Projecting the Impacts of Climate Change on Mountain Forests and Landscapes

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1. Introduction

Mountain forests fulfil a multitude of functions, including the provision of timber, fuelwood, edible and medicinal plants, the storage of carbon, the purification of air and water, the regulation and reduction of peak streamflow, the protection from natural hazards, and the contribution to the aesthetic beauty of the landscape. The importance of these functions varies greatly from one mountain region to the other, but in some way, forested landscapes and their fate under a changing climate are important for the capability of mountain regions to provide many of the goods and services that humanity depends on.

Empirical evidence as well as modeling studies suggest that mountain vegetation could be particularly sensitive to anthropogenic climate change (e.g. Grabherr et al. 1994; Bugmann 1997; Theurillat and Guisan 2001). Forest ecosystems are dominated by long-lived organisms that are able to withstand adverse environmental conditions for some time. Thus, in spite of their general sensitivity to climatic parameters, we may expect little change in these ecosystems over time periods of several years. This makes experimental approaches for studying climate change impacts on forests and forested landscapes difficult, and underlines the importance of synthetic tools to study these phenomena. Quantitative, mathematical models are among the tools that are suitable for projecting the long-term effects of environmental changes on mountain forests.

In mountain ecosystems, several factors are of crucial importance that may be nearly negligible elsewhere. Examples include (1) the role of slope angle and aspect for determining energy balance, (2) the significance of lateral (downhill) water flows because of the steep slopes, (3) the role of diverse root systems for slope stabilization, (4) high topographic heterogeneity, which induces strong biotic heterogeneity, and (5) the importance of vegetation, particularly forests, on steep slopes for protecting ecosystems and human infrastructure from natural hazards such as avalanches and rockfall. In addition, the tight coupling of the various processes in mountain regions makes it necessary to consider a range of ecological and hydrological processes simultaneously if we are to be able to project the impacts of climate change on these systems.

Historically, research into the impacts of climate change on mountain landscapes has taken place largely in a sectoral manner. For example, many forest ecologists examined the impacts on forest structure and composition using gap models (e.g. Bugmann et al. 2001); biogeochemists investigated possible changes in carbon, water and nitrogen exchange between forests and the atmosphere using physiologically based “big leaf” models (e.g. Keyser et al. 2000); landscape ecologists looked at the impacts of a changing disturbance regime on vegetation patterns at the landscape scale (e.g. He et al. 2002); and hydrologists examined changes in streamflow and related variables, including the risk of flooding (e.g. Pruski and Nearing 2002). Studies such as these are certainly timely and welcome because they highlight the potential for climate-induced changes in ecosystem goods and services in mountains.

However, most of these studies did not take into account the tight linkages between the various processes mentioned above, which are particularly pronounced in mountain areas. For example, gap modeling applications typically have neglected the effects of lateral water flows; hydrologists have tended to disregard the effects of vegetation changes on the flow regime by assuming a constant vegetation type across time; and landscape ecologists have focused on the effects of a changed disturbance regime, while de-emphasizing the importance of successional processes.

In the following section, we give an overview of recent research results obtained in our group that deal with the impacts of climate change on forests and landscapes in mountain regions; some of these studies continue to be sectoral, whereas others have begun to address the linkages between the sectors and processes mentioned above. In the last section, we try to pull together the insights gained so far to derive an outlook regarding future research directions.

2. Case studies

2.1 Forest structure, composition and biomass at the patch scale

Possible changes in the structure, composition and biomass of mountain forests have been a focus of our research over the past years (e.g. Bugmann 1996; 1997; Bugmann and Solomon 2000) because such changes could have significant impacts on the protective function, the carbon storage, and the aesthetic value of mountain forests. We have adapted, improved and refined forest gap models (Bugmann 2001), a widespread class of forest succession models that had originally been developed by Botkin et al. (1972).

Forest gap models simulate the establishment, growth and mortality of individual trees on small patches of land (often $^1/_{12}$ ha) as a function of the species' autecological requirements and the extrinsic and intrinsic conditions of the stand. To obtain forest development at larger spatial scales, the successional patterns of patches from many simulation runs are averaged. This concept is supported by many plant succession studies, which show that a forest ecosystem may be described by the average growth dynamics of a multitude of patches with different successional ages. The model ForClim (the acronym stands for *For*ests in a changing *Clim*ate), which is used here, consists of three independent submodels, representing the abiotic environment (ForClim-E), tree population dynamics (ForClim-P), and soil organic matter turnover (ForClim-S). The ForClim model was derived from an earlier gap model with the particular aim of a reliable representation of climatic influences on tree population dynamics.

We used this model to study the impacts of a range of climate scenarios for the year 2100 on forest properties at sites along an altitudinal gradient in the European Alps, including steady-state considerations as well as an evaluation of the dynamic properties of the simulated forest (cf. Bugmann 1997; 1999).

Forests on a north-facing and a south-facing slope at the site Bever in the Upper Engadine Valley, which is characterized today by a fairly continental climate, differ dramatically in their simulated species composition under current conditions (Fig. 1 top). In the simulation, the south-facing slope is characterized by a mixture of European larch (*Larix decidua*) and pine, with a strong dominance by Swiss stone pine (*Pinus cembra*) and some Scots pine (*Pinus sylvestris*). The north-facing slope, however, is simulated to be covered by forests that are dominated by Norway spruce (*Picea abies*). These simulation results correspond well to descriptions of the natural vegetation of this area, as discussed by Bugmann (1999).

Notably, these forests differ in their response to a regionalized scenario of climate change (cf. Gyalistras et al. 1994) that was applied across 100 years (mimicking the period 2000-2100; Fig. 1 top), in spite of their close spatial proximity. On the north-facing slope, the dominance of Norway spruce observed under current conditions continues under the future climate, while maple (*Acer* spp.), elm (*Ulmus* spp.) and other deciduous species are of minor importance only. On the south-facing slope, however, the stone pine forest is replaced by a mixed forest where Norway spruce is the most abundant species but contributes less than half of the total biomass (Fig. 1 top). Thus, under this climate scenario, future forests are simulated to be more similar to each other on opposing slopes than under current conditions, but considerable differences continue to exist many centuries into the future.

In addition, we wanted to know whether it might be possible to maintain the current species composition at two high-elevation sites, where tourism is the most important source of income today (Davos and Bever, Switzerland). In the face of environmental change, it is conceivable that attempts would be undertaken to mitigate

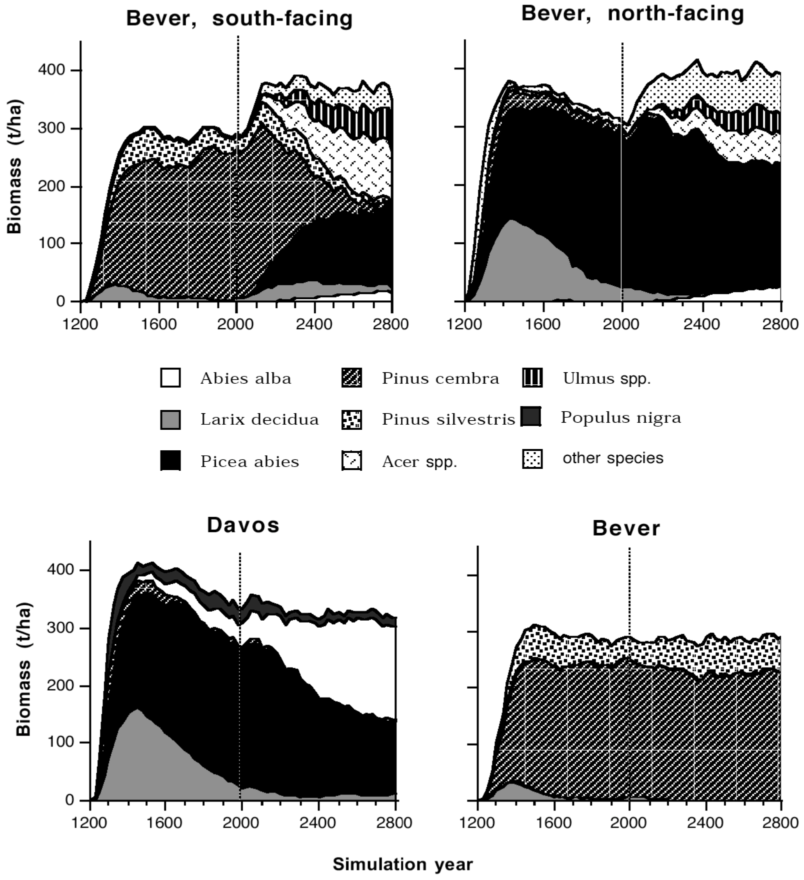

Figure 1: Impacts of climate change on forest composition and biomass in the European Alps. The scenarios of climate change are from Gyalistras et al. (1994) as extrapolated to the year 2100 by Bugmann (1997); they involve an increase of monthly mean temperature between 1.5 and 4.2°C and a precipitation increase between 0.9 and 3.8 cm/month, depending on season and site. Top: Response of forests on north- and south-facing slopes near Bever, Upper Engadine Valley under unmanaged conditions (Bugmann, unpublished). Bottom: Simulation results at two subalpine sites under the assumption that those tree species immigrating under a new climate would be eliminated by management in an attempt to maintain the current species composition.

climate-induced changes in the forest cover. This could be implemented, for example, by eliminating tree species that are immigrating but are less desirable from the point of view of landscape aesthetics, or by planting tree species that are characteristic of the current species assemblage but are unable to regenerate naturally in the future (e.g. because of a lack of chilling). We assessed the success of such management regimes through a series of simulations. These showed that any planting efforts would be irrelevant under the range of climate scenarios considered because according to the model it is not the regeneration niche that will determine the success or failure of the current species under a future climate, but rather competitive effects as the trees become larger. The “elimination” scenario, however, would be fairly successful in maintaining current forest composition far into the future (cf. Fig. 1 bottom), except for the conifer *Abies alba*, which would become quite abundant at Davos. Note that such a management practice would be quite difficult and costly to implement across large areas, and these artificially maintained forest stands would be likely to become more susceptible to disturbance agents, including pests and pathogens, which are not included in the current version of the ForClim model.

2.2 Disturbance dynamics and vegetation patterns at the landscape scale

Looking at patch scale dynamics (see above) is important for a number of reasons, but real mountain landscapes are strongly shaped by natural (e.g. windstorms, wildfires, avalanches) and anthropogenic (e.g. management) disturbances, and such large-scale spatial phenomena cannot be modeled at the patch scale. Changes of disturbance regimes are expected for the 21st century as a consequence of global change, particularly changes of climate and land use. However, the interactions between climate, disturbance dynamics and vegetation properties are not well researched. We started looking into these issues using temperate mountain regions in the European Alps as case studies. First, the sensitivity of the fire regime to altered environmental conditions, and to spatial heterogeneity of fuel availability is addressed. Secondly, the sensitivity of forest landscape patterns to the impacts of changes in fire regimes and climate is investigated. Other drivers of landscape dynamics, such as windthrows and avalanches, are also considered via simple parameterizations.

Landscape-level ecological simulation models are important tools for improving our understanding of the ecological consequences of such changes. We based our work on LANDIS, a modeling framework of landscape dynamics (He and Mladenoff 1999). LANDIS is a spatially explicit, raster-based, and stochastic model developed to simulate and analyze the interactions between forest plant behavior, site conditions and disturbance regimes such as fire, windthrow, and forest management. Vegetation succession, however, is implemented in a fairly simple manner, reflecting the assumption that the disturbance regime is of overriding importance for shaping landscape dynamics. In “weakly” disturbed landscapes such as those of the European Alps of the 20th century, we found that the succession submodel of LANDIS had to be reformulated. We therefore developed a succession submodel that (1) better represents the species’ relative competitive ability and (2) includes their responses to changes in the physical environment in more detail. With this approach we obtained a landscape-scale simulation model that incorporates a semi-mechanistic submodel of tree-tree interactions, a feature that is unique to our approach and allows us to study the transition from weakly disturbed to strongly disturbed landscapes. To derive relationships between the parameters that characterize the fire regime and climatic variables, an extensive analysis of fire data was conducted. To expand the bioclimatological space beyond European conditions, data from the (more fire-prone) western US were used.

As a first step, we used the new LANDIS version to examine the response of forests in the Dischma valley (Switzerland) to changes in climate that are directly tied to a change in the fire regime. The Dischma valley is located in the eastern part of the Swiss Alps in the transition zone between the wet northern Alps and the dry central Alps. It is a 43.3 km^2, north-northwest facing catchment. Elevation ranges from 1668 to 3146 m asl. The current vegetation pattern is influenced by the harsh climate, steep slopes, avalanches, wind disturbances and anthropogenic impacts. Fire plays no significant role in the present landscape.

The LANDIS model was initialized with forest characteristics derived from measured data that correspond to the current situation in the valley. Notably, the alpine treeline is significantly lower (ca. 2000-2100 m asl) today than under natural conditions because of historic and present cattle and sheep grazing as well as harvesting activities. Simulations were run for 500 years into the future under (1) current climatic conditions, assuming no forest management and no grazing, thus allowing the forest to expand into what is currently alpine tundra; and (2) a simple climate change scenario (year-round increase of temperature by 2°C and reduction of precipitation by 20%) that also includes a moderate fire regime. In all simulations, avalanche tracks were not available for spontaneous reforestation, i.e. we assumed a regular recurrence of avalanches, which thus prevents the establishment and persistence of large trees.

The simulation results for the current climate (Fig. 2, left panels) show that the dominance of *Picea abies* at the landscape scale (below 1900 m asl) would continue, which is reasonable considering that the species is thought to be the climax tree in this area. A considerable fraction of the forested area at lower elevations in the valley would be dominated by the early successional *Larix decidua*, as a consequence of windthrow disturbance. *Pinus cembra*, which is currently just a minor component of the forests at higher altitudes, would start to dominate the zone just below treeline. Treeline itself would shift upwards by roughly 150-200 m, in the absence of livestock grazing. Biomass is around 200-300 t/ha at the lower elevations in the valley and decreases rapidly between 1850 to 2100 m asl to very low values above 2100 m asl. All these features are characteristic of elevational gradients in high mountain catchments of the central European Alps, and the modified LANDIS version is capable of capturing them adequately.

The simulation results under the climate change scenario (Fig. 2, right panels) suggest that a strong increase of treeline elevation (up to ca. 2500 m asl) would occur, with a concomitant upward shift of the various forest types along the elevational gradient. Notably, these simulations suggest no significant "individualistic" behavior of the tree species under this scenario of climate change. Spatial heterogeneity would increase in the zone dominated by *P. abies*, due to the more frequent occurrence of disturbances, including wildfires. Note that species that are currently confined to the montane zone were not able to immigrate in this simulation because they are not included in the present model version. Further investigations will be necessary to evaluate the interactions of forest composition with the disturbance regime; the modified LANDIS model is an important tool towards achieving this goal.

2.3 Mountain ecosystem services at the catchment scale

As mentioned above, ecological and hydrological processes are tightly coupled

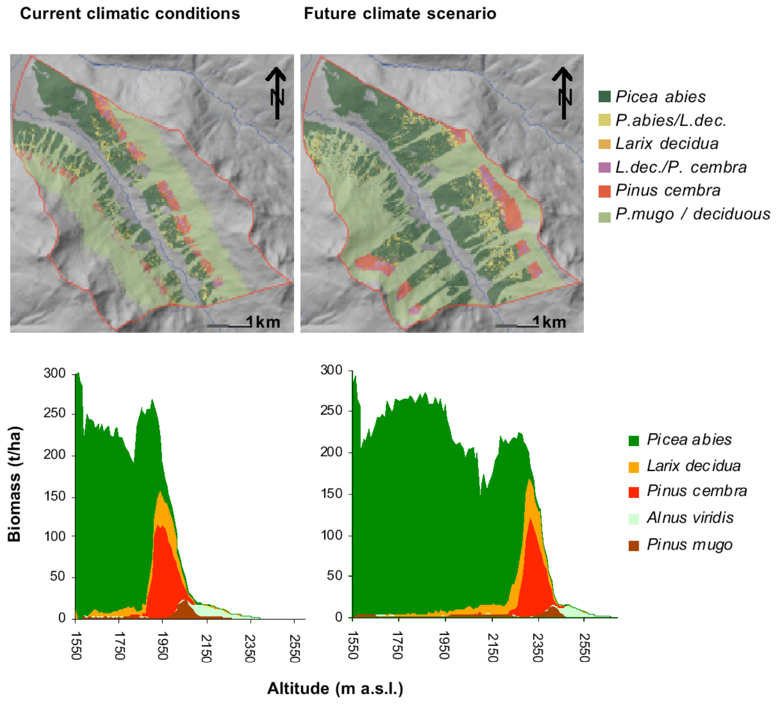

Figure 2: Impacts of climate change on landscape patterns in the Dischma valley, based on simulation results with the LANDIS model. Top: Landscape composition under current conditions (left) and under a simple scenario of a future climate (right). Bottom: Biomass distribution by altitude, excluding avalanche tracks, under current climatic conditions (left) and the future climate scenario (right).

in mountain regions. The integration of biogeochemistry and catchment hydrology in mountain regions requires simulating both the vertical fluxes between soil, vegetation, and atmosphere, and the lateral fluxes between adjacent vegetation patches. Band et al. (1993) and White and Running (1994) combined distributed flow modeling based on TOPMODEL with an ecophysiological canopy model based on BIOME-BGC and a climate interpolation scheme based on MTCLIM to build the regional hydroecological simulation system RHESSys. We build upon this tool in a research project that focuses on global change effects on mountain ecosystem goods and services, which is part of the EU project "Advanced Terrestrial Ecosystem Analysis and Modeling" (ATEAM, see http://www.pik-potsdam.de/ateam).

RHESSys is a spatially distributed daily time step model, designed to solve the coupled cycles of water, carbon, and nitrogen in mountain catchments. It has been widely used to simulate hydroecological processes in various mountain catchments in North America (Fagre et al. 1997; Hartmann et al. 1999; Baron et al. 2000; Tague and Band 2001).

We use RHESSys to analyze the impact of climate and land use change on river discharge and carbon storage in mountain catchments in Europe. As a first case study, we chose the Dischma catchment (cf. description in section 2.2). Within a few kilometers of the catchment, there are two meteorological stations maintained by MeteoSwiss. At the lower end of the catchment, river discharge is measured.

To perform a preliminary evaluation of the climatic sensitivity of hydrological and ecological processes in the Dischma catchment, we conducted simulations under current climate as well as under scenarios of a changed climate. Current climatic conditions are based on daily weather observations from 1981 to 2000. To generate two simple climate change scenarios, the data for the current climate were altered by either adding 2°C to minimum and maximum daily temperatures, or by decreasing daily precipitation by 10% throughout the year. Using these 20-year climate scenarios, river discharge and carbon storage were simulated with the model RHESSys.

The simulation results suggest a complex pattern of responses in carbon storage to shifts in temperature and precipitation (Fig. 3, top). Depending on the location within the catchment, rising temperature can lead to either an increase or a decrease of ecosystem carbon storage. In particular, water availability appears to control the responses of photosynthesis and carbon allocation to rising temperatures.

Decreased precipitation in the climate change scenario implies an increase in incoming solar radiation through decreased cloudiness. Consequently, there are two contrasting effects on photosynthesis. On the one hand, the precipitation decrease

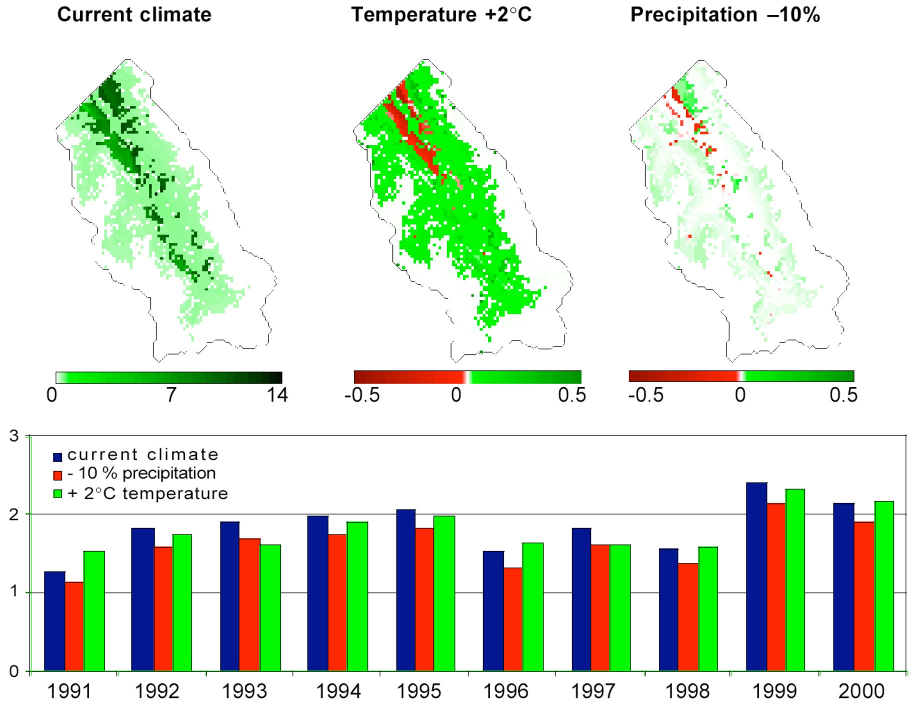

Figure 3: Impacts of climate change on carbon storage and streamflow in the Dischma valley. Top: Total carbon storage [kg/m^2] under current climate, and changes in carbon storage [kg/m^2] under two simple scenarios of climate change. Bottom: Response of average annual river discharge [m^3/s] in the Dischma under the same climate scenarios

leads to reduced soil water availability, which in turn decreases photosynthesis through stomatal closure. On the other hand, the increase of solar radiation brings about an increase of photosynthate production. The balance of the two effects determines the overall response of carbon storage, which obviously varies considerably within the catchment (Fig. 3, top).

As expected, decreasing precipitation diminishes river discharge, but it has no effect on the seasonality of discharge. In contrast, the timing of hydrological responses is highly sensitive to temperature changes. On average, annual river discharge decreases with rising temperatures as evapotranspiration increases (Fig. 3, bottom). However, an analysis of the seasonal effects of a temperature increase (data not shown) suggests strong seasonal differences: winter discharge increases, whereas summer discharge decreases with rising temperatures.

These seasonal differences illustrate the control of temperature over snow accumulation and snow melt, which in turn affects river discharge. Under a warmer climate, more precipitation during the winter season falls as rain, and the snow cover melts earlier. This water flows directly to the river, increases winter river discharge, and is unavailable to the ecosystems in the catchment, because the vegetation is dormant during this time of the year. It is well known that in the present climate, snow cover has an important function with respect to storing and buffering winter precipitation peaks, and releasing the water during the first half of the growing season. Our scenario study suggests that this function might be lost under a warmer climate.

3. Future research directions

A fairly sophisticated set of tools is available today for projecting the impacts of climate change on mountain forests and landscapes, resulting from research efforts that typically have focused on one single spatial (and often also temporal) scale, and most of these efforts have proceeded in a sectoral manner. As a consequence, we are not in a position to simultaneously evaluate the effects of (1) climatic changes on long-term successional processes; (2) changes in the disturbance regime and the associated vegetation feedbacks, and (3) the link between lateral flows of water and either the disturbance regime or successional processes. However, an integrated evaluation of these processes is required for mountain regions because of the tight coupling between them. Thus, how do we achieve this integration?

At first sight, one might perceive the best strategy to be the full coupling of existing models such as ForClim, LANDIS, and RHESSys. According to this strategy, one would try to combine the biogeochemical routines of the BIOME-BGC model, which is a part of RHESSys, with the description of tree population dynamics from ForClim and the representation of disturbance dynamics from LANDIS. We believe that there are two major reasons why such an endeavor would be exceedingly difficult, if not futile:

First (and more pragmatically), the coupling of complex ecosystem models is prone to great conceptual and technical difficulties. The various models differ in their underlying assumptions, in their representation of ecosystem components, and in the process formulations. It is not obvious that the input-output linkages between the different models could always be satisfied. Rather, we would expect that the seemingly simple enterprise of "linking" models would bring about the need to re-evaluate, adjust and revise model formulations (not just output-input relationships), which thus would lead to a modeling effort of its own.

Second (and more fundamentally), each of these models represents a fairly complicated and supposedly realistic representation of some aspects of ecosystem dynamics. Each model is characterized by several hundred parameters, and the coupling would most likely lead to an "integrated" model of greatest complexity whose dynamics are hard to understand, difficult to track to the underlying processes, and not amenable to a rigorous analysis of sensitivity and uncertainty. Thus, we surmise that such an "integrated" model would be of little value as a research tool, let alone as an assessment or management tool.

Therefore, we advocate a different route for achieving a more integrated model of ecological and hydrological processes in mountain regions. In the case of the LANDIS model (cf. section 2.2), we have attempted to replace a very simple representation of successional processes by a more detailed description that was developed by *abstracting* from the patch-level processes that are incorporated in forest gap models (such as ForClim, section 2.1). Here, *abstracting* refers to the process of deriving simplified, more aggregated descriptions of ecological phenomena for incorporation into coarser-scale models. Note that this is not the same as coupling ForClim to LANDIS. We believe that a similar approach could be taken towards integrating successional processes and disturbance dynamics into hydro-ecological simulators such as RHESSys, i.e. by abstracting crucial information from more detailed ecological models, and incorporating "scaled" process formulations into RHESSys, instead of attempting to couple the full models with each other. We still have a long way to go towards this goal, but we think this approach is promising and should be pursued further.

Finally, we would like to emphasize that a truly "integrated" approach to a model-based assessment of global change effects in mountain catchments (or mountain regions) would have to go far beyond the natural sciences, on which this contribution focused. Including land cover and land use dynamics together with socio-economic aspects (and perhaps even atmospheric dynamics) in a single modeling framework is an entirely different challenge. As in the case of natural sciences, the models for many sectoral considerations are available. Even more so than within the natural sciences, we are convinced that a truly integrated assessment of global change in mountain regions cannot be achieved simply by coupling existing models – a significant amount of research efforts will be required to arrive at solutions for this challenge.

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