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The Fate of Forests in a Changing Climate: Model Validation and Simulation Results From the Alps

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by

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THE ROLE OF FORESTS IN THE ALPS

In the context of climatic change forests are among the most important terrestrial ecosystems. First, forests can bind carbon, store it, and hereby withhold it from the atmosphere in significant amounts. For instance, on a global scale, forests store 80% of the aboveground, 40% of the below ground carbon, which amounts to 62–78% of all carbon stored in the terrestrial biosphere and ca. 61–77% of all carbon in the world's biomass (e.g. Dixon & Turner, 1991; Wisniewski *et al.*, 1993; Dixon *et al.*, 1994; Perruchoud & Fischlin, 1995). Therefore significant changes in the world's forests could exacerbate the radiative forcing by releasing large carbon pulses to the atmosphere (King & Neilson, 1992; Neilson, 1993; Smith & Shugart, 1993).

Aside from carbon, forests and the atmosphere form also an intertwined system, where temperature, precipitation, and winds mould forests and forests feedback to the climatic system via changes in albedo, surface roughness, and evapotranspiration (Manabe &

Weatherald, 1987; Woodward, 1987; Rind *et al.*, 1990; Running & Nemani, 1991; Neilson, 1994). On a regional scale studies have shown the potential of these feed-backs to affect a regional climate (Lean & Warrilow, 1989; Pielke *et al.*, 1994).

Moreover, forests are among the most pristine ecosystems left on this globe. Together with current trends in land-use changes (e.g. Aldhous, 1993; Skole & Tucker, 1993) the latter fact brings increasing importance to forests and their role as a warrant for biodiversity conservation.

On a regional or local scale forests in the Alps fulfil a multitude of other functions. They protect settlements from avalanches or landslides; they regulate runoff, thereby moderating the hydrological regime (Brooks *et al.*, 1991) and helping to prevent erosion at steep slopes; forests and meadows make a varied mountain landscape and provide the environment necessary for various recreational activities; finally, and not least, forests are exploited for fuel, pulpwood, and timber.

LUSH GREEN OR DESERT ? FORESTS AND CLIMATIC CHANGE

The current understanding of the systems and processes involved in the ecology of forests offers many, partly even controversial answers to the question how forests will react to a climatic change (Idso, 1980a; Idso, 1980b; Körner & Arnone-III, 1992b; Körner & Arnone-III, 1992a). The spectrum ranges from severe diebacks (e.g. Neilson, 1993), with the associated consequence of desertification and destabilized slopes, to a general increase in productivity due to elevated temperatures, precipitation and CO₂-concentrations (Kimball & Idso, 1983; Blum, 1991; Graybill & Idso, 1993; Idso & Idso, 1994) plus an invasion by trees into areas above the present timberline (e.g. Kienast, 1989; Kienast, 1991; Kräuchi & Kienast, 1993; Bugmann, 1994).

These deviating assessments are mainly due to the fact, that forest ecosystems combine processes which influence their dynamics in conflicting directions (e.g. potential growth enhancement by increased ambient CO₂-concentrations (e.g. Morison, 1987; Eamus & Jarvis, 1989; Robinson, 1994). vs. growth reduction by super optimal temperatures and drought). Moreover, these processes and their response to climatic change work at different temporal, spatial and organizational scales (photosynthesis: within minutes at leaf level vs. succession, century long at forest level (e.g. Solomon, 1988; Johnson *et al.*, 1993; Oechel *et al.*, 1993; Boutton *et al.*, 1994; Pitelka, 1994).). This makes it necessary to use for climate change impact studies tools which enable an appropriate integration of these factors in order to assess how they affect simultaneously the entire forest. Further difficulties are due to the fact that laboratory and field experiments studying the response of entire forests are exorbitantly expensive, if not impossible. Hence, specific tools such as dynamic models are needed to describe at least what we currently know in a well integrated manner. This helps to further our understanding of the processes at the interface between climate and forest ecosystems, since these models have now matured to a stage where they can actually be used for such purposes.

In the following we give an example of a study which assesses quantitatively by means of a dynamic forest model the possible impact of climatic change on forests in the Alps. We describe the problems involved, the needed methods, and results from selected, typical case studies. In a first section we introduce the model and explain its principle functioning; second, we illustrate the methods and problems of a model validation; finally we project possible forest dynamics as responses to climatic change scenarios as derived by collaborating scientists within the SPPE CLEAR project.

THE FOREST MODEL FORCLIM

In this study we used the dynamic forest model FORCLIM (Bugmann, 1994; Fischlin *et al.*, 1995) to project past as well as future forest responses to a changing climate.

FORCLIM is a patch model, i.e. it simulates the fate of individual age groups of trees (Fig. 1 a, b) within small (1/12 ha) patches by mimicking the following processes: establishment, growth and death. The growth submodel is deterministic, yet depends on randomly changing environmental conditions, whereas establishment and death are formulated as stochastic processes where the probabilities to establish or die are influenced by irradiation, temperature, precipitation, nutrients, and competition for light. Seeds of all tree species (see legend fig. 4) are assumed to be always present. Given the site characteristics, i.e. climate and soils, FORCLIM then is typically used to estimate the average temporal evolution of a forest (Fig. 1 c) by simulating 200 patches for 1'200 years, i.e. by running a Monte-Carlo-simulation.

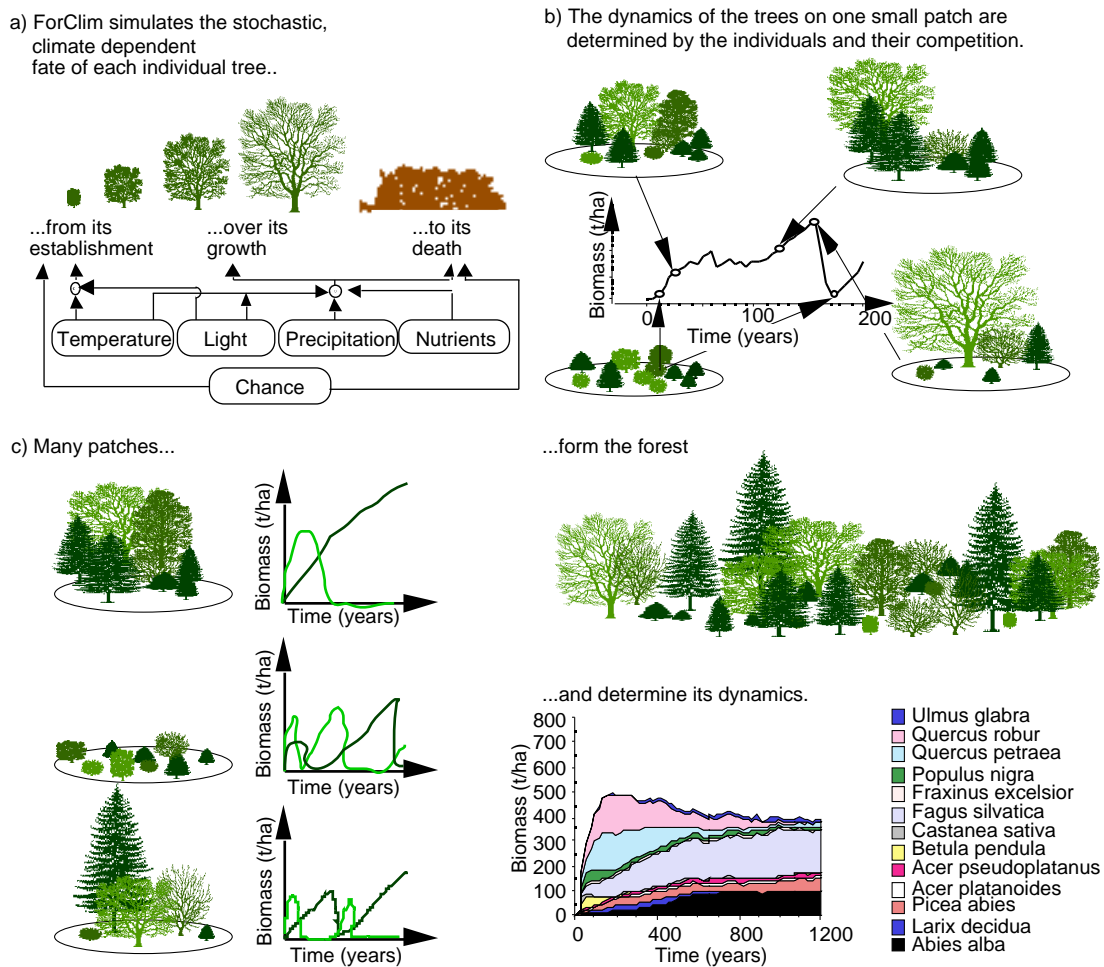


Fig. 1: Principle functioning of the forest model FORCLIM (Bugmann, 1994; Fischlin *et al.*, 1995) which was used in this study for a paleoecological model validation and for projecting possible future impacts of climatic change on forests in the Alps. Climatic parameters drive a weather generator used to simulate the influence of temperature and precipitation (a) on individual trees living on a small patch (1/12 ha) (b). Since the model is stochastic, its behavior over say 1200 years needs to be sampled repeatedly (c - Monte-Carlo simulation). In this study we sampled always 200 patches and used mean abundancies to describe the changes in species compositions (c - right).

In contrast to other patch models, FORCLIM is modularly built and consists of several clearly defined submodels. The latter can even be solved independently from each other. In particular the submodel responsible for the climatic forcing factors has been carefully redesigned (Fischlin *et al.*, 1995) plus growth and competition have been simplified, yet

improved to mimic European forests more realistically (Bugmann, 1994). Finally FORCLIM has been formulated as general as possible, so that it can potentially be run on any continent (e.g. North-America Bugmann & Solomon, 1995).

VALIDATION OF FORCLIM IN PRESENT AND PAST

Before being applied (Fig. 2c), generally every model needs to be validated (Fig. 2a,b), i.e. tested for its ability to predict a set of observations that was not used for structuring the model and estimating its parameters. Two sources of independent but simultaneous data are necessary: First, a record of the input data required by the model (e.g. temperature and rainfall parameters); second, measurements on all or a subset of those variables that the model calculates (e.g. species composition). Then the measured variables can be compared quantitatively to the calculated ones.

Model validation should be carried through for a range of various conditions, e.g. for climatic input, similar to the range of conditions expected for the planned model application. Hereby, not only the precision of a model under very specific conditions, but also its generality is tested. However, generality and precision are often in conflict with each another, and a decision has to be taken for one or the other, when judging the results of a validation.

For a climate driven forest model like FORCLIM such a range of conditions is given by climate gradients in space (validation in the presence at different locations, Fig. 2a) and time (paleoecological validation, Fig. 2b).

As data to validate various aspects of forest patch models a wealth of observations on past and current forests that potentially could be used, such as yield tables, forest inventory data, data from permanent plots in forest reserves, tree-ring chronologies, pollen records, remotely sensed data, and phytosociological descriptions of near-natural forests. However, most of these data either do not cover a long time (e.g. forest inventory and remotely sensed data), lack the temporal aspect and refer to a hypothesised equilibrium state of the system (e.g. phytosociological descriptions), are available at a small number of sites only and thus do not cover climate gradients (e.g. permanent plots, tree-ring chronologies, pollen records), or they assume that the forests are heavily managed (yield tables).

The validation of FORCLIM therefore has to rely on several of the above data sources. Two of them, phytosociological descriptions and pollen data, will be used to illustrate the potential and the pitfalls of the validation of a complex ecosystem model.

Validation With Present Data

The first type of validation of FORCLIM dealt with its behaviour along transects through the European Alps and through eastern North America (Bugmann, 1994; Bugmann & Solomon, 1995). The required input were the monthly expected values, standard deviations, and cross-correlations of temperature and rainfall in the respective regions, and the species specific parameter values of the most abundant tree species in Central Europe respectively. North America. The model output, i.e. the simulated species composition in the equilibrium was compared to semi-quantitative descriptions of the near-natural vegetation in the respective areas (Ellenberg & Klötzli, 1972; Rowe, 1972; Küchler, 1975).

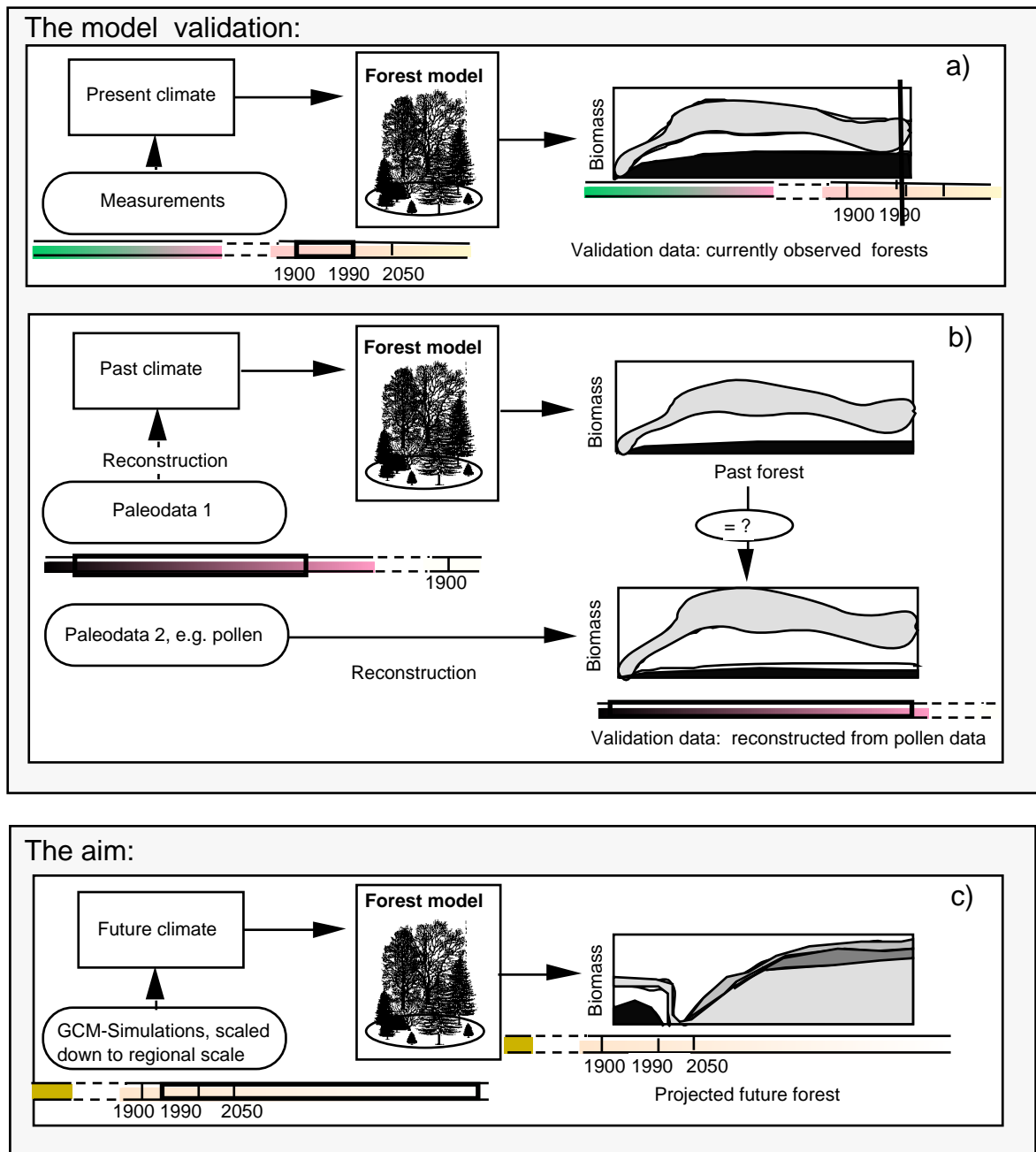


Fig. 2: **a)** Validation with present data: The forest model is validated with today's climate as input, by comparing the equilibrium species distribution with modern forests. **b)** Paleoecological validation: A validation of the transient behaviour of the model has to be done with past data. Here both climate input and comparison data have to be reconstructed from paleo data, e.g. from ice cores and pollen data, respectively **c)** Model application: The model is aimed to project the impact of a future climate change as derived from GCM simulations.

The simulated equilibrium species compositions and total aboveground biomass along the transects corresponded to the observed near-natural forests in most cases. For example, FORCLIM predicts a northern hardwood forest in the Upper Great Lakes Area, which is mainly composed of sugar maple (*Acer saccharum*) and eastern hemlock (*Tsuga canadensis*). These two species are dominating in the current landscape (Küchler, 1975; Frelich & Lorimer, 1991).

On the whole, the model showed satisfying results in a wide range of ecological conditions of the two subcontinents, i.e. a great generality.

However, a number of difficulties is associated with such a model validation. First of all, the simulation study did not include natural disturbances such as fire and wind throw, although these effects introduce additional stochastic variability which strongly shapes what we call “natural vegetation”.

Second, most forests in the simulated regions have been more or less intensively managed during the simulated last 1000 years, so that it is rarely possible to compare the simulated natural species compositions with the ones observed in today’s landscape.

Third, it is not sufficient that the simulated steady-state species composition correspond in general with observed and literature data. If we are to apply that model to study the impacts of transient climatic change, it is also necessary to assess its transient (i.e. time-dependent) behaviour.

Validation with Paleoecological Data

To validate the transient model behaviour, long time series of input and independent validation data were required. Both were obtained from paleoecological proxy data sources (Fig. 2b).

Table 1 gives an overview over the requirements to be met by these data for a paleoecological model validation. These requirements are connected with several problems:

Tab. 1: Paleoecological data requirements for forest model validation.

	Climatic input data	Paleobotanical data needed for comparison
Variables	Temperature, Precipitation (expected values, variances, cross-correlations)	Tree species composition (i.e. relative biomass of the tree species)
Reconstructed from	e.g. ice cores, tree rings	e.g. pollen data
Temporal resolution	monthly	decades
Spatial resolution	Site to homogenous region (e.g. Soppensee area)	Site to homogenous region (e.g. Soppensee area)
Time span	Centuries to millennia	Centuries to millennia
Initial conditions for simulation	–	Geographical tree species distribution at the beginning of paleoecological record

First, there is no direct data source for the required temperature and precipitation variables. Instead, these data have to be *reconstructed* e.g. (Lister, 1988; Lister, 1989; Graumlich, 1993; Guiot *et al.*, 1993) usually by using another model. Such data reconstruction models may contain errors of their own, and are of limited precision, e.g. (Bradley, 1991). Moreover, most often the temporal resolution of the Reconstruction is

restricted to annual or seasonal values, and it is not possible to reconstruct the full annual cycle (e.g. Guiot *et al.*, 1993). Hence, to arrive at a monthly resolution it is necessary to make additional assumptions, which add to the uncertainties of the reconstruction itself.

Second, forest patch models simulate abundancies or biomasses of tree species. Information about such variables in a distant past also has to be derived from proxy data, e.g. pollen found in lake or peat bog sediments, which provide one of the best opportunities to reconstruct the paleoecological variables over the required long time spans. Moreover, pollen records of the distant past (i.e. before 5'000 years BP) stem from landscapes that have probably not experienced strong human influences. The so-called Iversen factors (Faegri & Iversen, 1975) allow to convert the pollen data into relative biomass per tree species. They can be regarded as the coefficients of a linear, static model that assumes a constant production of pollen per unit biomass.

Third, the reconstructed temporal sequence of data must be mapped onto the time axis of the ecosystem model. However, the dating of proxy records may be inaccurate or biased (Lotter *et al.*, 1992), due to the coarse temporal resolution in the record as well as due to uneven sedimentation rates. Thus, differences between proxy data and model output are difficult to interpret, since they may stem from a system-intrinsic time lag or just a dating error.

Finally, the pollen accumulated in a lake sediment represent the plants of at least a whole catchment area. Often, such a pollen source area contains a number of forest site types, which are likely to differ, for example, in soil water holding capacity, slope, aspect, and climate. A forest model like FORCLIM, however, simulates a forest only at one particular site with a well defined set of specific characteristics. Therefore, it is implicitly assumed that the site characteristics used in the simulation represent all sites within the whole pollen source area.

In general, at least three models with all their inherent uncertainties are involved in paleoecological validation of an ecosystem model: The ecosystem model itself, and two auxiliary models to convert proxy data into the form needed for input and comparison data. Together with the uncertainty of dating and of the pollen source area these issues complicate a paleoecological model validation, which will be illustrated by the following example.

An example: Comparing FORCLIM Results With Pollen Data From Lake Soppensee

To compare the tree species succession as simulated by the forest patch model FORECE with a pollen succession, (Lotter & Kienast, 1992) used an annually layered pollen stratigraphy from Soppensee (Swiss Plateau, elevation 596 m) covering about 4'000 years (annual varves) of the early Holocene (Lotter, 1989); (Fig. 3, top) . Here, this experiment shall be repeated, however by using the model FORCLIM (Bugmann, 1994). This study is a first step towards a paleoecological model validation; it illustrates the potential and problems associated with such studies (Solomon *et al.*, 1980; Solomon *et al.*, 1981; Solomon & Tharp, 1985; Bonan & Hayden, 1990).

Data

Climatic input data & site conditions: There was no independent proxy for the climatic input available. The floating pollen chronology (Lotter, 1989) has been estimated to start at about 10'000 years BP (Fig. 3, top). Hence, although a gross simplification, we assumed that the climate had been constant over the whole period of 4000 a. It was assumed to be 1 °C warmer than the current climate at the nearby climate station Huttwil (SMA, 1901-1990) (Tab. 2a), and that precipitation was the same as measured. We had also to assume that the annual cycle of both variables was the same in the early

Holocene and today, which is actually rather unlikely (Huntley, 1990). Finally, we assumed a mesic soil with a field capacity of 30 cm water (Bugmann, 1994)

Initial conditions for the simulation: The initial conditions for the simulation experiment were estimated qualitatively based on the initial distribution of pollen in the pollen diagram (Fig. 2, top); the initial forest was assumed to consist of *Pinus silvestris*, *Betula pendula*, *Populus tremula* and *Salix alba*.

Tab. 2: Description of the simulation experiment performed for the paleoecological validation of the FORCLIM model: Initial species distribution and immigration scenario: Symbols: N – number of trees initially present; D – diameter of trees at a height of 1.37 m (“breast height”).

Genus	N [ha ⁻¹]	D [cm]	Age [years]	Year of immigration
<i>Abies</i>	–	–	–	2'450
<i>Pinus</i>	180	20	50	0
<i>Fagus</i>	–	–	–	2'750
<i>Quercus</i>	–	–	–	170
<i>Acer</i>	–	–	–	350
<i>Fraxinus</i>	–	–	–	1'200
<i>Ulmus</i>	–	–	–	135
<i>Tilia</i>	–	–	–	265
<i>Betula</i>	180	20	50	0
<i>Alnus</i>	–	–	–	350
<i>Populus</i>	240	8	15	0
<i>Salix</i>	240	8	15	0
<i>Corylus</i>	–	–	–	120

Pollen to biomass transfer function: The simulated species-specific biomass values were converted to pollen production values using inverted Iversen factors of pollen representation (Faegri & Iversen, 1975; Lotter & Kienast, 1992).

The migration problem: The first simulation studies based on the above experimental setup yielded a forest dominated by *Fagus sylvatica* and *Abies alba* towards the end of the first 1'000 years. The pollen record certainly reflects to a certain degree the immigration history of tree species into the Swiss Plateau after the last glaciation; the above two species immigrated rather late (Huntley & Birks, 1983). Therefore, it was assumed that the complete absence of a species in the pollen diagram was not due to competition effects, but to delayed immigration. Consequently, the tree species were allowed to establish in the model only after they had turned up the first time in the pollen record (Tab. 2b).

Results and Discussion

The simulation results obtained from the FORCLIM model (Fig. 3, bottom) show a reasonable qualitative agreement with the pollen record (Fig. 3, top). The model simulates the transition from the early *Betula-Pinus* forest (0-500 years) to a *Quercus-Ulmus* forest (500-2'700 years) followed by a mixed deciduous forest where *Abies* becomes important as well as *Fagus* (years 2'700-4'000). Major quantitative discrepancies are (1) an over representation of *Quercus* and *Fagus*, which is difficult to interpret and may represent an anomaly, and (2) an underestimation of *Tilia*, *Fraxinus*, and *Alnus*.. Especially the latter two genera include species which are able to grow on temporarily flooded soils (Landolt, 1977). In the simulation, the region was regarded as uniform with an average field capacity, which favours other more competitive species. From present conditions (Landeshydrologie und –geologie, 1992), however,

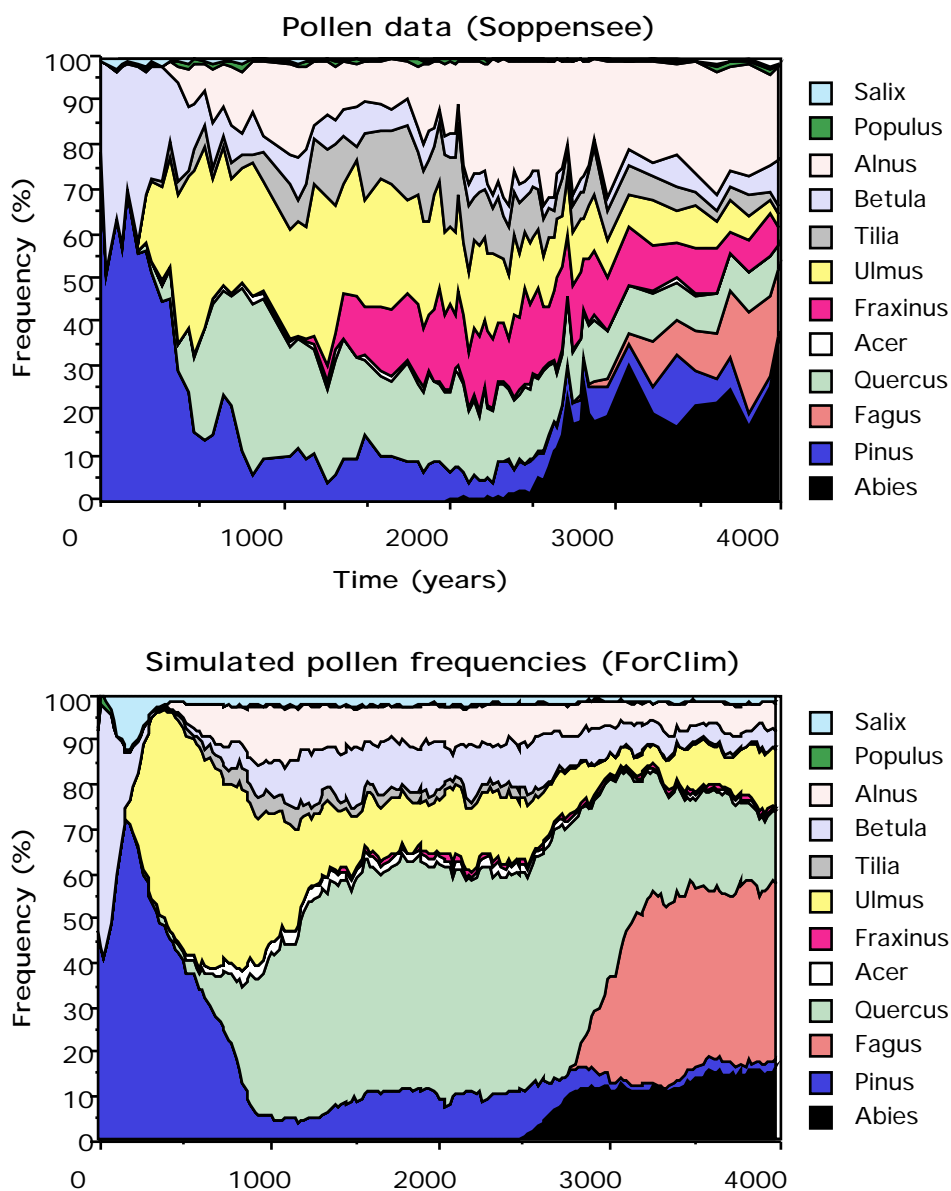


Fig. 3: Comparison of the 4000-year pollen record reconstructed based on a stratigraphy from Soppensee (top, redrawn from (Lotter and Kienast 1992)) with the vegetation simulated by FORCLIM (Bugmann 1994, Fischlin et al. 1995) during 4000 years (bottom). In both cases, the pollen sum includes only arboreal pollen without *Corylus*. The biomass values simulated by FORCLIM were converted to pollen frequencies using inverted pollen representation factors (Faegri and Iversen 1975).

we have to assume that the pollen source area consisted of various soil types, including very wet soils, where the flooding resistant species *Alnus* and *Fraxinus* had a competitive advantage.

Inferring the time of immigration and the initial population densities of all the species from the pollen record is clearly a violation of the requirement that the input data should be independent of the data used to evaluate the behaviour of the model. However, the simulation results remain essentially unchanged if all the species except *Abies* and *Fagus* are allowed to establish throughout the simulation (results not shown), if the same initial conditions are used. For these two species there is good reason to assume that their absence really is due to delayed immigration (Huntley & Birks, 1983), the only odd thing remaining is that it would be desirable to estimate the point of immigration from an independent data source, or by explicit modelling of tree migration. Such migration models are highly desirable, since they do not only allow to study tree migration in a past climate change, but also to assess the role of migration under a future climate change.

Furthermore, temperatures were not constant in the regarded period, as assumed in the simulations. Forest dynamics, however, are determined strongly by the actual temperatures and not by the means over 4'000 years. Therefore in further validation studies, non-stationary climate values should be used as model input.

Hence there are many uncertainties associated with the use of paleoecological data for validating ecosystem models. Not only relate these uncertainties to the proxy data themselves, i.e. both in terms of the reconstruction of climatic input data and of adequate biotic data that can be used in a model-data comparison, but also do they relate to the formulation of the simulation experiment, i.e. the derivation of the initial state, the treatment of phenomena not explicitly modelled, e.g. migration phenomena, and the representativeness of the simulated site for the whole lake catchment area.

FORCLIM AND FOREST RESPONSES TO FUTURE CLIMATES IN THE ALPS: SURPRISES AND INERTIA

Despite the mentioned difficulties in model validation, simulations with a dynamic model such as FORCLIM are particularly useful to project quantitatively forest responses to a future changing climate, because they are the only way to integrate in a mathematically defined manner the quantitative relationships within and between several levels of time scale (cf. Fig. 1). Using the same global climatic change scenario it is first possible to study with such a model the impact on various types of forests as given by differing site-specific properties like local climatic and soil parameters. Secondly, we can explore the effect of the variability within the climatic change scenarios at the same site. Using FORCLIM our goal was primarily to focus on the sensitivity of FORCLIM's behavior to the variations in the climatic, site specific input variables. In all the selected case-studies we deliberately refuse to call the obtained results forecasts, they are mere projections, heavily dependent on the underlying scenario assumptions.

BREAKDOWN AND INERTIA: DIFFERENT FOREST RESPONSES AT DIFFERENT SITES

At several sites at various altitudes in the European Alps we used the site-specific monthly temperature and precipitation anomalies. They were obtained from semi-empirical downscaling (Gyalistras & Fischlin, 1995) of transient GCM-Simulations as described in Gyalistras *et al.* (Gyalistras *et al.*, 1994; Gyalistras *et al.*, 1995). All used scenarios were derived from the same GCM (ECHAM Cubasch *et al.*, 1992) simulations, all based on the IPCC "Business-As-Usual" CO₂ scenario A (Houghton *et al.*, 1990). The simulations were run for about 1000 years with present climatic conditions, to allow the simulated forests to reach an equilibrium state. The climate in

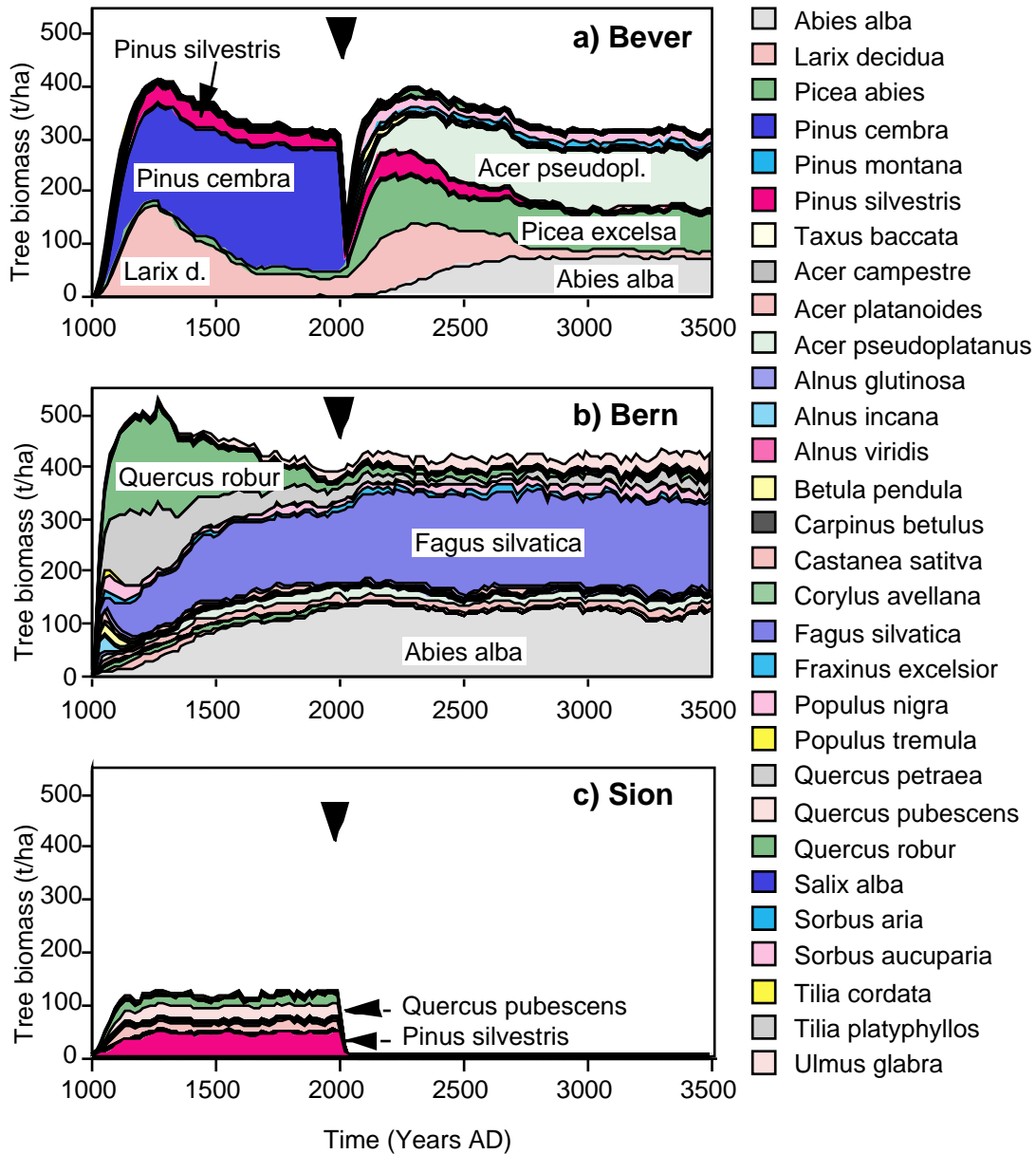


Fig. 4: Projected step responses of forests at selected sites in the Alps to a climatic change as down-scaled from a transient IPCC "Business-As-Usual" GCM run (Gyalistras *et al.*, 1994; Gyalistras & Fischlin, 1995; Gyalistras *et al.*, 1995) for the year 2080. All simulations were made with the forest model FORCLIM (Bugmann, 1994; Fischlin *et al.*, 1995), assuming the climate to remain constant after the year of climate change (step at arrow).

2080 (Cubasch *et al.*, 1992) was sampled and assumed to change instantaneously in the very same year and afterwards the climate was held constant. Within 1000 years the simulated forests were again allowed to adapt to the new climatic conditions (step response) in order to assess a new equilibrium vegetation (Bugmann & Fischlin, 1992; Bugmann & Fischlin, 1994).

The found step responses demonstrated that a large range of possible responses are to be expected from the same projected global climatic change, depending on the climatic characteristics of the site and the forests simulated for present conditions (Fig. 4):

At mid altitudes, represented by the simulations for Bern, no harmful changes in the species composition were found to be caused by the projected climatic changes (Fig. 4b). This type of forest appears to be well buffered against the projected climatic changes. At high altitudes as e.g. in Bever however, the species composition responded strongly (Fig. 4a); the subalpine forest simulated for present was replaced by a forest similar to the present forests of the montane zone, hereby reflecting an altitudinal shift of the forest belts. These changes are drastic and the associated transient forest die-backs may cause erosion problems up to possible slope destabilizations in vulnerable areas. Finally, surprisingly strong responses were found at the low altitude site Sion (Fig. 4c) in a central part of the Alps, where none of the tree species present in the model survived. Here the projected warming in combination with a relatively small change in the precipitation regime increased the water pressure deficit and the difference between potential respectively actual evapotranspiration (PET-AET) to such an extend (Fischlin *et al.*, 1995), that an enduring drought stress prevented the survival of all trees in the simulation.

SENSITIVITY TO UNCERTAINTIES IN CLIMATE SCENARIOS

The whole chain of assumptions, methods, and models used to obtain regionally differentiated climatic change scenarios contains many uncertainties. Sources for main uncertainties range from CO₂ emission scenarios over GCM-simulations to the downscaling of their results to the regional scale (Gyalistras *et al.*, 1994; Gyalistras & Fischlin, 1995; Gyalistras *et al.*, 1995).

We tested the effect of these uncertainties on the behavior of the forest model by simulating step responses (as described above) for a set of downscaled climate scenarios at the same site, e.g. Bever (Fig. 5) (see also Bugmann, 1994; Fischlin *et al.*, 1995). Here we show only the simulated species composition at equilibrium (Fig. 5): The bar in the centre represents the best estimate (ToPo) for the changes in temperature (T) and precipitation (P). Those shown to the left respectively right represent low and high estimates for temperature respectively precipitation. The signs

in the scenario labels (i.e. in T-P-, T-P+, T+P+, T+P-) refer to the estimated upper (+) and lower (-) limits of the 95% confidence interval of the down-scaled scenario variants (Gyalistras *et al.*, 1994).

We found that some forests may show strongly differing responses (e.g. Fig. 5), some are likely to respond barely to the unavoidable differences among the variants of any set of down-scaled climatic change scenarios (cf. Fig. 4b).

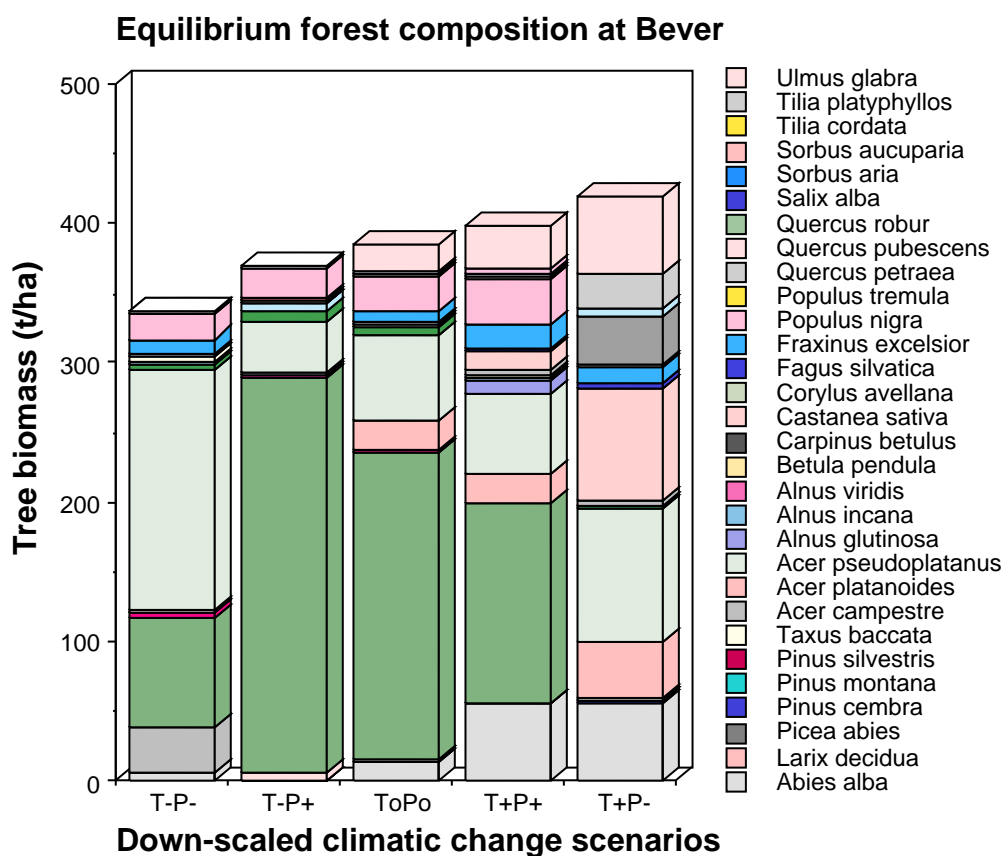


Fig. 5: Simulated sensitivity of species compositions at equilibrium to uncertainties within the climatic change scenarios. All climate scenarios were down-scaled (Gyalistras *et al.*, 1994; Gyalistras & Fischlin, 1995; Gyalistras *et al.*, 1995) from the ECHAM-GCM (Cubasch *et al.*, 1992) simulations based on the transient IPCC "Business-As-Usual" global CO₂-emission scenario A (Houghton *et al.*, 1990) for 2080. Simulations were made with the ecosystem model FORCLIM (Bugmann, 1994; Fischlin *et al.*, 1995). T - Temperature, P - Precipitation; ToPo - Best estimate, T-P- respectively. T+P+ - Minimal respectively maximal changes (95% confidence interval).

Discussion of Forest Response Simulations

The results of our sensitivity studies demonstrated that a large range of possible responses is to be expected in the Alps, even in the same projected global climatic change; depending on the current site characteristics and the present forests the results differed significantly:

- At mid altitudes, i.e. colline and montane forests at the border of the Alps, the assumed projected climatic changes are likely to cause no significant changes in the species composition (e.g. at Bern).
- At high altitudes, i.e. in the subalpine zone (e.g. Bever), the species composition may respond strongly to the projected climatic changes; the subalpine forests may be replaced by forests from the montane zone; such changes are drastic and the associated temporary forest die-backs may cause erosion problems up to possible slope destabilizations in vulnerable areas.
- Finally, surprisingly strong responses can be found at low altitudes if they are located in the central parts of the Alps, e.g. Sion). At Sion the projected warming combined with a relatively small change in the precipitation regime lead to an enduring drought stress, which prevented the survival of any of the simulated tree species. Thus, only the importing and planting of tree strains with a higher tolerance to drought stress might enable the growing of trees around Sion again.

Note-worthy is the observation, that the model's sensitivity to the uncertainties in the underlying climatic scenarios were correlated with the sensitivity due to the site specific characteristics.

CONCLUSIONS

Model Validation

Validation of dynamic forest models requires the combination of different approaches, which all together test the transient and equilibrium behavior of the model under a sufficiently large spectrum of conditions.

From the case study of model validation using the Soppen-see pollen proxy data we concluded that paleoecological validation of forest ecosystem models offers on one hand promising potentials, yet suffers at the same time from strong limitations.

The potential of paleoecological model validation is due to the following reasons: Paleoecological proxy data are the only data sources that offer long-enough time series of unmanaged forest dynamics. Moreover, with paleoecological data we can validate forests under a climate that changed at various rates, so increasing our confidence that the model behaves realistically under scenarios of future climatic change.

There are still strong limitations to a paleoecological model validation, as for instance became evident from the many uncertainties outlined in the present study. A "failure" of the validation may be due to errors in the ecosystem model, e.g. wrong parameter values, as well as due to errors in the reconstruction of the past climate or the past vegetation. Further uncertainties remain because of the unknown nature of the pollen source area in the past.

This study also revealed the need for improvements and possible directions of progress:

First, an independent, high quality record of the past climatic input conditions is as much needed as the good record to be used for the actual comparisons with the model behavior. Second, a process-oriented model of pollen production, transport, and sedimentation appears to be worth-developing and worth-studying. It could be used to replace the transfer functions often used to reconstruct past vegetation compositions. Thirdly, models of tree migration are highly needed, since migration potentially plays a key role in the transient forest responses to climatic change, especially during phases of strong climatic changes such as the end of the last ice age and as projected for the following century.

The Fate of Forests in an Alpine Region

Due to current data limitations respectively not yet fully developed methods of generating bioclimatic scenarios at any ecologically interesting site, our results remain restricted to the few presented case studies. Yet, some general, tentative conclusions could be drawn:

While some forests may in the Alps slightly profit from the envisaged climatic changes or will not be affected at all, some may suffer drastically. Hence, no uniform, simple response of the mountain forests to a climatic change is to be expected. Biggest sensitivities were found in areas which border a continental climate already in the present and in sub-alpine conditions. All these conditions can be traced back to the fact that the studied locations are within mountains. Especially when these findings are contrasted with what we learned about the peripheral forests at lower altitudes, we concluded the following: Mountain forests are among those forests which are especially sensitive to climatic change.

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