Analysis of Three Forest Gap Models

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Abstract: *The complexity of forest ecosystems together with the large temporal and spatial scales involved in successional processes render experimental approaches to study forest succession extremely difficult. Forest gap models have been used successfully to synthesize the existing knowledge on successional dynamics of forests. However, the complexity of these models in turn bears problems. The three models FORECE, FORCLIM-E/P and FORCLIM-E/P/S are used in this study.*

Introduction

Global industrialization, increase in population and the reduction of natural resources are threatening ecosystems all around the world. Climate change is one result of this development. There are strong evidences that intact forests can play an important role in keeping the global system in balance.

Forests in mountainous areas have a multitude of functions: they may protect settlements and roads from avalanches, they regulate runoff and prevent erosion, and they form a part of the largest terrestrial biotic carbon pool. Forests and meadows make a varied landscape and provide the environment necessary for many touristic activities, and – last but not least – forests are exploited for fuel and pulpwood.

Any assessment of the possible effects of the future climatic change on forest ecosystems is faced with twofold problem:

- First, there is a considerable uncertainty inherent in the predictions of future climate, both on the global and even more pronounced on the regional scale.
- Second, every forest model incorporates different and highly simplified parameterizations of ecological processes; these certainly contain errors both on the quantitative and maybe even on the conceptual level.

Thus, it appears to be more promising to analysis the behavior of several ecological models under several scenarios of climatic change instead of focusing on just one model and one scenario. This approach also emphasizes that such studies are tests of the sensitivity of forests ecosystems to climatic changes, and not predictions of their future structure and functioning.

Over the past 30 year, almost all of the assumptions and equations described above have been challenged, scrutinized, or replaced by alternative formulations in specific gap models. This as led to a large variety of gap models , most of which continue to share many features.

Forest gap models have undergone rapid development over the past 20 year, with distinct versions available for use in different parts of the world [8]. These models are based on the concepts and models developed by Botkin et al. [1] and Shugart & West [6]. Gap models simulate forest succession in an opening in a closed forest canopy caused by the death of a mature individual. In the earliest gap models, tree growth was constrained by empirical relationship between tree growth and growing degree days and solar radiation.

The value of ecological models , including gap models, is not that they would be able to “predict” the future; rather, it is that they can help us to understand processes and patterns in nature by allowing us to explore the consequences of a set of explicitly stated assumptions that are too complex to explore by other methods.

1. Gap Modeling Concept in Forest Ecology

Most ecologists are interested in variations in individuals and appreciate spatial variations as being quite important. Increasingly, models that simulate the dynamics of ecological systems by accounting for changes in each of a large number of individuals in the system have been developed and applied in population and ecosystems ecology [3].

Among the earliest individual-based models in ecology were models of forests based on the growth of the individual trees the comprise the forest stand. These models werre developed by quantitatively oriented foresters and were focused from their inception toward practical issues in production forestry.

Individual-based models in forestry were focused on solving several general problems involving stand yield tables. Modern forestry uses stand yield tables as a scientific basis for making decisions about the expected productivity of forest stands under different conditions to plan harvest and thining schedules.

In a gap model, as with other individual-based models, each tree is simulated as an independent entity. The model structure emphasizes two features important to a dynamic description of a vegetation pattern:

- The response of the individual tree to the prevailing environmental conditions.
- How the individual tree modifies those environmental conditions.

The models are hierarchical in that the higher level patterns observed (population, community, and ecosystem) are the integration of plant responses to the environmental constraints defined at the level of the individual.

Gap models simulateeach individual tree’s response to light availability at height intervals on the plot. The sizes of individuals are used to construct a vertical leaf area profile. Other resources are incorporated to varying degrees in different gap models. These include soil moisture, fertility, temperature, as well as disturbancessuch as fires, floods and wind throw. In most of the models, the environmental responses are modeled via a constrained potential paradigm; a tree has a maximum potential behavior under optimal conditions. This optimum is then reduced according to the environmental context of the plot, to yield the realized behavior under ambient conditions.

Competition in the model depends on the relative performance of different trees under the environmental conditions on the model plot. These environmental conditions may be influenced by the trees themselves, or may be modeled as extrinsic and not influenced by the trees.

The feasibility of including more physiological detail in forest gap models is discussed, and it is concluded that we often lack the data base to implement such approaches for more than a few commercially important tree species. Hence, it is important to find a compromise between using simplistic parameterizations and expanding gap models with phisiology-based functions and parameters that are difficult to estimate.

1.1. The “FORECE” Model

Forest gap models [1], although conceptually simple, have grown to complex ecological models with a huge parameter space. The analysis of the FORECE model showed that the level of complexity reached in these stochastic models calls for a careful evaluation of the model formalism and the statistical properties of the underlying stochastic process.

These issues appear to be related to the sheer impossibility of publishing all the equations of the mathematical model in detail, which is indispensable because other researchers using the model must understand its assumptions and limitations, but which is not usually possible given the page limitations of scientific journals. In order to become familiar with a forest gap model, it is often necessary to extract its conceptual elements from the simulation model. Like this it is easily possible that artifacts are introduced when adding new features, or that the model is run under conditions where it produces inconsistent results. Hence, the analysis of forest gap models provided a safer basis for model simplifications, refinements, extensions, and the design of simulation experiments.

The analysis of the sensitivity of FORECE to structural simplifications allowed to quantify the importance of the various factors included in the model. Sensitivity of FORECE is representative of the sensitivity of real forests, a quantitative hypothesis could be derived on the most important ecological factors governing the long-term successional properties of forest ecosystems in the mountain.

The analysis of the formulation of climate-dependent factors in forest gap models revealed that many conventional models implicitly assume a constant climate, and that model behavior is sensitive to relaxing these assumptions.

1.2. The “FORCLIM” Models

The construction of FORCLIM as a forest gap model composed of three submodels provided the flexibility to evaluate the behavior of each submodel and any desirable combination of the submodels:

- Environment – this submodel provides time-dependent abiotic variables. It generates weather data and uses these data to calculate bioclimatic output variables. The environment submodel does not depend on any of the other submodels and acts as an input model.
- Plants – the plant submodel calculates establishment, growth, and mortality of trees on a forest patch.
- Soil – the soil submodel tracks the decay of plant litter and humus in the soil as a function of bioclimatic variables. It calculates the amount of nitrogen available for plant growth.

This constitutes a distinct advantage over conventional forest gap models, where the complete model is the single scope of simulation studies.

The quality of a large fraction of the litter produced by FORCLIM-P submodel does not vary with the species producing it, i.e. twig, wood, and root litter, which constitute up to 90% of the total litter production.

The possible direct effects of atmospheric CO_2 on tree growth are still hotly debated in the literature [4]. While the short-term effects of enhanced CO_2 concentrations on photosynthesis and water-use efficiency of tree seedlings and saplings seem to be well established, the long-term effects on older trees and whole ecosystems remain undetermined and can not be extrapolated simply from the findings at smaller scales [2]. These authors also noted that at the ecosystem scale *“recourse must be made… to modeling”*. Simulation studies dealing with this problem typically found that the response at the ecosystem scale is much smaller than the increase in the growth rate of the single trees or even that there is not response at the ecosystem scale at all [7]. Based on these studies and in view of the large uncertainties concerning this issue, the hypothesized direct effects of atmospheric CO_2 on tree growth are neglected in FORCLIM.

FORCLIM-S is the first submodel for belowground carbon and nitrogen turnover used in a gap model for European conditions, and the simulation studies with it were encouraging. However, this submodel should be scrutinized carefully, several of its equations should be reformulated on a more mechanistic basis, and it should be validated extensively.

Nitrogen is one of the major plant nutrients, and its availability limits plant growth in many terrestrial ecosystems. The nitrogen cycle in forests is intimately coupled with the carbon cycle [5]:

the amount of organic matter returned to the soil depends on primary productivity, which is limited by nitrogen availability. In turn, nitrogen availability is largely determined by nitrogen mineralization.

The basic paradigm for most decomposition models developed to date is formalized in a simple exponential-decay model. However, the parameters of this model are specific for each soil, depending on climate and the type of litter returned to the soil. Thus, it was a logical step to relate decay rates to environmental parameters such as temperature and precipitation. Several models of the carbon cycle were constructed for forests, and glassland.

In FORCLIM-E submodel, the sensitivity of the drought stress index to small changes of actual evapotranspiration raises the question whether it is robust enough to be used for parametrizing the ecological effects of drought on tree growth.

In the **FORCLIM-E/P** model, the abiotic environment is stochastic; thus, it is not restricted to average conditions but includes some of the natural variability of the weather and the habitat.

In version of the **FORCLIM-E/P/S** model, neither the weather nor the availability of nitrogen are kept constant, and it is also possible to evaluate the amount of belowground organic matter.

2. Sensitivity of Models

FORCLIM-E/P/S is comparably robust to the values of its species parameters when they are varied within their range of plausibility. Thus the simulated species composition is not an artifact of arbitrarily chosen parameters, which increases arbitrarily chosen parameters, which increases our confidence that the simulation results obtained for FORCLIM represent reliable hypotheses on the forests under study.

The simulated species composition is also sensitive to the scaling constant in the tree growth equation. Since tree growth is directly linked to competitive ability, this sensitivity appears to be quite realistic. The other parameters have a stronger influence on older trees only.

The sensitivity analysis revealed that the precision of the biomass estimates obtained from FORCLIM is low, i.e. the abundance of a given species varies considerably depending on the values of the parameters used to characterize its natural history.

The three models FORECE, FORCLIM-E/P and FORCLIM-E/P/S all produced plausible species composition when applied at sites along a climatological gradient in the European mountains. Based on these results alone, it would not be possible to favor one of the models over the others, although the formulation of FORCLIM is mathematically more rigorous, it depends to a larger extent on causal relationship, and it is simpler. Only the systematic simulation studies performed in a climatological parameter space spanned by the annual mean temperature and the annual precipitation sum revealed that FORECE contains several unrealistic thresholds and that it produces unrealistic species composition in a larger fraction of this space than FORCLIM.

The investigation of the behavior of the FORCLIM-E/P model under three different climate scenarios suggest that forests close to the current alpine or dry timberline are especially sensitive to the climatic changes expressed in the various scenarios. Given that the sensitivity of FORCLIM is representative of real forests, these are two important implications of these findings:

- The forests currently growing at these sites may be affected drastically by the expected changes of temperature and precipitation;
- Predict the potential future forest composition at specific locations, the forecasts of future climate would have to be more precise than this appears to be currently possible.

The comparison of the behavior forest gap models under one scenario of climatic change shows that the models disagree most sharply at sites close to the alpine timberline. Thus, under these conditions the models are sensitive to climatic parameters as well as to the formulation of ecological factors. Although there is less divergence as the other sites and is felt that FORCLIM-

E/P and FORCLIM-E/P/S are most trustworthy of all the five models studied, it is daunting to see the differences the three models produce.

Even if the best scenario of climatic change could be unequivocally identified, there would remain some uncertainty in it. The investigation of the propagation of the uncertainties inherent in a state-of-the-art scenario obtained from large-scale data showed that, again mainly at sites close to timberline, a bewildering array of possible future forest composition is obtained. Thus also such a climate scenario does not currently match the precision requirements of forest ecosystem models.

FORCLIM was developed to include reliable formulation of the influence of temperature and precipitation on ecological processes. Thus it may hypothesized that the model is trustworthy enough to assess the possible impact of climatic change on forest ecosystems in the European mountains.

These results support the hypothesis that forest gap models are powerful tools for exploring the dynamics of forest ecosystems on scales that are not directly observable, and that the models can be used successfully to interface the ecological knowledge from various disciplines.

The analysis of the sensitivity of FORECE to structural simplifications made it possible to derive a hypothesis on the most important factors determining the successional dynamics. Major factors influencing sapling establishment are winter minimum temperature, browsing, and again light availability [9].

Several problems remain when attempting to use FORCLIM to study the impact of climatic change on near-natural forests: first, such applications basically deal with extrapolations in time and beyond current ecological conditions. Some factors that are important in mountainous terrain are not considered in FORCLIM, such as soil erosion and landslides, which may occur after forest dieback phenomena and may render large areas inappropriate for forest growth. Moreover, air pollution in conjunction with climatic change may lead to unexpected synergistic effects, such as increased sensitivity of forests to climatic change, and herbivores could also modify the response of forests to climatic change.

3. Conclusions

The effects of the anticipated climatic change on forest ecosystems differ strongly depending on the geographical location considered. At some sites, the forests simulated by one model under various scenarios of climatic change have little in common except that they are different from current forests. It is not possible to identify unequivocally which of these scenarios describes the future climate best and to ignore the others. Hence we have to conclude that the precision of the forecasts of future climatic change falls short relative to the sensitivity of the forest models, and it is therefore not possible to predict the potential natural vegetation at a given time and a given place in the future. Moreover, there are marked differences between the projections obtained from various forest models under the same scenario of climatic change. Hence there is also a considerable uncertainty concerning the number of ecological factors to be included in forest gap models and, even more pronounced, their specific formulation.

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