as problems were most pronounced there (Fig AIV-2).

In the first attempt I varied the values of the initial LAI to see whether stands would respond as sensitive as the ones discussed in Appendix II.



**Figure AIV-1.** New stress mortality probability based on the relative diameter (rD) of a tree.

In the second attempt patch size was reduced to  $100 \text{ m}^2$ , since Rasche (unpublished) found that trees did not grow as thick on small patches as on bigger ones. It was hoped that with fewer big trees the trees in the understory would receive more light and thus not be as stressed as before.

The last attempt was to reduce stress through shading by switching off the self-shading of trees, so that trees only were shaded by taller ones and not by themselves any more.

## Results

An improvement in the simulation of dense stands was not apparent when using FORCLIM v3.0, and there was a strong loss of basal area in all five reserves (Fig. AIV-2). This loss was not confined to single species but affected all, with oak being the only exception.

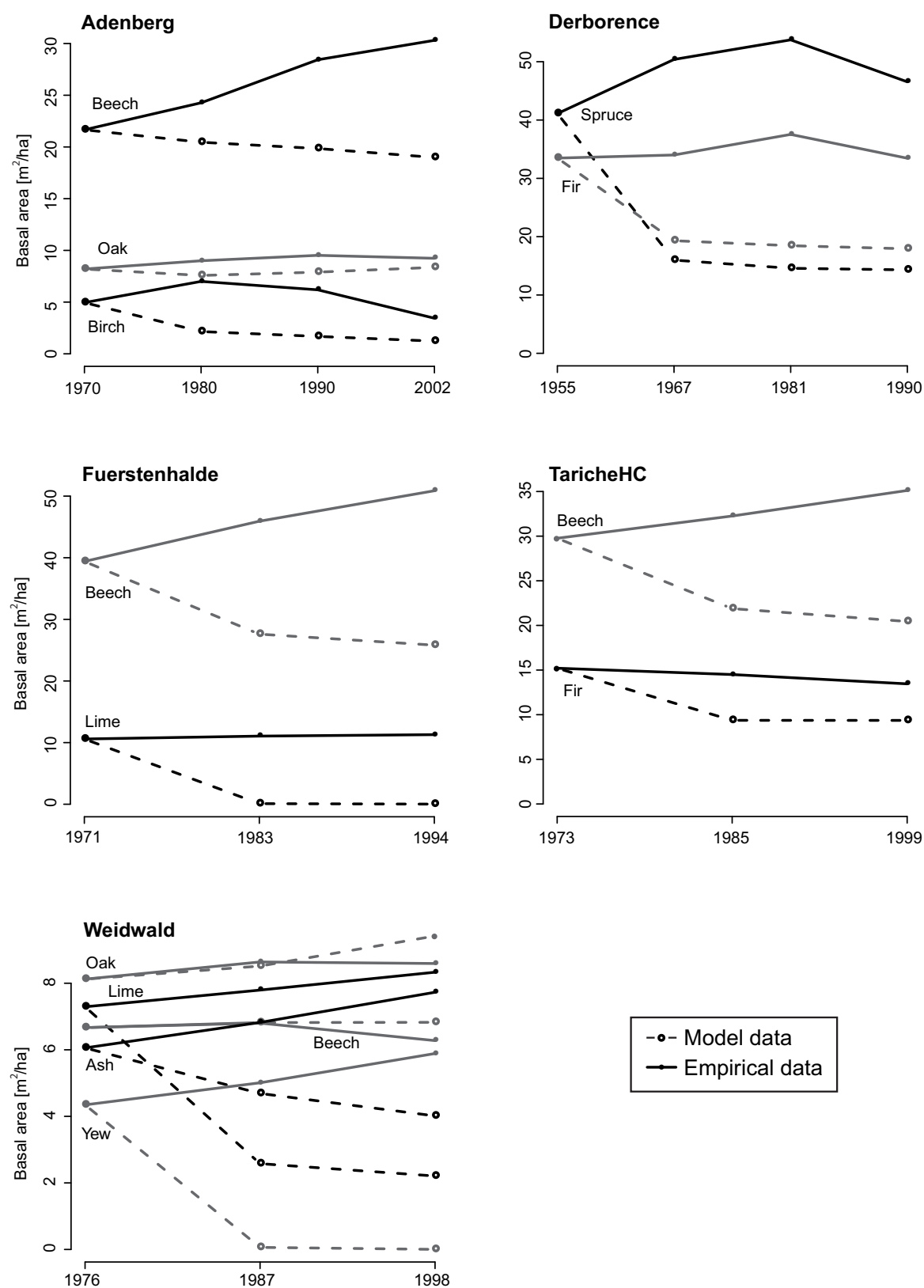
Fig. AIV-3 shows that stress mortality dependent on  $rD$  could curb the excessive mortality present in v3.0. It was also obvious, however, that mortality still took place and that the expected growth of spruce failed to occur.

There were slight differences between the simulations with different initial LAIs, but sensitivity was not high, and better results could not be achieved with other values (not shown). Furthermore, neither the reduction of patch size nor the removal of self-shading had a significant positive impact on simulation results in Derborence. Basal area still was massively underestimated due to the stress mortality.

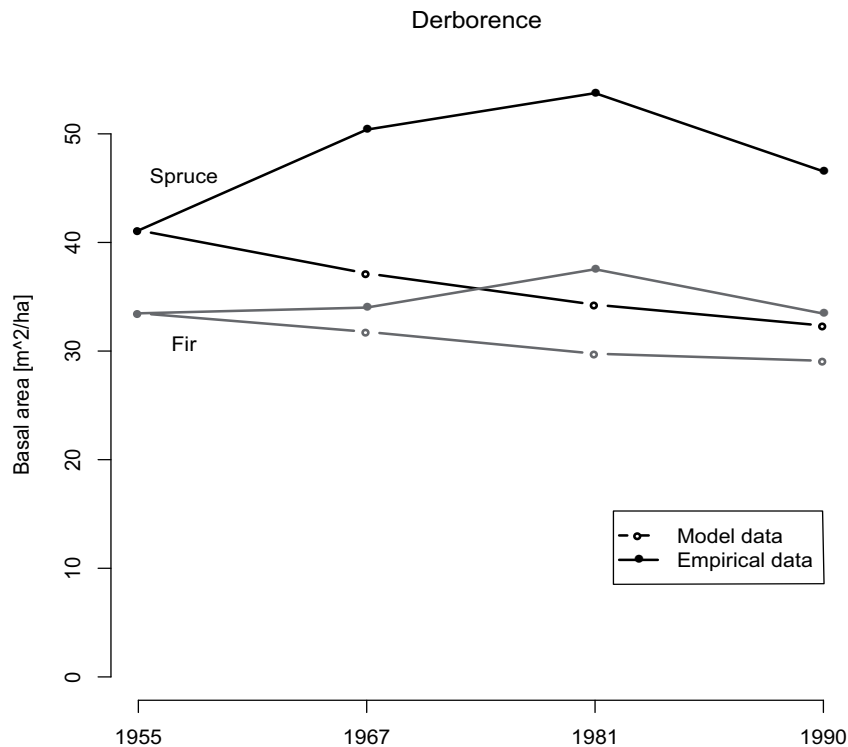
## Discussion

The results of this study showed that the FORCLIM model in its current form is not well suited for the simulation of dynamics in forest reserves. More effort needs to be put especially in the formulation of growth, since it is my impression that working on the formulation of mortality is really just treating the symptoms, not the cause. Many trees died that should have grown enough to avoid being stressed. As Didion et al. (2009) have already worked on the problem of getting more light into the stands, it stands to reason that either the parameter of the optimal growth rate ( $kG$ ) or the growth constraining factors should be scrutinized.

Concerning the new formulation of stress mortality, it clearly did not solve the problem, but it may be an idea that is worth pursuing further. There is, however, the problem that although it might work well for even-aged stands, it is not applicable to uneven-aged ones due to their reverse-J-shaped form of diameter distribution. My attempt at recalibrating the sensitivity of the model worked well in this context, yet the lack of an empirical basis does not recommend the approach. However, as Bigler et al. (2007) have shown, mortality does depend on diameter; thus finding a way to formulate a diameter-dependent new formulation of mortality that does not lead to drawbacks in the general applicability of the model should be pursued further.



**Figure AIV-2.** Basal area of five forest reserves simulated with FORCLIM v3.0.



**Fig. AIV-3.** Basal area development in Derborence, simulated with the new stress mortality.

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# Appendix V

## Source code of the management submodel

### Class Management

```
//=====
// FORCLIM: Management sub-model
// Livia Rasche 2009
//=====

using System;
using ETH.FE.XML;
using System.Collections.Generic;
using System.Collections;
using FE.Random;

class Management : SubModel
{
    //-----
    // Input sub-model references
    //-----
    public Plant[] plant;
    ManagementTimeline mtl;
    ManagementPhase mph;
    ManagementView mvi;
    //-----
    // Parameter data references
    //-----

    //-----
    //Auxilliary component references
    //-----
    public UniformRandom uniRand;
    //-----
    //State variables
    //-----

    //-----
    // Input variables
    //-----

    //-----
    // Output variables
    //-----

    //-----
    //Model parameter
    //-----
    //Base parameters
    public DataNode configData; //for access to setup file
    public XmlParser xmlParser; //parser for reading xml files
    public string configFileNames; //name & absolute path of setup file
    public int runNumber; //number of patches in simulation
    public double kPatchSize; //size of patch

    //Auxiliary parameters
    int[] PhaseOpArray; //array with phase and operation ID of current action
    bool isAction; //true if action is scheduled for this year
    int gPatchNb; //number of patches to be harvested
    int gPatchCounter; //auxiliary counter for FemelSize()
    public string treatment; //name of treatment, for log file
    public ArrayList FemelList; //list with the number of patches to be harvested now
    public bool isPlanting; //true if planting is scheduled
    public int[,] plantingSpecies; //array with ID and number of saplings to be planted
    public int gPlantingSpeciesnumber; //number of species that should be planted

    //Lists for the harvest log file
    public ArrayList cutTreeList; //list with the number of trees removed in action
    public ArrayList cutBAList; //list with BA of trees removed in specific action
}
```

```

public ArrayList cutDList;      //list with diameter of trees removed in specific action
public ArrayList cutHList;     //list with height of trees removed in specific action

//-----
// Get-functions for lokal and global outputs
//-----

//-----
// Sub-model constructor
//-----
public Management(int id, string configFileNames)
: base(id)
{
    xmlParser = new XmlParser();
    xmlParser.loadFile(configFileName);
    configData = xmlParser.getData();

    runNumber = Convert.ToInt16(configData["simulation"]["runNumber"].Value);

    mph = new ManagementPhase(this);
    mtl = new ManagementTimeline(this);
    mvi = new ManagementView(this);

    this.configFileName = configFileNames;

    plant = new Plant[runNumber];
    uniRand = randomData.Uniform;
    PhaseOpArray = new int[2];
}
//-----
// Implementation of SubModel abstract methods
//-----
public override void Initialise()
{
    //the mastertimeline is calculated only once at the very beginning of the simulation
    mtl.CalculateMastertimeline();
    mvi.Initialise();                //print header for harvest log file
    gPatchCounter = 0;
    isPlanting = false;
    kPatchSize = plant[0].kPatchSize; //get patch size from first patch
}
//-----
public override void Input()
{
}
//-----
public override void Update()
{
    isAction = false;

    //Compare dates in masterTimeLine (keys) to current time and copy phase-
    //and operation-ID of this key to new array if there is a match

    foreach (KeyValuePair<int, ArrayList> pair in mtl.masterTimeLine)
    {
        if (pair.Key == Time)
        {
            Array.Copy((int[])pair.Value.ToArray(typeof(int)), PhaseOpArray, 2);
            isAction = true;
        }
    }

    //If there is an action scheduled for the current year, execute harvesting routine
    if (isAction == true)
    {
        //Get kType and name of scheduled operation
        int kType = Convert.ToInt16(mtl.managementData["operations"]
        [PhaseOpArray[0]][PhaseOpArray[1] + 4]["kType"].Value);
        treatment = mtl.managementData["harvest"][kType]["name"].Value;

        //Temporary solution for specific management: Get Intensity for this operation
        double kIntensity = Convert.ToDouble(mtl.managementData["operations"]
        [PhaseOpArray[0]][PhaseOpArray[1] + 4]["kIntensity"].Value);
        double kResBA = Convert.ToDouble(mtl.managementData["operations"]
        [PhaseOpArray[0]][PhaseOpArray[1] + 4]["kResBA"].Value);

        //Read harvest species file and write all species to be harvested into an array
        string Listname = ((DataNode)mtl.managementData["operations"][PhaseOpArray[0]].
        selectNodesByPath("operation")[PhaseOpArray[1]]["speciesList"]["name"].Value;

```

```

string Listpath = ((DataNode)mtl.managementData["operations"][PhaseOpArray[0]].
selectNodesByPath("operation")[PhaseOpArray[1]]["speciesList"]["path"].Value;
xmlParser.loadFile(Listpath + Listname);
DataNode speciesData = xmlParser.getData();

int gSpeciesnumber = speciesData.ChildCount;
int[] harvestSpeciesArray = new int[gSpeciesnumber];

for (int i = 0; i < gSpeciesnumber; i++)
{ harvestSpeciesArray[i] = Convert.ToInt16(speciesData[i]["kID"].Value); }

//Check if planting is planned (after clearcut, targetcut or shelterwood)
if (kType >= 5 && kType < 8)
{
isPlanting = Convert.ToBoolean(((DataNode)mtl.managementData["operations"]
[PhaseOpArray[0]].selectNodesByPath("operation")[PhaseOpArray[1]]
["planting"]["isPlanting"].Value);
if (isPlanting == true)
{
//If planting is desired, read in the planting species file and get the
//species ID and corresponding number of saplings per hectare. Store
//data in a 2-D array (ID/sapling number).
string PlantingName = ((DataNode)mtl.managementData["operations"]
[PhaseOpArray[0]].selectNodesByPath("operation")
[PhaseOpArray[1]]["planting"]["name"].Value;
string PlantingPath = ((DataNode)mtl.managementData["operations"]
[PhaseOpArray[0]].selectNodesByPath("operation")
[PhaseOpArray[1]]["planting"]["path"].Value;
xmlParser.loadFile(PlantingPath + PlantingName);
DataNode plantingData = xmlParser.getData();

gPlantingSpeciesnumber = plantingData.ChildCount;
plantingSpecies = new int[gPlantingSpeciesnumber, 2];

for (int i = 0; i < gPlantingSpeciesnumber; i++)
{
plantingSpecies[i, 0] = Convert.ToInt16(plantingData[i]["kID"].Value);
plantingSpecies[i, 1] = Convert.ToInt16(plantingData[i]["kNumber"].Value);
}
}
}

//Initialize ManagementPhase.cs
mph.Initialize(modelData, configData);

//Run scheduled action
switch (kType)
{
case 0: mph.Thinning(kType, mtl.managementData, harvestSpeciesArray); break;
case 1: mph.Thinning(kType, mtl.managementData, harvestSpeciesArray); break;
case 2: mph.Thinning(kType, mtl.managementData, harvestSpeciesArray); break;
// case 0: mph.Thinning(kType, mtl.managementData, harvestSpeciesArray, kIntensity); break;
// case 1: mph.Thinning(kType, mtl.managementData, harvestSpeciesArray, kIntensity); break;
// case 2: mph.Thinning(kType, mtl.managementData, harvestSpeciesArray, kIntensity); break;
case 3: mph.Stripfelling(kType, mtl.managementData, harvestSpeciesArray); break;
case 4: gPatchNb = FemelSize(); mph.Femel(kType, mtl.managementData,
harvestSpeciesArray, gPatchNb); break;
case 5: mph.Targetcut(kType, mtl.managementData, harvestSpeciesArray); break;
case 6: mph.Clearcut(kType, mtl.managementData, harvestSpeciesArray); break;
case 7: mph.Shelterwood(kType, mtl.managementData, harvestSpeciesArray); break;
// case 8: mph.Plenter(kType, mtl.managementData, harvestSpeciesArray, kResBA); break;
case 8: mph.Plenter(kType, mtl.managementData, harvestSpeciesArray); break;
}
}

//-----
public override void Output()
{
//Write to harvest log
if (isAction == true)
{ mvi.WriteLog(); }
}

//-----
public override void ConnectTo(SubModel subModel)
{
int id = subModel.ID;
if (subModel is Plant)
this.plant[id] = subModel as Plant;
}

```

```

//-----
public override void Dispose()
{
}
//-----
public override void Finalise()
{
}
//-----
//Auxiliary method to determine the number of patches to be harvested now:
//-----
public int FemelSize()
{
    //The FemelList ist filled in CalculateDatesFemel()
    //Each time the action femel is called, take next number in the FemelList
    //When the list has run through once, it starts at the beginning again
    if (gPatchCounter >= FemelList.Count) { gPatchCounter = 0; }
    int Number = (int)FemelList[gPatchCounter];
    gPatchCounter++;
    return Number;
}
}
//=====

```

## Class Management Timeline

```

//=====
// FORCLIM: Management class that assembles the master timeline
// with the dates of all harvest actions
// Livia Rasche 2009
//=====

using System;
using ETH.FE.XML;
using System.Collections.Generic;
using System.Collections;

class ManagementTimeline
{
    Management m;
    public static int[] TimeLineArray;           //Array with the dates of the actions
    public static int[,] IDArray;                //Array with the corresponding IDs
    public static int Length;                   //Length of these arrays
    public ArrayList IDList;                    //List with phase ID and operation ID
    public DataNode managementData;             //node that allows access to Management.xml
    public Dictionary<int, ArrayList> masterTimeLine;
    //-----
    public ManagementTimeline(Management management)
    {
        m = management;
    }
    //-----
    public void CalculateMastertimeline()
    {
        string name = m.configData["managementParam"]["name"].Value;
        string path = m.configData["managementParam"]["path"].Value;

        m.xmlParser.loadFile(path + name);
        managementData = m.xmlParser.getData();

        ManagementPhasetime managementPhasetime = new ManagementPhasetime(m, this);
        masterTimeLine = new Dictionary<int, ArrayList>();

        int phasenumber = managementData["operations"].ChildCount; //number of harvest phases in
        //this simulation
        int[] phaseIDArray = new int[phasenumber]; //array in which IDs of the phases is stored

        //Write the IDs of all phases into an array
        for (int i = 0; i < phasenumber; i++)
        { phaseIDArray[i] = Convert.ToInt16(managementData["operations"][i]["ID"].Value); }

        //For each phase run through the calculations to determine the operation dates
        //Add the dates of each individual PhaseTimeLine as keys to the MasterTimeLine dict.
        //Add an array with the phase and operation ID for this date as value
        foreach (int y in phaseIDArray)
        {
            //Check first if the phase is stripfelling or femel, as calculation is different
            //To do this check kType of first operation of phase, as both actions can only have
            //one operation per phase

```

```

int type = Convert.ToInt16(managementData["operations"][y]["operation"]["kType"].Value);

if (type == 3)
{
    if (managementData["operations"][y].selectNodesByPath("operation").Count>1)
    {
        Message.WriteLine("Problem with strip felling: too many operations in phase.");
        Message.WriteLine("Only one operation is allowed when using this treatment.");
        FORCLIM.Terminate();
        Environment.Exit(0);
    }
    managementPhasetime.CalculateDatesStrip(type, y, managementData, m.configData);
}
else if (type == 4)
{
    if (managementData["operations"][y].selectNodesByPath("operation").Count>1)
    {
        Message.WriteLine("Problem with group selection: too many operations in phase.");
        Message.WriteLine("Only one operation is allowed when using this treatment.");
        FORCLIM.Terminate();
        Environment.Exit(0);
    }
    managementPhasetime.CalculateDatesFemel(type, y, managementData, m.configData);
}
else { managementPhasetime.CalculateDates(y, managementData); }

//For all the actions that have been calculated in ManagementPhasetime.cs, add date
//and IDs to the mastertimeline
for (int i = 0; i < Length; i++)
{
    IDList = new ArrayList();
    IDList.Add(IDArray[i, 0]);
    IDList.Add(IDArray[i, 1]);
    masterTimeLine.Add(TimeLineArray[i], IDList);
}
}
}
}
//=====

```

## Class Management Phasetime

```

//=====
// FORCLIM: Management subclass that calculates the dates for all harvest actions
// Livia Rasche 2009
//=====

using System;
using ETH.FE.XML;
using System.Collections;

class ManagementPhasetime
{
    Management m;
    ManagementTimeline mtl;

    //-----
    public ManagementPhasetime(Management management, ManagementTimeline managementTimeline)
    {
        m = management;
        mtl = managementTimeline;
    }
    //-----
    public void CalculateDates(int y, DataNode managementData)
    {
        int kStart = Convert.ToInt16(managementData["operations"][y]["kStart"].Value);
        int kEnd = Convert.ToInt16(managementData["operations"][y]["kEnd"].Value);
        int kCycleLength = Convert.ToInt16(managementData["operations"][y]["kCycleLength"].Value);
        int gOperationsNumber = managementData["operations"][y].selectNodesByPath("operation").Count;
        int[] kCycleYearArray = new int[gOperationsNumber];

        //Populate array with all the kCycleYear values in the xml file
        for (int i = 0; i < gOperationsNumber; i++)
        { kCycleYearArray[i] = Convert.ToInt16(((DataNode)(managementData["operations"][y]

```

```

        .selectNodesByPath("operation")[i]))["kCycleYear"].Value); }

//Declare simple array to calculate and sort the operation dates
//Set size to dummy value, as length is not known now. Resize later.
int[] tempTimeLineArray = new int[1000];

//Calculate date of first action of each operation and save it to tempTimeLineArray
for (int i = 0; i < gOperationsNumber; i++)
{ tempTimeLineArray[i] = kCycleYearArray[i] = kCycleYearArray[i] + kStart; }

//Calculate dates of all further actions and save them to tempTimeLineArray, too
int a = 0;
for (int i = 0; i < gOperationsNumber; i++)
{
    while (kCycleYearArray[i] <= kEnd - kCycleLength)
    {
        tempTimeLineArray[a + gOperationsNumber] = kCycleYearArray[i] = kCycleYearArray[i]
            + kCycleLength;
        a++;
    }
}

//Calculate number of actions and resize tempTimeLineArray accordingly. Sort.
int gLength = a + gOperationsNumber;
Array.Resize(ref tempTimeLineArray, gLength);
Array.Sort(tempTimeLineArray);

//New array with 2 columns and "Length" rows; 1st row phase-IDs, 2nd row operation-IDs
int[,] tempIDArray = new int[gLength, 2];
int x = 0;
for (int i = 0; i < gLength; i++)
{
    tempIDArray[i, 0] = Convert.ToInt16(managementData["operations"][y]["ID"].Value);
}

for (int i = 0; i < gLength; i++)
{
    tempIDArray[i, 1] = x;
    x++;
    if (x > gOperationsNumber - 1) { x = 0; }
}

//Initialize arrays and copy tempTimeLineArray and tempIDArray to them
ManagementTimeline.IDArray = new int[gLength, 2];
Array.Copy(tempIDArray, ManagementTimeline.IDArray, gLength * 2);

ManagementTimeline.TimeLineArray = new int[gLength];
Array.Copy(tempTimeLineArray, ManagementTimeline.TimeLineArray, gLength);
ManagementTimeline.Length = gLength;
}

//-----
//Calculates the dates for the treatment "strip felling" (harvest whole area once in the
//time of kCycleLength thereby harvesting the same number of patches each action)

public void CalculateDatesStrip(int type, int y, DataNode managementData, DataNode configData)
{
    int kStart = Convert.ToInt16(managementData["operations"][y]["kStart"].Value);
    int kEnd = Convert.ToInt16(managementData["operations"][y]["kEnd"].Value);
    int kCycleLength = Convert.ToInt16(managementData["operations"][y]["kCycleLength"].Value);
    int kCycleYear = Convert.ToInt16(managementData["operations"][y]["operation"]
        ["kCycleYear"].Value);
    int kArea = Convert.ToInt16(((DataNode)managementData["harvest"]).selectNodesByPath
        ("kType")[type]["kArea"].Value);
    int runNumber = Convert.ToInt16(configData["simulation"]["runNumber"].Value);
    //total number of patches
    double[] tempTimeLineArray = new double[1000];

    //Calculate dates of actions: whole area is harvested once in time of kCycleLength
    double actionNumber = (double)runNumber / kArea; //number of actions needed
    if (actionNumber > kCycleLength)
    {
        Message.WriteLine("Problem with strip felling: stand cannot be harvested in one
            cycle.");
        Message.WriteLine("Please increase value kArea in management xml file.");
        FORCLIM.Terminate();
        Environment.Exit(0);
    }
}

```

```

double intervall = kCycleLength / actionNumber;    //years between actions

//Date of first action is the value kCycleYear
tempTimeLineArray[0] = kStart + kCycleYear;

//Set Length to 1 (there is already one action in the array)
//Calculate the dates of all further actions
int tempLength = 1;
int ActionNumber = (int)Math.Round(actionNumber);
for (int i = 1; i < ActionNumber; i++)
{
    tempTimeLineArray[i] = tempTimeLineArray[i - 1] + intervall;
    tempLength++;
}

//To get whole numbers as years, round each item in tempTimeLineArray
for (int i = 0; i < tempTimeLineArray.Length; i++)
{ tempTimeLineArray[i] = Math.Round(tempTimeLineArray[i]); }

//Calculate the dates of the actions of all further cycles (if any)
int Counter = tempLength;
for (int i = 0; i < kEnd - kStart; i++)
{
    if (tempTimeLineArray[i] + kCycleLength >= kEnd) { break; }
    tempTimeLineArray[i + tempLength] = tempTimeLineArray[i] + kCycleLength;
    Counter++;
}
int gLength = Counter;
Array.Resize(ref tempTimeLineArray, gLength);

//Create a 2D-Array with the IDs for phase and operation
int[,] tempIDArray = new int[gLength, 2];
for (int i = 0; i < gLength; i++)
{tempIDArray[i, 0] = Convert.ToInt16(managementData["operations"][y]["ID"].Value);}
for (int i = 0; i < gLength; i++)
{ tempIDArray[i, 1] = Convert.ToInt16(managementData["operations"][y]["operation"]
    ["ID"].Value); }

//Copy the temp arrays to new arrays MasterTimeline.cs has access to
ManagementTimeline.IDArray = new int[gLength, 2];
Array.Copy(tempIDArray, ManagementTimeline.IDArray, gLength * 2);

ManagementTimeline.TimeLineArray = new int[gLength];
for (int i = 0; i < gLength; i++)
{ ManagementTimeline.TimeLineArray[i] = (int)tempTimeLineArray[i]; }
ManagementTimeline.Length = gLength;
}
//-----
//Calculates the dates for the treatment "group selection" (harvest whole area once in
//the time of cyclelength; harvesting an increasing number of patches each action)

public void CalculateDatesFemel(int type, int y, DataNode managementData, DataNode configData)
{
    int kStart = Convert.ToInt16(managementData["operations"][y]["kStart"].Value);
    int kEnd = Convert.ToInt16(managementData["operations"][y]["kEnd"].Value);
    int kCycleLength = Convert.ToInt16(managementData["operations"][y]["kCycleLength"].Value);
    int kCycleYear = Convert.ToInt16(managementData["operations"][y]["operation"]
        ["kCycleYear"].Value);
    int kArea = Convert.ToInt16(((DataNode)managementData["harvest"]).selectNodesByPath
        ("kType")[type]["kArea"].Value);
    int runNumber = Convert.ToInt16(configData["simulation"]["runNumber"].Value);
    int[] tempTimeLineArray = new int[1000];
    int actionNumber = 1;
    int intervall;
    int[] patchCounter = new int[100];
    patchCounter[0] = kArea;    //in the first action "kArea" patches are harvested
    m.FemelList = new ArrayList(); //stores the number of patches that are
        //harvested each action (to be used in Management.cs)
    m.FemelList.Add(patchCounter[0]);

    //Determine number of actions needed to harvest whole area once. Start with one
    //patch in the middle, increase the "circle" by a half patch each date
    int p = 0;
    for (int j = 0; j < 100; j++)
    {
        if (patchCounter[j] >= runNumber) { break; }
        patchCounter[j + 1] = patchCounter[j] + kArea * (3 + p);
        m.FemelList.Add(patchCounter[j + 1] - patchCounter[j]);
        actionNumber++;
    }
}

```

```

        p = p + 2;
    }

    //If more patches are scheduled to be harvested than patches exist, calculate the
    //rest and write that number to the last place in the FemellList
    Array.Resize(ref patchCounter, actionNumber);
    if (patchCounter[actionNumber-1] > runNumber)
    { m.FemellList[actionNumber-1] = runNumber - patchCounter[actionNumber-2]; }

    if (actionNumber > kCycleLength)
    {
        Message.WriteLine("Problem with group selection: stand cannot be harvested in
        one cycle.");
        Message.WriteLine("Please increase value kArea in management xml file.");
        FORCLIM.Terminate();
        Environment.Exit(0);
    }

    //Calculate dates of actions: whole area is harvested once in time of kCycleLength
    intervall = kCycleLength / actionNumber;

    //Date of first action is the value kCycleYear
    tempTimeLineArray[0] = kStart + kCycleYear;

    //Set Length to 1 (there is already one action in the array)
    //Calculate the dates of all further actions
    int tempLength = 1;

    for (int i = 1; i < actionNumber; i++)
    {
        tempTimeLineArray[i] = tempTimeLineArray[i - 1] + intervall;
        tempLength++;
    }

    //Calculate the dates of the actions of all further cycles (if any)
    int Counter = tempLength;
    for (int i = 0; i < kEnd - kStart; i++)
    {
        if (tempTimeLineArray[i] + kCycleLength >= kEnd) { break; }
        tempTimeLineArray[i + tempLength] = tempTimeLineArray[i] + kCycleLength;
        Counter++;
    }
    int gLength = Counter;
    Array.Resize(ref tempTimeLineArray, gLength);

    //Create a 2D-Array with the IDs for phase and operation
    int[,] tempIDArray = new int[gLength, 2];
    for (int i = 0; i < gLength; i++)
    {tempIDArray[i, 0] = Convert.ToInt16(managementData["operations"][y]["ID"].Value);}

    for (int i = 0; i < gLength; i++)
    { tempIDArray[i, 1] = Convert.ToInt16(managementData["operations"][y]["operation"]
    ["ID"].Value); }

    //Copy the temp arrays to new arrays the MasterTimeLine has access to
    ManagementTimeline.IDArray = new int[gLength, 2];
    Array.Copy(tempIDArray, ManagementTimeline.IDArray, gLength * 2);

    ManagementTimeline.TimeLineArray = new int[gLength];
    Array.Copy(tempTimeLineArray, ManagementTimeline.TimeLineArray, gLength);

    ManagementTimeline.Length = gLength;
}
}
//=====

```

## Class Management Phase

```

//=====
// FORCLIM: Management subclass with description of all silvicultural treatments
// Livia Rasche 2009
//=====

using System;
using ETH.FE.XML;
using System.Collections;

```

```

class ManagementPhase
{
    Management m;           //parent class

    int runNumber;           //Number of stochastic runs
    double TotTrs;           //number of trees on patch
    int gClassWidth;         //width of diameter classes
    int DDArrLength;         //length of array that stores the diameter distribution
    int[] DDArr;             //array with the diameter distribution in classes
    int kArea;               //amount of patches to be harvested each time
    int gTrs;                //number of trees in cohort
    int dTrs;                //dead trees
    double kIntensity;        //percentage of trees to be harvested on one patch
    int gCallim;             //callipering limit
    bool isTarget;           //flag for allowing target cutting after shelterwood

    ArrayList gdeadCohortList; //auxiliary list
    ArrayList DList;           //arraylist with the diameters of all trees in the stand
    ArrayList DListPatch;     //arraylist with the diameters of all trees on one patch
    ArrayList patchList;      //List of patch IDs, keeps track of patches still to be
                                //harvested in Strip and Femel
    ArrayList patchIDList;     //List with IDs of all patches (usually 0-199)

    public ManagementPhase(Management management)
    {
        m = management;
        patchList = new ArrayList();
        //Initialize patchList here so that its data is stored throughout simulation
        for (int d=0; d<m.runNumber; d++)
        { patchList.Add(d); }

        isTarget = true;
    }
}
//-----
public void Initialize(ModelData modelData, DataNode configData)
{
    runNumber = Convert.ToInt16(configData["simulation"]["runNumber"].Value);
    gClassWidth = 1;
    DDArrLength = 450;      //dummy value
    gCallim = 1;

    m.cutTreeList = new ArrayList();
    m.cutBAList = new ArrayList();
    m.cutDList = new ArrayList();
    m.cutHList = new ArrayList();

    patchIDList = new ArrayList();
    for (int d=0; d<m.runNumber; d++)
    { patchIDList.Add(d); }
}
//-----
//Depending on thinning type, remove single trees that fall into the chosen diameter class
//until an optimal basal area is reached on patch
public void Thinning(int kType, DataNode managementData, int[] harvestSpeciesArray)
//public void Thinning(int kType, DataNode managementData, int[] harvestSpeciesArray,
//    double kIntensity)
{
    double kIntensity = Convert.ToDouble(managementData["harvest"][kType]["kIntensity"].Value);
    double kKb = Convert.ToDouble(managementData["harvest"][kType]["kb"].Value);
    int gClassWidth = 1;      //width of diameter classes
    double gActBA = 0.0;     //actual total basal area on patch
    double availBA = 0.0;    //BA of all the species in the harvest species file
    double OptBA;            //optimal basal area of patch
    double D63;              //diameter that 63% of trees on patch are thinner than
    double D95;              //diameter that 95% of trees on patch are thinner than
    double cAB;              //Weibull parameter
    double aAB;              //Weibull parameter
    double bGB;              //Weibull parameter
    double bAB;              //Weibull parameter
    double DThin;            //diameter of tree to be removed
    int DClass;              //diameter class of cohort
    int DThinClass;          //diameter class of cohort to be thinned
    int dTrs;                //number of dead trees in cohort
    ArrayList harvestCohortList; //list with harvestable species
    ArrayList harvestSpeciesIDList; //auxiliary list for storing those species
                                //that own cohorts that can be harvested
}

```

```

//Adjust callipering limit if the type is 00
//Note: adjustment not necessary right now, as gCallim is 1 already
if (kType == 0)
{ gCallim = 1; }

//Calculate Weibull parameters once for whole stand
D63 = Percentil()[0];
D95 = Percentil()[1];
aAB = Percentil()[2];
if (D63 == aAB) {D63 = aAB + 0.01;} //fail-safe against dividing by 0
cAB = 1.09719 / Math.Log((D95 - aAB) / (D63 - aAB));
bGB = D63 - aAB;
bAB = bGB / kKb;

//Go to each patch now and actually remove the trees there
for (int i = 0; i < runNumber; i++)
{
    //DDistribution(i); //Calculate diameter distribution for patch
    DDistribution(i, harvestSpeciesArray);

    //Get the actual basal area on patch, but consider only those trees larger
    //than the callipering limit and those marked as harvestable
    gActBA = 0;
    foreach (Species species in m.plant[i].speciesArray)
    {
        if (((IList)harvestSpeciesArray).Contains(species.kID))
        {
            foreach (Cohort cohort in species.cohortList)
            {
                if (cohort.Diameter >= gCallim)
                { gActBA += cohort.BasalArea; }
            }
        }
    }

    //Determine the target basal area depending on percentage to be removed
    OptBA = gActBA - (gActBA * kIntensity);
    //OptBA = kResBA*m.kPatchSize;

    //Check if optimal basal area can be reached using only the species in the harvest file
    availBA = 0;
    foreach (Species species in m.plant[i].speciesArray)
    {
        if (((IList)harvestSpeciesArray).Contains(species.kID))
        {
            foreach (Cohort cohort in species.cohortList)
            {
                if (cohort.Diameter > gCallim)
                { availBA += cohort.BasalArea; }
            }
        }
    }

    if (availBA < gActBA - OptBA)
    {
        Message.WriteLine("Problem with thinning: Optimal basal area cannot be reached.");
        Message.WriteLine("Please expand the species list in the harvest species file or reduce
        the intensity.");
        FORCLIM.Terminate();
        Environment.Exit(0);
    }

    //Calculate diameter of tree to be thinned and remove it from a fitting random
    //cohort of random species. Continue until the optimal basal area is reached
    while (OptBA < gActBA)
    {
        //Calculate the diameter
        DThin = bAB * Math.Pow((-Math.Log(1 - m.uniRand.NextDouble())),(1 / cAB)) + aAB;

        //Determine its class
        DThinClass = (int)DThin / gClassWidth;

        //Determine whether the diameter distribution has trees in this class. If not,
        //go one class higher until there are trees
        bool breakLoop = false;
        while (breakLoop == false && DThinClass < DDArrayLength)
        {
            if (DDArray[DThinClass] > 0) { breakLoop = true; }
        }
    }
}

```

```

        else { DThinClass++; }
    }

    //If there were no trees left at all in the higher classes, assign 0
    //to the class to let it fall through
    if (DThinClass == DArrayLength) { DThinClass = 0; }

    //Write all cohorts with the specified diameter class into a list and
    //pick one randomly. Write the corresponding species-ID in a separate
    //list to be able to remove the correct cohort later
    harvestCohortList = new ArrayList();
    harvestSpeciesIDList = new ArrayList();
    int dummyID = 0; //construct
    foreach (Species species in m.plant[i].speciesArray)
    {
        if (((IList)harvestSpeciesArray).Contains(species.kID))
        {
            foreach (Cohort cohort in species.cohortList)
            {
                DClass = (int)cohort.Diameter / gClassWidth;
                if (DClass == DThinClass)
                {
                    harvestCohortList.Add(cohort);
                    harvestSpeciesIDList.Add(dummyID);
                }
            }
        }
        dummyID++;
    }

    //This "if" is necessary to let diameters fall through if they have
    //been set to 0 because in this case the harvestCohortList is empty
    if (harvestCohortList.Count > 0)
    {
        int randomCohort = m.uniRand.Next(harvestCohortList.Count - 1);
        Cohort harvestCohort = (Cohort)harvestCohortList[randomCohort];
        int SpID = (int)harvestSpeciesIDList[randomCohort];

        dTrs = 0;
        dTrs++;
        collectData(harvestCohort); //collect for the harvest log
        DArray[DThinClass]--; //reduce tree no in dc. by one
        double biomass = harvestCohort.Biomass;

        //update tree number in cohort; if there are no trees left, remove it
        if (harvestCohort.Chop(dTrs))
        {
            CohortsSQLiteView.AddDeadCohort(i, SpID, 2, 1, harvestCohort.
            Height, harvestCohort.Diameter, biomass-harvestCohort.Biomass);
            m.plant[i].speciesArray[SpID].cohortList.Remove(harvestCohort);
            m.plant[i].speciesArray[SpID].deadCohortList.Add(harvestCohort);
            harvestCohortList.Remove(harvestCohort);
            harvestSpeciesIDList.RemoveAt(randomCohort);
        }
        //Recalculate the basal area of patch
        gActBA = 0;
        foreach (Species species in m.plant[i].speciesArray)
        {
            if (((IList)harvestSpeciesArray).Contains(species.kID))
            {
                foreach (Cohort cohort in species.cohortList)
                {
                    if (cohort.Diameter >= gCallim)
                    { gActBA += cohort.BasalArea; }
                }
            }
        }
    }
}

//-----
//Perform clearcut on a static number of randomly chosen patches each harvest date
//Cut each patch only once per cycle
public void Stripfelling(int kType, DataNode managementData, int[] harvestSpeciesArray)
{
    kArea = Convert.ToInt16(managementData["harvest"][kType]["kArea"].Value);
    int i = 0; //patch-ID, is chosen randomly to pick the next patch for harvest

```

```

for (int l = 0; l < kArea; l++)
{
    //Draw ID from patch to be harvested from patch list. Remove the ID. If patch
    //list is empty, copy IDs to it again.
    if (patchList.Count == 0) {patchList.AddRange(patchIDList);}
    i = (int)patchList[0];
    patchList.RemoveAt(0);

    //On the chosen patch, remove all cohorts (if they belong to a species that is allowed to
    //be harvested)
    for (int j = 0; j < m.plant[i].speciesArray.Length; j++)
    {
        gdeadCohortList = new ArrayList();
        foreach (Cohort cohort in m.plant[i].speciesArray[j].cohortList)
        {
            if (((IList)harvestSpeciesArray).Contains(m.plant[i].speciesArray[j].kID))
            {
                gTrs = cohort.Trees;
                dTrs = gTrs;
                for (int k = 0; k < gTrs; k++) { collectData(cohort); }
                double biomass = cohort.Biomass;
                cohort.Chop(dTrs);
                gdeadCohortList.Add(cohort);
                CohortsSQLiteView.AddDeadCohort(i, j, 2, dTrs, cohort.Height,cohort.Diameter,
                biomass-cohort.Biomass);
            }
        }
        foreach (Cohort cohort in gdeadCohortList)
        {
            m.plant[i].speciesArray[j].cohortList.Remove(cohort);
            m.plant[i].speciesArray[j].deadCohortList.Add(cohort);
        }
    }
}

}
//-----
//Perform clearcut on an increasing number of randomly chosen patches each harvest date
//Cut each patch only once per cycle
public void Femel(int kType, DataNode managementData, int[] harvestSpeciesArray, int gPatchNb)
{
    int i = 0; //randomly chosen patch for harvest
    //Note: gPatchNb gives the number of patches to be harvested this timestep
    //More patches than runs exist are scheduled for harvest. Stop harvest when every patch
    //has been harvested once
    for (int l = 0; l < gPatchNb; l++)
    {
        //Draw ID from patch to be harvested from patch list. Remove the ID. If patch
        //list is empty, copy IDs to it again.
        if (patchList.Count == 0) {patchList.AddRange(patchIDList);}
        i = (int)patchList[0];
        patchList.RemoveAt(0);

        //On the chosen patch, remove all cohorts (if they belong to a species that is
        //allowed to be harvested)
        for (int j = 0; j < m.plant[i].speciesArray.Length; j++)
        {
            gdeadCohortList = new ArrayList();
            foreach (Cohort cohort in m.plant[i].speciesArray[j].cohortList)
            {
                if (((IList)harvestSpeciesArray).Contains(m.plant[i].speciesArray[j].kID))
                {
                    gTrs = cohort.Trees;
                    dTrs = gTrs;
                    for (int k = 0; k < gTrs; k++) { collectData(cohort); }
                    double biomass = cohort.Biomass;
                    cohort.Chop(dTrs);
                    gdeadCohortList.Add(cohort);
                    CohortsSQLiteView.AddDeadCohort(i, j, 2, dTrs, cohort.Height,cohort.Diameter,
                    biomass-cohort.Biomass);
                }
            }
            foreach (Cohort cohort in gdeadCohortList)
            { m.plant[i].speciesArray[j].cohortList.Remove(cohort);
              m.plant[i].speciesArray[j].deadCohortList.Add(cohort); }
        }
    }
}
//-----

```

```

//Cut those trees that have reached the target diameter (intensity can be modified)
public void Targetcut(int kType, DataNode managementData, int[] harvestSpeciesArray)
{
    if (isTarget==false) { return; }
    kIntensity = Convert.ToDouble(managementData["harvest"][kType]["kIntensity"].Value);
    double kTargetDBH = Convert.ToInt16(managementData["harvest"][kType]["kTargetDBH"].Value);
    //target DBH at which tree is harvested
    double Diameter; //Cohort diameter

    for (int i = 0; i < runNumber; i++)
    for (int j = 0; j < m.plant[i].speciesArray.Length; j++)
    {
        gdeadCohortList = new ArrayList();
        foreach (Cohort cohort in m.plant[i].speciesArray[j].cohortList)
        {
            if (((IList)harvestSpeciesArray).Contains(m.plant[i].speciesArray[j].kID))
            {
                Diameter = cohort.Diameter;
                gTrs = cohort.Trees;
                dTrs = 0;
                for (int k = 0; k < gTrs; k++)
                {
                    if (m.uniRand.NextDouble() <= kIntensity && Diameter >= kTargetDBH)
                    { dTrs++; collectData(cohort); }
                }
                double biomass = cohort.Biomass;
                if (cohort.Chop(dTrs))
                {
                    gdeadCohortList.Add(cohort);
                    m.plant[i].speciesArray[j].deadCohortList.Add(cohort);
                }
                CohortsSQLiteView.AddDeadCohort(i, j, 2, dTrs, cohort.Height, cohort.Diameter,
                    biomass-cohort.Biomass);
            }
        }
        foreach (Cohort cohort in gdeadCohortList)
        { m.plant[i].speciesArray[j].cohortList.Remove(cohort); }

        //If planting is true, forward species IDs and sapling numbers to Planting()
        if (m.isPlanting == true)
        {
            for (int k = 0; k < m.gPlantingSpeciesnumber; k++)
            {
                if (m.plantingSpecies[k, 0] == m.plant[i].speciesArray[j].kID)
                { Planting(i, j, k); }
            }
        }
    }
}

//-----
//Cut down each cohort (intensity can be modified)
public void Clearcut(int kType, DataNode managementData, int[] harvestSpeciesArray)
{
    kIntensity = Convert.ToDouble(managementData["harvest"][kType]["kIntensity"].Value);

    for (int i = 0; i < runNumber; i++)
    for (int j = 0; j < m.plant[i].speciesArray.Length; j++)
    {
        gdeadCohortList = new ArrayList();
        foreach (Cohort cohort in m.plant[i].speciesArray[j].cohortList)
        {
            if (((IList)harvestSpeciesArray).Contains(m.plant[i].speciesArray[j].kID))
            {
                gTrs = cohort.Trees;
                dTrs = 0;
                for (int k = 0; k < gTrs; k++)
                {
                    if (m.uniRand.NextDouble() <= kIntensity)
                    { dTrs++; collectData(cohort); }
                }
                double biomass = cohort.Biomass;
                if (cohort.Chop(dTrs))
                {
                    gdeadCohortList.Add(cohort);
                    m.plant[i].speciesArray[j].deadCohortList.Add(cohort);
                }
                CohortsSQLiteView.AddDeadCohort(i, j, 2, dTrs, cohort.Height, cohort.Diameter,
                    biomass-cohort.Biomass);
            }
        }
    }
}

```

```

    }
    foreach (Cohort cohort in gdeadCohortList)
    { m.plant[i].speciesArray[j].cohortList.Remove(cohort); }

    //If planting is true, forward species IDs and sapling numbers to Planting()
    if (m.isPlanting == true)
    {
        for (int k = 0; k < m.gPlantingSpeciesnumber; k++)
        {
            if (m.plantingSpecies[k, 0] == m.plant[i].speciesArray[j].kID)
            { Planting(i, j, k); }
        }
    }
}
}
//-----
//Cut all trees except some that are left standing to shelter the saplings (intensity of cut
//can be modified)
public void Shelterwood(int kType, DataNode managementData, int[] harvestSpeciesArray)
{
    kIntensity = Convert.ToDouble(managementData["harvest"][kType]["kIntensity"].Value);
    double kShelterDens = Convert.ToDouble(managementData["harvest"][kType]["kShelterDens"].Value);
    //density of sheltering trees
    int kMinH = Convert.ToInt16(managementData["harvest"][kType]["kMinH"].Value);
    //minimum height of sheltering trees
    int kMaxH = Convert.ToInt16(managementData["harvest"][kType]["kMaxH"].Value);
    //maximum height of sheltering trees
    double Height; //cohort height
    int gShelterTreeCounter = 0; //variable to count the trees in the height window

    for (int i = 0; i < runNumber; i++)
    {
        //Check first if there are trees in the specified height window. If not, abort action.
        for (int j = 0; j < m.plant[i].speciesArray.Length; j++)
        {
            foreach (Cohort cohort in m.plant[i].speciesArray[j].cohortList)
            {
                if (((IList)harvestSpeciesArray).Contains(m.plant[i].speciesArray[j].kID))
                {
                    Height = cohort.Height;
                    if (Height <= kMaxH && Height >= kMinH)
                    { gShelterTreeCounter += cohort.Trees; }
                }
            }
        }
    }

    if (gShelterTreeCounter < runNumber/4 || kShelterDens == 0.0) { isTarget=false; return; }
    else { isTarget = true; }

    for (int i = 0; i < runNumber; i++)
    for (int j = 0; j < m.plant[i].speciesArray.Length; j++)
    {
        gdeadCohortList = new ArrayList();
        foreach (Cohort cohort in m.plant[i].speciesArray[j].cohortList)
        {
            //Concerns the species that is/are meant to shelter
            if (((IList)harvestSpeciesArray).Contains(m.plant[i].speciesArray[j].kID))
            {
                Height = cohort.Height;
                gTrs = cohort.Trees;
                dTrs = 0;
                for (int k = 0; k < gTrs; k++)
                {
                    //cut those trees of the sheltering species that have the wrong height
                    if (Height > kMaxH || Height < kMinH)
                    {
                        if (m.uniRand.NextDouble() <= kIntensity)
                        { dTrs++; collectData(cohort); }
                    }
                }
                //remove some of the sheltering trees depending on specified density
                else
                {
                    if (m.uniRand.NextDouble() > kShelterDens)
                    { dTrs++; }
                }
            }
        }
        double biomass = cohort.Biomass;
        if (cohort.Chop(dTrs))
    }
}

```

```

    {
        gdeadCohortList.Add(cohort);
        m.plant[i].speciesArray[j].deadCohortList.Add(cohort);
    }
    CohortsSQLiteView.AddDeadCohort(i, j, 2, dTrs, cohort.Height, cohort.Diameter,
    biomass-cohort.Biomass);
}
//Concerns all other species
else
{
    gTrs = cohort.Trees;
    dTrs = 0;
    for (int k = 0; k < gTrs; k++)
    {
        if (m.uniRand.NextDouble() <= kIntensity)
        { dTrs++; collectData(cohort); }
    }
    double biomass = cohort.Biomass;
    if (cohort.Chop(dTrs))
    {
        gdeadCohortList.Add(cohort);
        m.plant[i].speciesArray[j].deadCohortList.Add(cohort);
    }
    CohortsSQLiteView.AddDeadCohort(i, j, 2, dTrs, cohort.Height, cohort.Diameter,
    biomass-cohort.Biomass);
}
}
foreach (Cohort cohort in gdeadCohortList)
{ m.plant[i].speciesArray[j].cohortList.Remove(cohort); }

//If planting is true, forward species IDs and sapling numbers to Planting()
if (m.isPlanting == true)
{
    for (int k = 0; k < m.gPlantingSpeciesnumber; k++)
    {
        if (m.plantingSpecies[k, 0] == m.plant[i].speciesArray[j].kID)
        { Planting(i, j, k); }
    }
}
}
}
//-----
//Calculate an ideal number of trees in certain diameter classes and remove the surplus
public void Plenter(int kType, DataNode managementData, int[] harvestSpeciesArray)
//public void Plenter(int kType, DataNode managementData, int[] harvestSpeciesArray, double kResBA)
{
    double kq = Convert.ToDouble(managementData["harvest"][kType]["kq"].Value);
    int kTargetDBH = Convert.ToInt16(managementData["harvest"][kType]["kTargetDBH"].Value);
    double kResBA = Convert.ToDouble(managementData["harvest"][kType]["kResBA"].Value);
    gClassWidth = Convert.ToInt16(managementData["harvest"][kType]["kClassWidth"].Value);
    double k2 = Math.PI / 40000; //parameter
    double k3 = 0.0; //parameter
    int gClassesPlent = 0; //number of classes left according to plenter equation
    double N1 = 0.0; //number of trees in largest dbh-class
    double[] EquDDArray; //array with equilibrium number of trees for each class
    int DClass; //diameter class of cohort (class width 1cm)
    int dTrs; //number of dead trees in cohort
    double Diameter; //Cohort diameter
    ArrayList harvestCohortList; //list with harvestable species
    ArrayList harvestSpeciesIDList; //auxiliary list for storing species with harvest. coh.

    //Calculate parameter for plenter equation
    gClassesPlent = kTargetDBH / gClassWidth; //should be gClassWidth+1, but Cancino et al.
    //count differently
    k3 = k2 * Math.Pow(gClassWidth, 2) * ((Math.Pow(gClassesPlent, 2) / (1 - kq)) - ((2 *
    gClassesPlent * kq) / Math.Pow((1 - kq), 2)) + ((kq * (1 + kq) * (1 -
    Math.Pow(kq, gClassesPlent))) / (Math.Pow((1 - kq), 3))));

    //Calculate ideal number of trees in largest class per hectar
    N1 = kResBA / k3;

    //Calculate ideal number of trees in all other classes and store them in arrayList
    //(Class with smallest diameter first, counting up until last occupied class)
    EquDDArray = new double[(int)gClassesPlent];
    for (int j = 0; j < gClassesPlent - 1; j++)
    {
        //--1 because last space in array is filled outside the for loop
        EquDDArray[j] = Math.Pow(kq, gClassesPlent - (j + 1)) * N1; }
    EquDDArray[(int)gClassesPlent - 1] = N1; //Add largest class to the end of the array
}

```

```

//In a first step remove all trees thicker than the desired target diameter
for (int i = 0; i < runNumber; i++)
for (int j = 0; j < m.plant[i].speciesArray.Length; j++)
{
    gdeadCohortList = new ArrayList();
    foreach (Cohort cohort in m.plant[i].speciesArray[j].cohortList)
    {
        Diameter = cohort.Diameter;
        if (Diameter >= kTargetDBH)
        {
            gTrs = cohort.Trees;
            dTrs = gTrs;
            for (int k = 0; k < gTrs; k++) { collectData(cohort); }
            double biomass = cohort.Biomass;
            cohort.Chop(dTrs);
            gdeadCohortList.Add(cohort);
            m.plant[i].speciesArray[j].deadCohortList.Add(cohort);
            CohortsSQLiteView.AddDeadCohort(i, j, 2, dTrs, cohort.Height, cohort.Diameter,
            biomass-cohort.Biomass);
        }
    }
    foreach (Cohort cohort in gdeadCohortList)
    { m.plant[i].speciesArray[j].cohortList.Remove(cohort); }
}

//In a second step remove the surplus trees in the diameter classes of the equilibrium //equation.
First determine the actual basal area and compare it to the desired one. Proceed //only if the basal
area is larger and then only until the desired BA is reached.

//Recalculate ResBA from ha to stand (and from m2 to ha (area) and from m2 to cm2 (BA) -> cancels each
other)
double gResBA = kResBA * (m.kPatchSize * m.runNumber);
double gActBA = 0.0;

for (int i = 0; i < runNumber; i++)
{
    foreach (Species species in m.plant[i].speciesArray)
    {
        gActBA += species.BasalArea;
    }
}

//Create array with shuffled patch-IDs
ArrayList tempPatchList;
ArrayList randPatchList;
tempPatchList = new ArrayList();
randPatchList = new ArrayList();
int t = 0;
int d = 0;

for (int j = 0; j < runNumber; j++)
{tempPatchList.Add(j); }

for (int k = 0; k < runNumber; k++)
{
    t = m.uniRand.Next(tempPatchList.Count);
    d = (int)tempPatchList[t];
    randPatchList.Add(d);
    tempPatchList.Remove(d);
}

foreach(int i in randPatchList)
//for (int i = 0; i < runNumber; i++)
{
    if (gActBA > gResBA)
    {
        //Determine number of diameter classes on patch
        DDistribution(i); //Calculates the current diameter distribution of this patch
        Array.Resize(ref DArray, (int)gClassesPlent);

        //Declare new array and recalculate tree numbers of EquDDArray from ha to patchsize
        double[] EquDDPatchArray = new double[(int)gClassesPlent];
        Array.Copy(EquDDArray, EquDDPatchArray, (int)gClassesPlent);
        for (int j = 0; j < EquDDPatchArray.Length; j++)
        { EquDDPatchArray[j] = Math.Round((EquDDPatchArray[j] / 10000) * m.kPatchSize); }

        //If there are more trees in a class than the equilibrium would recommend, reduce number
        //of trees in this class to optimum
        for (int n = 0; n < EquDDPatchArray.Length; n++)
        {
            if (EquDDPatchArray[n] < DArray[n] && gActBA > gResBA)

```

```

    {
        //Write all cohorts with the specified diameter class into a list
        //Write the corresponding species-ID in a separate list to remove cohort later
        harvestCohortList = new ArrayList();
        harvestSpeciesIDList = new ArrayList();
        int gSpeciesArrayPos = 0;
        foreach (Species species in m.plant[i].speciesArray)
        {
            if (((IList)harvestSpeciesArray).Contains(species.kID))
            {
                foreach (Cohort cohort in species.cohortList)
                {
                    DClass = (int)cohort.Diameter / gClassWidth;
                    if (DClass == n)
                    {
                        harvestCohortList.Add(cohort);
                        //harvestSpeciesIDList.Add(species.kID);
                        harvestSpeciesIDList.Add(gSpeciesArrayPos);
                    }
                }
                gSpeciesArrayPos++;
            }
        }

        //Determine the number of trees that should theoretically be removed and compare this number
        //to the trees available on this patch. Decrease the number if there are not enough.
        int treesToGo = (int)Math.Round(DDArray[n] - EquDDPatchArray[n]);
        int availTrees = 0;
        foreach (Cohort cohort in harvestCohortList)
        { availTrees += cohort.Trees; }
        if (availTrees < treesToGo)
        { treesToGo = availTrees; }

        //Remove trees randomly as long as the equilibrium number for this class is not reached
        while (treesToGo > 0)
        {
            int randomCohort = m.uniRand.Next(harvestCohortList.Count - 1);
            Cohort harvestCohort = (Cohort)harvestCohortList[randomCohort];
            int SpID = (int)harvestSpeciesIDList[randomCohort];
            dTrs = 1;
            treesToGo--;
            collectData(harvestCohort);
            gActBA = gActBA - ( harvestCohort.BasalArea / harvestCohort.Trees );
            double biomass = harvestCohort.Biomass;

            //update tree number in cohort; if there are no trees left, remove it
            if (harvestCohort.Chop(dTrs))
            {
                m.plant[i].speciesArray[SpID].cohortList.Remove(harvestCohort);
                m.plant[i].speciesArray[SpID].deadCohortList.Add(harvestCohort);
                harvestCohortList.Remove(harvestCohort);
                harvestSpeciesIDList.RemoveAt(randomCohort);
            }
            CohortsSQLiteView.AddDeadCohort(i, SpID, 2, dTrs, harvestCohort.Height,
            harvestCohort.Diameter, biomass-harvestCohort.Biomass);
        }
    }
}

//-----
public void Planting(int i, int j, int k)
{
    int nTrs = 0;
    //Convert number of saplings per hectare to number of saplings per patch
    nTrs = (int)Math.Round(m.kPatchSize * m.plantingSpecies[k, 1] / 10000);

    //Adds a new cohort of the specified species with the specified number of trees
    m.plant[i].speciesArray[j].cohortList.Add(new Cohort(m.plant[i],
    m.plant[i].speciesArray[j], nTrs));
}

//-----
//Auxiliary methods for Thinning() and Planter()
//-----
public void DDistribution(int i, int[] harvestSpeciesArray)
//Calculate the diameter distribution of current patch
{
    DListPatch = new ArrayList();

```

```

for (int j = 0; j < m.plant[i].speciesArray.Length; j++)
{
    if (((IList)harvestSpeciesArray).Contains(m.plant[i].speciesArray[j].kID))
    {
        foreach (Cohort cohort in m.plant[i].speciesArray[j].cohortList)
        {
            gTrs = cohort.Trees;
            for (int k = 0; k < gTrs; k++)
            {
                DListPatch.Add(cohort.Diameter);
                TotTrs++;
            }
        }
    }
}
DListPatch.Sort();

int DCls = 0;
DDArray = new int[DDArrayLength];

foreach (double d in DListPatch)
{
    DCls = (int)d / gClassWidth;
    DDArray[DCls] = DDArray[DCls] + 1;
}
}
//-----
public void DDistribution(int i)
//Calculate the diameter distribution of current patch
{
    DListPatch = new ArrayList();
    for (int j = 0; j < m.plant[i].speciesArray.Length; j++)
    {
        foreach (Cohort cohort in m.plant[i].speciesArray[j].cohortList)
        {
            gTrs = cohort.Trees;
            for (int k = 0; k < gTrs; k++)
            {
                DListPatch.Add(cohort.Diameter);
                TotTrs++;
            }
        }
    }
    DListPatch.Sort();

    int DCls = 0;
    DDArray = new int[DDArrayLength];

    foreach (double d in DListPatch)
    {
        DCls = (int)d / gClassWidth;
        DDArray[DCls] = DDArray[DCls] + 1;
    }
}
//-----
public double[] Percentil()
//Determine the DBH that 63% of trees are thinner than and smallest DBH on patch
{
    DList = new ArrayList(); //arraylist with the diameters of all trees on patch
    double[] gArray = new double[3]; //vehicle for returning three values from this method
    int gTrs; //auxiliary variable for total number of trees in each cohort
    TotTrs = 0.0; //total number of trees on patch
    int p63Trs; //63% of all trees
    int p95Trs; //95% of all trees

    for (int i = 0; i < runNumber; i++)
    for (int j = 0; j < m.plant[i].speciesArray.Length; j++)
    {
        foreach (Cohort cohort in m.plant[i].speciesArray[j].cohortList)
        {
            if (cohort.Diameter >= gCallim)
            {
                gTrs = cohort.Trees;
                for (int k = 0; k < gTrs; k++)
                {
                    DList.Add(cohort.Diameter);
                    TotTrs++;
                }
            }
        }
    }
}

```

```

    }
}
DList.Sort();
p63Trs = (int)Math.Round(TotTrs / 100 * 63);
p95Trs = (int)Math.Round(TotTrs / 100 * 95);

gArray[0] = (double)DList[p63Trs];           //DBH 63% of trees are smaller than
gArray[1] = (double)DList[p95Trs];           //DBH 95% of trees are smaller than
gArray[2] = (double)DList[0];                 //1.27;    //smallest diameter present on patch

return gArray;
}

//-----
//Method to collect the data for the harvest log file
//-----
public void collectData(Cohort cohort)
{
    m.cutTreeList.Add(cohort.Trees / cohort.Trees);
    m.cutBAList.Add(cohort.BasalArea / cohort.Trees);
    m.cutDList.Add(cohort.Diameter);
    m.cutHList.Add(cohort.Height);
}
//-----
}
//=====

```

## Class Management View

```

//=====
// FORCLIM: Management subclass that writes harvest log
// Livia Rasche 2009
//=====

using System;
using System.IO;
using System.Collections;

class ManagementView
{
    Management m;
    StreamWriter strmWriter;           //Output stream writer
    PatchStat rTreeSumArray;           //pre-defined array, has useful method PatchStat.Mean
    PatchStat rBASumArray;

    public ManagementView(Management management)
    {
        m = management;

        string name = m.configData["results"]["name"].Value;
        string path = m.configData["results"]["path"].Value;
        string simName = m.configData["simulation"]["name"].Value;
        string dirName = path + name + "_" + simName + "_Results/Stand_Results/";

        strmWriter = new StreamWriter(dirName + "HarvestLog.DAT");
    }

    public void Initialise()
    {
        //Write output file header
        strmWriter.WriteLine();
        strmWriter.WriteLine("=====");
        strmWriter.WriteLine("Log file for harvest operations");
        strmWriter.WriteLine("=====");
        strmWriter.WriteLine();
        strmWriter.Write("{0,38}", "Stand residual");
        strmWriter.Write("{0,47}", "Stand harvested");
        strmWriter.WriteLine();
        strmWriter.Write("{0,14}", "Treatment");
        strmWriter.Write("{0,8}", "Time");
        strmWriter.Write("{0,16}", "Stem number");
        strmWriter.Write("{0,12}", "BA");
        strmWriter.Write("{0,9}", "mD");
        strmWriter.Write("{0,9}", "mH");
    }
}

```

```

        strmWriter.Write("{0,17}", "Stem number");
        strmWriter.Write("{0,12}", "BA");
        strmWriter.Write("{0,9}", "mD");
        strmWriter.Write("{0,9}", "mH");
        strmWriter.Write("{0,14}", "D5/95");
        strmWriter.Write("{0,11}", "H5/95");
        strmWriter.WriteLine();
        strmWriter.Write("{0,14}", "[-]");
        strmWriter.Write("{0,8}", "[yrs]");
        strmWriter.Write("{0,16}", "[#/ha]");
        strmWriter.Write("{0,12}", "[m^2/ha]");
        strmWriter.Write("{0,9}", "[cm]");
        strmWriter.Write("{0,9}", "[cm]");
        strmWriter.Write("{0,17}", "[#/ha]");
        strmWriter.Write("{0,12}", "[m^2/ha]");
        strmWriter.Write("{0,9}", "[cm]");
        strmWriter.Write("{0,9}", "[cm]");
        strmWriter.Write("{0,14}", "[cm]");
        strmWriter.Write("{0,11}", "[cm]");
        strmWriter.WriteLine();
        strmWriter.WriteLine();

        strmWriter.Flush();
    }

    public void WriteLog()
    {
        //Calculate expanse of simulated area, convert from m^2 to ha
        double gHa = m.runNumber * m.kPatchSize / 10000;
        int precision = 1; //amount of digits after comma

        //Get number of residual trees per hectare
        double rTreeSum = 0;
        rTreeSumArray = new PatchStat(m.runNumber);
        for (int i = 0; i < m.runNumber; i++)
        { rTreeSumArray[i] = m.plant[i].Trees(); }
        rTreeSum = Math.Round(rTreeSumArray.Mean);

        //Get basal area of residual stand per hectare
        double rBASum = 0;
        rBASumArray = new PatchStat(m.runNumber);
        for (int i = 0; i < m.runNumber; i++)
        { rBASumArray[i] = m.plant[i].BasalArea(); }
        rBASum = Math.Round(rBASumArray.Mean, precision);

        //Calculate mean diameter and height of residual trees
        double rMeanD = 0.0;
        double rMeanH = 0.0;
        int gTrs = 0;
        double DSum = 0.0;
        double HSum = 0.0;
        ArrayList rDList = new ArrayList();
        ArrayList rHList = new ArrayList();
        for (int i = 0; i < m.runNumber; i++)
        {
            for (int j = 0; j < m.plant[i].speciesArray.Length; j++)
            {
                foreach (Cohort cohort in m.plant[i].speciesArray[j].cohortList)
                {
                    gTrs = cohort.Trees;
                    for (int k = 0; k < gTrs; k++)
                    {
                        rHList.Add(cohort.Height);
                        rDList.Add(cohort.Diameter);
                    }
                }
            }
        }
        if (rDList.Count == 0)
        { rMeanD = 0; }
        else
        {
            foreach (double dummyD in rDList)
            { DSum += dummyD; }
            rMeanD = Math.Round(DSum / rDList.Count, precision);
        }

        if (rHList.Count == 0)
        { rMeanH = 0; }
        else
        {

```

---

```

        foreach (double dummyH in rHList)
        { HSum += dummyH; }
        rMeanH = Math.Round(HSum / rHList.Count);
    }

    //Calculate number of felled trees per hectar
    double treeSum = 0;
    foreach (int o in m.cutTreeList)
    { treeSum += o; }
    treeSum = Math.Round(treeSum / gHa);

    //Calculate basal area of felled trees per hectar, convert from cm^2 to m^2
    double BASum = 0;
    foreach (double p in m.cutBAList)
    { BASum += p; }
    BASum = Math.Round((BASum / gHa) / 10000, precision);

    //Calculate mean diameter of felled trees
    double meanD = 0;
    if (m.cutDList.Count == 0)
    { meanD = 0.0; }
    else
    {
        foreach (double q in m.cutDList)
        { meanD += q; }
        meanD = Math.Round(meanD / m.cutDList.Count, precision);
    }

    //Calculate mean height of felled trees
    double meanH = 0;
    if (m.cutHList.Count == 0)
    { meanH = 0.0; }
    else
    {
        foreach (double r in m.cutHList)
        { meanH += r; }
        meanH = Math.Round(meanH / m.cutHList.Count);
    }

    //Calculate 5 and 95 percentile from cutDList
    double Perc5D = 0.0;
    double Perc95D = 0.0;
    int cutDListLength = m.cutDList.Count;
    int D5 = (int)Math.Round((double)cutDListLength / 100 * 5);
    int D95 = (int)Math.Round((double)cutDListLength / 100 * 95);
    if (D95 > cutDListLength - 1)
    { D95 = cutDListLength - 1; }
    double[] CutDArray = new double[cutDListLength];
    Array.Copy((double[])m.cutDList.ToArray(typeof(double)), CutDArray,
        cutDListLength);
    Array.Sort(CutDArray);
    if (cutDListLength == 0)
    {
        Perc5D = 0.0;
        Perc95D = 0.0;
    }
    else
    {
        Perc5D = Math.Round(CutDArray[D5], precision);
        Perc95D = Math.Round(CutDArray[D95], precision);
    }

    //Calculate 5 and 95 percentile from cutHList
    double Perc5H = 0.0;
    double Perc95H = 0.0;
    int cutHListLength = m.cutHList.Count;
    int H5 = (int)Math.Round((double)cutHListLength / 100 * 5);
    int H95 = (int)Math.Round((double)cutHListLength / 100 * 95);
    if (H95 > cutHListLength - 1)
    { H95 = cutHListLength - 1; }
    double[] CutHArray = new double[cutHListLength];
    Array.Copy((double[])m.cutHList.ToArray(typeof(double)), CutHArray,
        cutHListLength);
    Array.Sort(CutHArray);
    if (cutHListLength == 0)
    {
        Perc5H = 0.0;
        Perc95H = 0.0;
    }

```

---

```

else
{
    Perc5H = Math.Round(CutHArray[H5]);
    Perc95H = Math.Round(CutHArray[H95]);
}

//Write to harvest log
strmWriter.Write("{0,14}", m.treatment);
strmWriter.Write("{0,8}", m.plant[0].Time);
strmWriter.Write("{0,16}", rTreeSum);
strmWriter.Write("{0,12}", rBASum);
strmWriter.Write("{0,9}", rMeanD);
strmWriter.Write("{0,9}", rMeanH);
strmWriter.Write("{0,17}", treeSum);
strmWriter.Write("{0,12}", BASum);
strmWriter.Write("{0,9}", meanD);
strmWriter.Write("{0,9}", meanH);
strmWriter.Write("{0,14}", Perc5D + "/" + Perc95D);
strmWriter.Write("{0,11}", Perc5H + "/" + Perc95H);
strmWriter.WriteLine();

    strmWriter.Flush();
}
}
//=====

```

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