Modeling the Biophysical Impacts of Global Change in Mountain Biosphere Reserves

Authors: Bugmann, Harald, Gurung, Astrid Björnsen, Ewert, Frank, Haeberli, Wilfried, Guisan, Antoine, et al.

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Harald Bugmann, Astrid Björnsen Gurung, Frank Ewert, Wilfried Haeberli, Antoine Guisan, Dan Fagre, Andreas Kääb, and GLOCHAMORE participants

Modeling the Biophysical Impacts of Global Change in Mountain Biosphere Reserves

Mountains and mountain societies provide a wide range of goods and services to humanity, but they are particularly sensitive to the effects of global environmental change. Thus, the definition of appropriate management regimes that maintain the multiple functions of mountain regions in a time of greatly changing climatic, economic, and societal drivers constitutes a significant challenge. Management decisions must be based on a sound understanding of the future dynamics of these systems. The present article reviews the elements required for an integrated effort to project the impacts of global change on mountain regions, and recommends tools that can be used at 3 scientific levels (essential, improved, and optimum). The proposed strategy is evaluated with respect to UNESCO's network of Mountain Biosphere Reserves (MBRs), with the intention of implementing it in other mountain regions as well.
First, methods for generating scenarios of key drivers of global change are reviewed, including land use/land cover and climate change. This is followed by a brief review of the models available for projecting the impacts of these scenarios on (1) cryospheric systems, (2) ecosystem structure and diversity, and (3) ecosystem functions such as carbon and water relations. Finally, the cross-cutting role of remote sensing techniques is evaluated with respect to both monitoring and modeling efforts. We conclude that a broad range of techniques is available for both scenario generation and impact assessments, many of which can be implemented without much capacity building across many or even most MBRs. However, to foster implementation of the proposed strategy, further efforts are required to establish partnerships between scientists and resource managers in mountain areas.

Keywords: *Biodiversity; climate change; cryosphere; impact assessment; land cover; land use; remote sensing.*

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Introduction

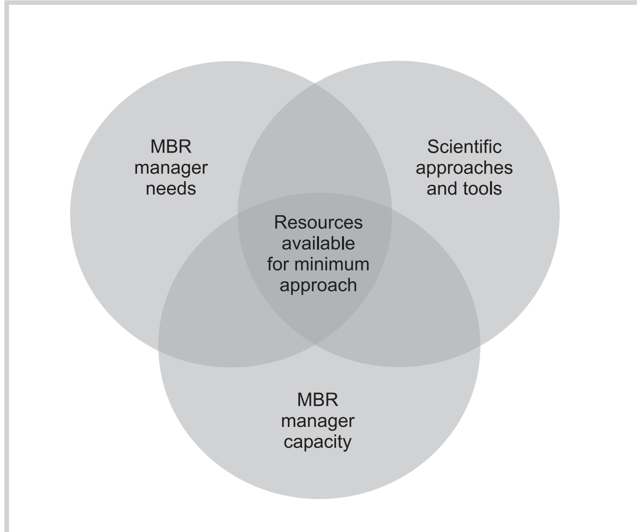
Mountains and mountain societies are particularly sensitive to the effects of global environmental change (Huber et al 2005). The EU-funded GLOCHAMORE project (Global Change and Mountain Regions) addressed the environmental challenges facing the world's mountain regions in the 21st century with the aim of developing a global change research strategy. This strategy was not simply to create more scientific knowledge, but also to make this knowledge useful to managers, decision-makers and policymakers (Björnsen Gurung 2005). Specifically, the project aimed to 1) develop an integrative research strategy for detecting signs of global environmental change in mountain environments; 2) identify the impacts of these changes on mountain regions and the many lowland areas that are dependent on mountain goods and services; and 3) facilitate the development of sustainable resource management regimes for mountain regions. In this context, 4 methodological foci were defined (Becker and Bugmann 2001): (1) long-term monitoring of environmental and societal changes in mountain regions (Grabherr et al 2005); (2) studies of global change processes in mountain regions, with an emphasis on altitudinal gradients; (3) evaluation of tools and methodologies for contributing to and fostering sustainable resource management in these regions; and (4) providing model-based projections of the impacts of global change on mountain regions (the topic of the present article).

The network of UNESCO's Biosphere Reserves, many of which are located in mountains, provides ideal natural global change laboratories. For more information, see http://www.unesco.org/mab/BRs.shtml and for mountain-specific aspects http://www.unesco.org/mab/ecosyst/mountains/gcmbr.shtml. These reserves have a core protected area surrounded by lower-elevation buffer zones with stronger anthropogenic influence. The strong altitudinal gradients within Mountain Biosphere Reserves (MBRs) provide excellent opportunities to detect and analyze global change processes and phenomena from both a socioeconomic and a scientific perspective (Körner 2000; Becker and Bugmann 2001).

The wide geographical distribution of mountain regions, and thus of MBRs, provides opportunities for comparative inter- and intra-regional studies of global change impacts. To assess the biophysical impacts of these changes at continental to global scales, a standardized approach to global change research in mountain regions is required. Similarly, mountain regions are subject to socioeconomic changes driven by globalization. Apart from the direct effects of climate change, other factors such as resource use, land use and land cover change, and tourism render these systems highly complex and dynamic. Hence, the definition of appropriate mid- to long-term management regimes that maintain the multiple functions of MBRs in a time of strongly changing climatic, economic, and societal drivers is a significant challenge to the management of many MBRs and mountain regions in general.

To provide MBR managers and policymakers with a sound basis for decision-making, user-driven research should be combined with interests from both the natural and social science research communities and integrated into a joint research framework.

FIGURE 1 Scheme of the set of scientific approaches and tools that are available for predicting the impacts of global change on mountain regions (right), the set of MBRs managers' needs (left), and the set of MBR managers' (or 'local' scientists') capacity to implement such research activities in a given MBR (bottom). Evidently, the contents of the set will vary from one continent to the other, or even from one MBR to the other.



The GLOCHAMORE project was set up to take advantage of the infrastructure and ongoing research activities in a selection of UNESCO's MBRs around the globe, with the explicit long-term goal of implementing the research strategy in MBRs and other protected areas in both developed and developing countries. Thus, the active participation of MBR managers in development of the research strategy is an integral part of the project (Figure 1).

From a conceptual point of view, drivers of change can be distinguished from impacts of change. Impacts of global change are of particular importance for snow and ice, ecosystem composition, biodiversity, and function. The present article considers 2 key drivers of such change: climate and land use. The crucial elements of the proposed assessment methodology are monitoring, process studies, modeling of impacts, and scenario analyses. Therefore, the objectives of this paper are twofold: First, to briefly review the methods available for deriving scenarios of land use and climate change in mountain regions; and second, to discuss the methods that are available for assessing (modeling) the impacts of Global Change on the cryosphere, ecosystem structure, and biodiversity, as well as ecosystem function, including a discussion of the role of novel remote sensing techniques.

Scenarios of drivers of change

Land use and land cover

MBRs are strongly influenced by land use and land cover (LULC) change within and outside the MBRs through a variety of spatial ecological processes that often encompass MBRs or extend across MBR boundaries. LULC change through agriculture, resource extraction, and urbanization increases rapidly around many nature reserves in the world (de Fries et al 2005), and the associated impacts within park boundaries are of increasing concern. Natural resource managers often see LULC change as a more immediate concern as compared to climate change. Unlike climate change, LULC change is more immediately subject to policy control. Not only does LULC change affect other key MBR resources and services; it also sets the framework that controls the expression of climate change impacts across landscapes. Information about LULC change is therefore essential to analyze and model the impacts of global change in MBRs.

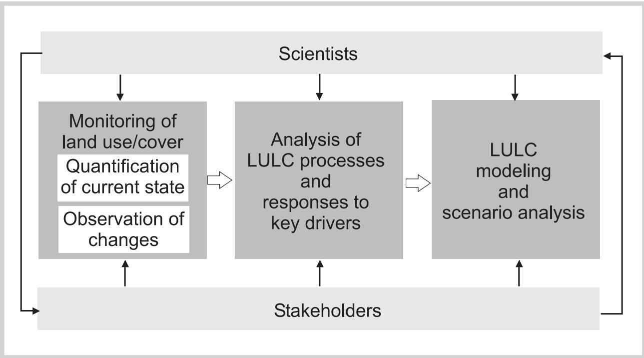
Environmental and LULC change are closely interrelated (Lambin et al 2000), and LULC is also a result or indicator of natural and human-induced changes. The variety of drivers affecting LULC change (Rounsevell et al 2006) may be grouped into natural, socioeconomic and political drivers (Ewert et al 2005; Rounsevell et al 2005). Changes in these drivers are often the result of larger-scale processes; for instance, changes in prices for agricultural products are closely related to changes in regional or even global markets, but may have very local implications for land use and land cover. LULC change is thus a global change phenomenon, often orthogonal to climate change. Modeling (and monitoring) LULC change should consider drivers and relationships relevant to MBRs.

As environmental and socioeconomic conditions differ among MBRs, there is no single classification of LULC change that would be applicable to MBRs. Instead, understanding of the local factors and processes determining LULC change is required to support modeling and estimation of LULC change. Uncertainty about changes in key drivers has made scenario analysis necessary in the exploration of possible futures. The Special Report on Emission Scenarios (SRES; Nakienovi et al 2000) of the IPCC provides an attractive framework for the development of LULC change scenarios. A recent methodology for LULC change in Europe (Rounsevell et al 2006) was based on the SRES scenario framework combining environmental and socioeconomic drivers of LULC change from global to regional scales. The proposed approach can also be used to guide the development of LULC change scenarios in MBRs.

A basic prerequisite for any LULC change research in MBRs is that the current state of land use and land cover be quantified, including characterization of current LULC change trajectories and understanding of the underlying processes of change (Figure 2).

The *essential level* of a GLOCHAMORE strategy addressing LULC change consists of developing the capacity in MBRs to view and manipulate spatial data and imagery. While many MBRs have GIS facilities and

FIGURE 2 Proposed steps of a strategy for LULC change research in MBRs.



experienced technical staff, a considerable number do not. Thus, success here involves both equipment and training. Capacity building must go along with establishing access to spatial data pertinent to both the current state of land use and land cover, and to its rate of change. Fortunately, the most basic data (including digital elevation models and repeated satellite imagery) are available virtually for free (Thuiller et al 2004; for instance through the European Environment Agency, http://dataservice.eea.eu.int/dataservice, or the Earth observing system of NASA, http://eospso.gsfc.nasa.gov/index.php). Finally, this most basic strategy involves classification and analysis of land use data to achieve a comprehensive view of land use and land cover conditions and trends. Change detection through comparison of repeated imagery holds particular promise for quickly locating and quantifying the nature of LULC change.

An *improved level* of an LULC change research strategy also includes process studies to understand the origins of the observed change and, associated with this, collection of data to validate specific land use models. This research will require a clear definition of the nature of the expected change (eg change in range condition) and development of specific hypotheses (eg changes in production practices of red deer as a function of market prices). An essential next step for those MBRs ready to embark on this medium level is to define these 2 elements.

Finally, the *optimum level* involves the development of future land use scenarios based on spatial data portraying past land use and land cover, and spatial modeling of potential future changes. LULC change scenarios become an integrated part of the modeling and assessment process (Figure 3). It may be possible to find a shortcut by simply specifying future land use and land cover scenarios through a stakeholder process (ie the land use and land cover equivalent of declaring a warmer and wetter climate change scenario without using General Circulation Models or Regional Climate Models), but the power of such scenarios will depend almost entirely on the credence and plausibility accorded to them by decision-makers and stakeholders.

Climate

Providing scenarios of climate change that are specific to mountain regions is of great importance for the sustainable management of natural resources in these areas, including MBRs. However, global climate models (GCMs) (Houghton et al 2001) are based on highly simplified topography, and although research is in progress to develop high-resolution models, they are available for a few specific mountain regions only (Schär et al 2004). Therefore, the GLOCHAMORE strategy focuses on a selection of key elements that make it possible to describe likely climate change with minimal effort and thus in MBRs around the globe.

At the *essential level*, the proposed strategy builds on the global climate projections of Houghton et al (2001) to guide simple analyses with impact models. In such an approach, the IPCC data would be used to define a number of scenarios for setting up simulation studies. As these scenario data are global in nature, such analyses could not qualify as "predictions" of the future trajectories of particular mountain systems (Bugmann 2003). Yet they can be useful for elucidating the *sensitivity* of certain ecosystem goods and services to climatic changes, a factor that is crucial for setting management goals. For natural resource management, it would be important to identify so-called "valued ecosystem components" (VECs) that are sensitive to climate change or are at the margins

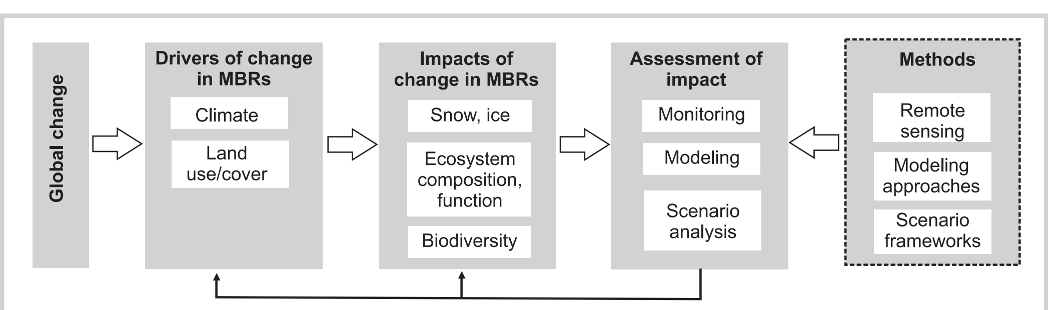


FIGURE 3 Proposed elements of a strategy for modeling and assessment of global change impacts on MBRs.

of their climatic range (Welch 2005), such as keystone species or biodiversity (Munn 2002; Guisan 2005). Developing models and scenarios for the impact of climate change on specific VECs in terms of sensitivity is of particular interest to the managers of protected areas. Combined with considerations regarding the *adaptive capacity* of MBRs to the projected changes, particularly *vulnerable* VECs could be identified.

At the second, *improved level*, the output of GCMs, some of which are available free of charge on the Internet, can be used in a "brute-force" downscaling effort, ie by using the climate anomalies of the nearest grid cell(s) of the climate model for driving impact models in a given MBR. While it is clear that such an approach ignores any fine-scale details that are quite important for weather and climate in mountain regions, it has the advantage of providing some regional (or at least continental) details that are absent from the essential level, where only global average data are being used. Thuiller et al (2005), for instance, used such GCM scenarios to assess impacts on European flora. They identified several mountain regions as being particularly at risk of species loss.

The *optimum level* includes a more refined downscaling technique, such as statistical downscaling or the application of high-resolution Regional Climate Models (RCMs), which can provide climatic information at a spatial grain of a few kilometers and at a spatial extent of several 100 km^2 (Beniston et al 2003; Schär et al 2004). Applying such techniques, however, requires the collaboration of impact researchers in MBRs with climate modelers.

It is important to keep in mind that climatic parameters are changing in concert with other drivers of global change, such as human populations, land use, atmospheric CO_2 concentrations and nitrogen deposition, to name a few. Thus, wherever possible, the joint effect of these drivers should be considered through a set of systematic simulation studies with impact models, where scenarios for each driver are applied in isolation as well as in factorial combinations, with scenarios that include the full set of drivers. Such an approach is highly valuable because it allows us to determine the relative importance of the specific drivers for a given system/service in a given MBR and to assess their importance in comparison with other mountain systems.

The MBRs included in the GLOCHAMORE project were found to differ greatly in terms of experience with scenarios of climatic change. While in some MBRs fully-fledged regional climate model simulations are available to the managers and research staff, in many parts of the world the focus has been on other drivers (such as land use changes) to date, rather than on climatic change.

Modeling of impacts

Snow and ice

The differing response characteristics of snow, glaciers, and permafrost, as well as the numerous interactions and feedbacks between these components, cause continuous deviations from equilibrium conditions in high-mountain geosystems to develop with continued climate change. Numerical modeling must, therefore, primarily address the transient behavior of these systems, and it should anticipate the possible occurrence of new processes.

Snow

Relatively simple (ie one-layer) energy and mass balance models are typically used as part of SVAT (Snow–Vegetation–Atmosphere Transfer) schemes in larger-scale models (Slater et al 2001). The application of one-dimensional models can provide important quantitative information, eg concerning the evolution of the water equivalent within the snow cover. Only a few models treat processes within the snow cover (such as metamorphism or phase changes) and thus are capable of providing information on structural and mechanical snow properties (Etchevers et al 2005). Models for MBR applications should provide structural details of the snow cover and especially projections of their spatial distribution (ALPINE3D; Lehning et al 2004). Data on snow structure and stability support avalanche warning systems and provide estimates of the conditions for animal mobility. Further, representative snowmelt curves help to determine mass and energy fluxes between snow and vegetation or the underlying substrate (soil, permafrost). Large MBRs may span several zones/belts of different snow characteristics and may extend from maritime to continental climate conditions, thus inducing a high variety of snow conditions. However, even in these MBRs a representative ensemble of snow covers can be simulated on the basis of a few meteorological stations only.

At the *essential level*, simple global change experiments for a sample of representative MBR sites can be performed to simulate the hydrological response of the snow cover (snowmelt curve) based on a few global change scenarios. In this way, fairly general information can be produced, eg to estimate water supply from snowmelt. More sophisticated investigations can be performed at *improved* and *optimum levels* (see the detailed descriptions in Haeberli and Dedieu 2004).

Glaciers

A process chain links glacier fluctuations to climate change. This first includes the Surface Mass Balance (SMB) via the surface energy balance. As a consequence of changes in SMB, glaciers change their geometry (and temperature in case of non-temperate glaciers), and the length of their tongues adjusts to new equilibrium conditions within the dynamic response time. A number of numerical models at different levels of sophistication have been developed for both the glacier mass/energy balance and the dynamic response of glacier tongues, for individual glaciers as well as for large sets of unmeasured glaciers (eg Haeberli and Hoelzle 1995; Oerlemans 2001; Klok and Oerlemans 2002; Greuell and Genthon 2003; Hoelzle et al 2003). A specific problem occurring with distributed energy balance approaches relates to snow redistribution by wind and avalanches (Lehning 2005). Numerical glacier modeling constitutes an essential component of modern glacier monitoring strategies and serves to extrapolate observed developments in space and time (Haeberli 2004). Thus, observation and modeling efforts within MBRs should be integrated into existing networks and monitoring strategies, such as the Global Hierarchical Observing Strategy (GHOST) within the Global Terrestrial Observing System (GTOS; Haeberli and Dedieu 2004).

At the *essential level*, all MBRs containing glaciers should observe and model their evolution as a key indicator of climate change. Basic requirements are a digital elevation model and a satellite image for delineating glacier extent. Models at the essential level can then be applied immediately and with a minimum of input data. They enable estimates of mass balance change versus altitude, and thus average mass balances can be inferred from calculated shifts in equilibrium line altitude (ELA). Moreover, the easily documented cumulative length changes for different glaciers can be converted into average mass change over time periods of a few decades, which correspond to the characteristic dynamic response time of medium-size mountain glaciers. Distributed mass balance models can be applied at the *improved level* and be combined with flow models at the *optimum level*.

Permafrost

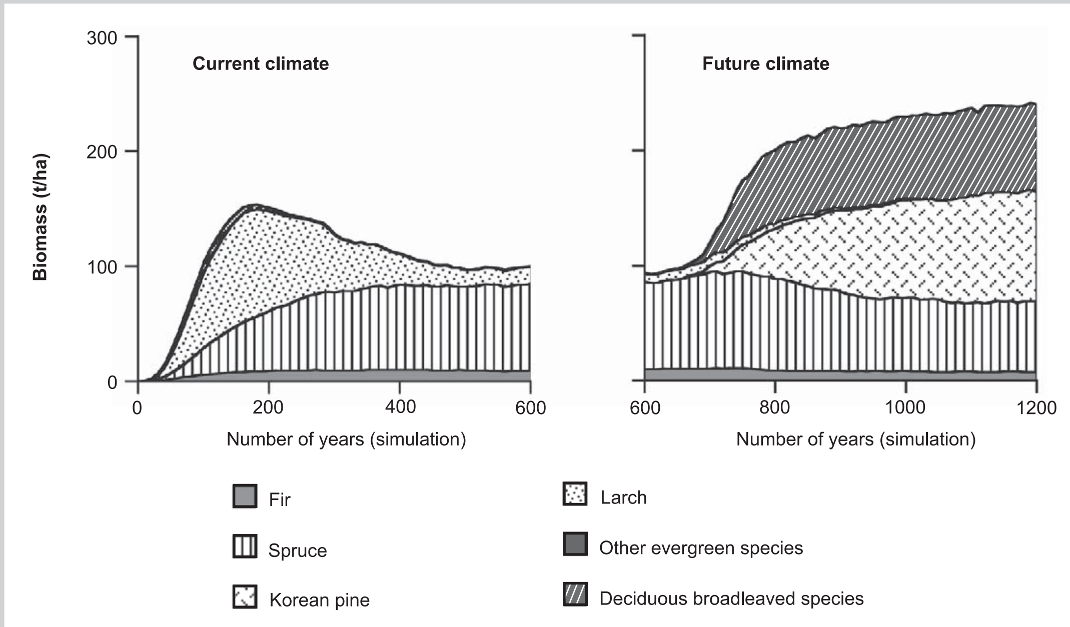
Permafrost distribution models combine stochastic with deterministic elements. They can be divided into 2 types: regionally calibrated empirical-statistical models (simple models) and more physically-based, process-oriented models (complex models). Empirical-statistical models directly relate documented permafrost to topographically controlled microclimatic factors (altitude, slope and aspect, mean air temperature, solar radiation), which can be measured or computed easily (Keller 1992). Detailed energy exchange processes at the surface and within the active layer are not treated explicitly but rather as a gray box with topographic/microclimatic factors being selected according to their relative influence in the energy balance. Process-oriented models focus on a more detailed understanding of the energy fluxes between the atmosphere and the permafrost. They explicitly parameterize solar radiation, sensible heat, surface albedo, heat conduction, etc, are often complex, and need comparably large amounts of precisely measured or computed data. Such approaches allow for spatio-temporal extrapolation and are especially well suited for sensitivity studies with respect to interactions and feedback involved in climate change scenarios. They enable surface temperatures to be computed and, hence, thermal conditions at depth and transient effects to be estimated (Hoelzle et al 2001; Gruber et al 2004). Capturing the complicated processes within the active layer (ie between the surface and the permafrost table) remains a primary challenge for every modeling exercise of mountain permafrost.

At the *essential level*, empirical/statistical steady-state models calibrated with field measurements should be applied in each MBR. These models provide a spatial overview of the potential permafrost distribution patterns under present-day climatic conditions in different mountain areas. Basic prerequisites are digital elevation models, satellite imagery for characterizing different surface characteristics (forest, meadows, debris, bedrock), and GIS software. The MBRs should collect data on the occurrence of mountain permafrost for calibrating and validating numerical models. Corresponding cheap and simple-to-use tools consist of measurements of the bottom temperature of winter snow cover combined with miniature temperature loggers within the active layer of the permafrost at sites with different surface characteristics. More sophisticated validation tools (geophysical soundings, drilling, borehole observations) are available for more in-depth studies. At the *improved level*, time-dependent one-dimensional models based on snow/ground-coupled energy balance approaches can be applied (Lütschg et al 2003). At the *optimum level*, complex time-dependent 3D-models based on energy balance approaches including meteorological information, digital elevation data and documentation by remote sensing can be applied.

Ecosystem composition and biodiversity

Apart from physical changes, climate change will lead to profound changes in the composition of ecosystems. Change will occur not only due to changes in temperature and water regimes, but also due to the changing ability of pests, pathogens, and weeds to invade new regions (Welch 2005). Here we emphasize 3 different methodological aspects for modeling ecosystem composition and biodiversity: 1) models of vegetation cover and its dynamics; 2) models of species distribution and

FIGURE 4 Application of the ForClim succession model to study the impacts of climatic change on the composition and biomass of high-elevation conifer forests of the Changbaishan MBR. Left: Model behavior at an elevation of 1690 m under current climatic conditions for 600 simulation years, starting from “bare ground” conditions (no forest in simulation year 0) until an equilibrium between climate and vegetation composition is reached. Right: Continuation of the simulation with 100 years (simulation years 600–700) of a linear change of climatic conditions (here, a 3 K temperature increase and a 20% decrease of precipitation throughout the year relative to current conditions), followed by a new, constant climate in the simulation years 700–1200. (After Shao et al 2001)



biodiversity; and 3) models of large-scale disturbance dynamics, taking the example of fire.

First, basic models are available for projecting vegetation cover using simple approaches. The Holdridge (1967) Life Zone model, for instance, requires only long-term monthly mean temperature and precipitation data. At the other end of the spectrum, sophisticated, state-of-the-art models such as the BIOME model family (Kaplan 2001) are available for use in those MBRs that have well-trained research staff and/or good collaborations with research institutes. Obviously, these latter models require more input data, but they also provide much richer scenarios of future change of vegetation at the level of plant functional types. Detailed dynamic models of the long-term dynamics of forest and grassland structure are also available (Bugmann 2001), but they require fairly detailed information regarding the properties of individual species as well as input data for climate and soils. An example of the application of such a model to assess the possible impacts of climatic change on the development of unmanaged forests in the Changbaishan Mountain Biosphere Reserve is shown in Figure 4, suggesting that current forests may undergo dramatic change in terms of species composition and carbon storage due to anthropogenic changes in the climate.

Second, predictive modeling of species or community distribution is now strongly facilitated by user-friendly software packages (eg DIVA, Hijmans et al 2001; BIOMAPPER, Hirzel et al 2002). Hence, MBR staff can perform most of this modeling themselves, although they may require some early training, with students visiting other, more trained MBRs or specialized research laboratories. A large spectrum of approaches for modeling the distribution of species and other biological entities have now been implemented in many modeling packages (see Guisan and Thuiller 2005 for a review of available tools and techniques). These are mostly statistical approaches relating the observed distribution of the modeled entity with a set of environmental descriptors extracted from a GIS database, extrapolated to the whole area (Guisan and Zimmermann 2000). As both the species and GIS data usually correspond to specific periods in time, these models are said to be static (snapshot views). More sophisticated approaches, implemented in cellular automata, now tend to additionally consider population dynamics and species dispersal to more realistically simulate future changes in distribution (Iverson et al 2004). From a conservation perspective, these models can support single species management to guide the search for new populations of endangered species (Guisan et al 2005), or be combined to assemble community or ecosystem level entities. Clearly, their application to MBRs would typically require additional technical support.

Finally, in many parts of the world, mountain landscapes are greatly shaped by natural (eg windstorms, wildfires, avalanches) and anthropogenic (ie management) disturbances. Such large-scale spatial phenomena cannot be modeled easily at the patch scale; this is the realm of so-called “landscape models.” Changes in disturbance regimes are expected for the 21st century as a consequence of global change, particularly changes in climate and land use. Therefore, we cannot ignore possible changes in the disturbance regime in MBRs when making assessments of their future ecosystem properties. However, almost all of the models reviewed above either ignore these spatially explicit processes altogether, or they contain only highly simplified formulations that are likely to provide insufficient detail when the models are applied at the local to regional scale in MBRs. Thus, additional and complementary approaches are needed to look into disturbance regimes. These range from simple fire indices (Gerstengarbe and Werner 1999) to fully-fledged landscape models that try to simulate the wildfire regime as a function of climate, soils and topography, and vegetation properties (Schumacher 2004). Again, while the simpler approaches can be applied nearly everywhere, the more sophisticated models require considerable technical and capacity building efforts.

The modeling skills for addressing ecosystem properties are distributed quite unequally among the MBRs. Thus, training and capacity building are key aspects of a research strategy that aims at projecting the impacts of global change on vegetation composition and biodiversity in MBRs worldwide. Also, monitoring networks are crucial for providing basic data for fitting preliminary models that may then be used to support the design of complementary sampling and monitoring strategies, eventually saving considerable costs.

Initiating a cross-comparison study of all selected MBRs, based on model projections, is a priority modeling issue for global change research in mountain regions. It would promote the development of standardized modeling procedures applicable to all MBRs. Data to be used for this endeavor are monitoring data on plant species in permanent plots, vegetation maps, and occurrence data for emblematic species; most of these are available for many MBRs. Basic GIS data are now available worldwide at no or reduced cost (eg worldclim: http://biogeo.berkeley.edu/worldclim/worldclim.htm). Thus, basic modeling efforts may at least use topographic, climatic, and remote sensing-derived descriptors, and many MBRs are currently initiating their own GIS database. Thus, more refined GIS predictors are likely to become available soon (see the section on remote sensing, below).

Ecosystem function (biogeochemistry and hydrology)

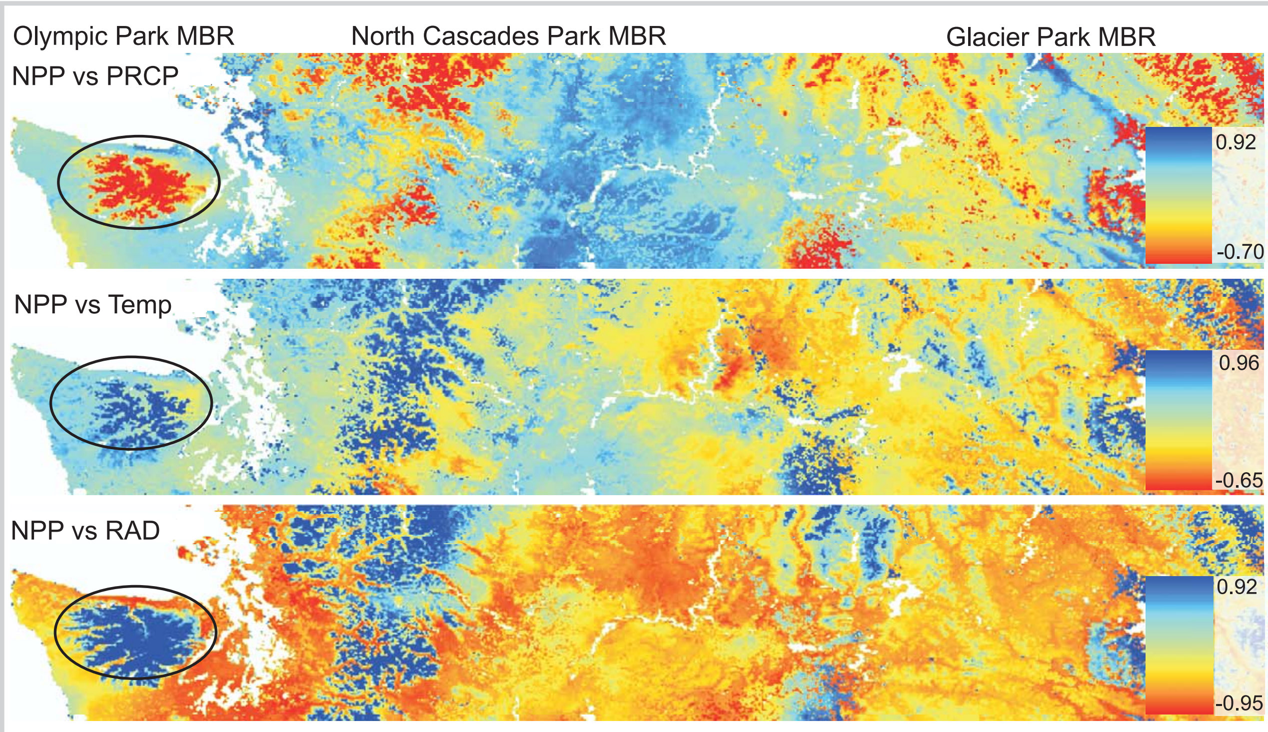
Besides changes in the structure and composition of ecosystems, functional aspects such as biomass turnover or water yield are of key concern for many natural resource managers in mountain regions, including MBRs. MBR managers need to understand these functional changes to make timely adaptations of their management practices to reduce vulnerability to the effects of climate change. In a simplified approach, 3 basic functions describe the ecosystem dynamics: 1) annual net primary productivity, 2) carbon pool size, and 3) hydrological output. MBR managers expressed strong interest in knowing more about these functions because of the key ecosystem services they represent.

Annual net primary productivity, for instance, is a measure of ecosystem growth that is sensitive to climatic patterns such as drought. Many MBRs have grazing or other resource extraction that must be adjusted to variations in net primary productivity to maintain desired ecosystem conditions. Carbon pool size represents the amount of carbon stored in the ecosystem and may become a strategic advantage in the future, as carbon sequestration and carbon credit trading become part of national policies. Finally, hydrological output from MBRs is a key concern almost everywhere on the globe, as human demand for water is growing while temperature and precipitation patterns are changing.

Because some of these ecosystem functions are difficult and expensive to monitor directly, ecosystem models are commonly used instead, in addition to being applied to make assessments of possible future changes. These models often use remotely sensed data from satellite platforms (eg Landsat Thematic Mapper) to derive broad patterns of vegetation and distribute these vegetation characteristics in complex topography using digital elevation models. Both these data sources are widely available for most parts of the globe. Ecosystem models then use local meteorological data and well-established rules about how plants grow to calculate energy and biogeochemical fluxes to capture the basic processes of vegetation growth, soil carbon exchange, and water balance. Estimates of these ecosystem functions need to be validated in the field, which is not always easy. However, some functions—such as the hydrologic output at the bottom of a watershed—are relatively easily measured, but only as the result of many interactions between climate, vegetation, and soils, thus making it difficult to assess whether an ecosystem model captures all processes correctly if it produces the correct overall output of the system.

There is a broad spectrum of purposes, approaches, and scales of ecosystem models. At the *essential level*, MBRs can implement the "environmental envelope" approach where specific plant communities are associated with specific climate conditions (eg number of frost-free days) in a digital elevation model (see previous section). When climate change scenarios are applied, the optimum climatic conditions for the plant communities will move, perhaps to higher elevations, and the various vegetation communities are assumed to eventually follow. Estimates of annual net primary productivity, carbon pools, and hydrologic output can then be made, but they are not dynamically linked to

FIGURE 5 Spatial distribution of the correlation between simulated Net Primary Productivity (NPP, kg C m^{-2} yr^{-1}) vs precipitation (PRCP, mm yr^{-1}), temperature (Temp, °C), and incident shortwave radiation (RAD, MJ m^{-2} d^{-1}) for 1980–1997, based on results of the BIOME–BGC model in the perimeter of the CLIMET (Climate Landscape Interactions – Mountain Ecosystem Transect) Programme. This area contains remarkable climatic and ecological diversity, ranging from temperate rainforests (left) to deserts (center) and includes 3 major mountain systems. The high mountains of Olympic Park MBR (circled) show a negative correlation (orange) between NPP and PRCP because PRCP is primarily snow that suppresses tree growth (shorter growing season) and moisture is generally not limiting. Conversely, a positive correlation (blue) exists for Temp and RAD because these are limiting in the cold, cloud-covered mountains. The spatially variable climatic controls on NPP illustrate how mountain ecosystems will respond to future climate change. (Figure redrawn from Kang et al 2004)



changes in vegetation structure. However, this approach can indicate trends in ecosystem functions and map the redistribution of these functions for simple climate change scenarios. An example of this approach is found in an animation of the Glacier National Park MBR response to climate change (accessible at http://www.nrmsc.usgs.gov/research/glacier_model.htm; cf. Hall and Fagre 2003).

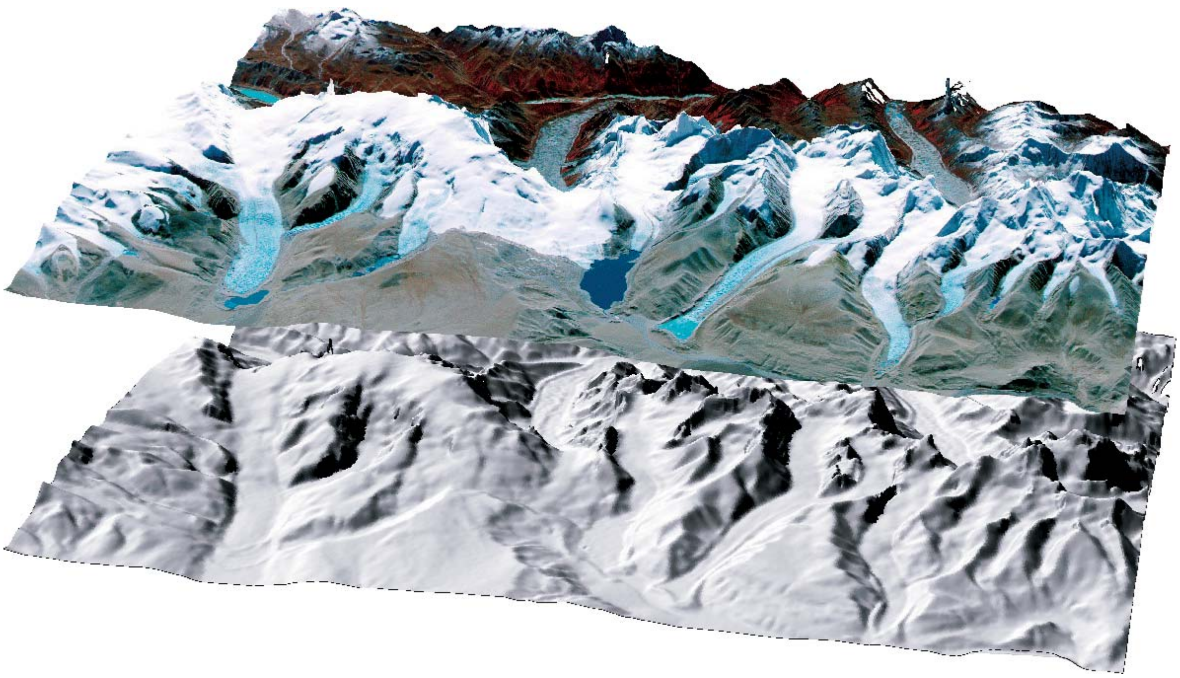
An *improved level* might utilize models such as the Regional Hydro-Ecological Simulation System (RHESSys; White et al 1998), which could be run on a desktop personal computer at each MBR. This model is dynamically linked and provides better estimates of ecosystem functions but is also more difficult to use and requires more input data. Initially, a small team of modelers could establish the capability at each MBR and help prepare the input datasets. Implementing the RHESSys PC model across the MBR network would provide a first, general assessment of ecosystem function at each MBR using a common tool that would highlight differences among MBRs. Apart from a common approach and shared tools, science questions relevant to all MBRs should be asked across the MBR network. In a next step, MBR managers should examine modeling results by applying similar future climate scenarios to test the resilience of ecosystem functions to climate change in the MBRs.

The *optimum level* of ecosystem modeling comprises forest demography, biogeochemistry, and disturbance processes such as wildfires (eg FIRE-BGC; Keane et al 1999), which would also make it necessary to expand the scope of the analysis to include interactions between the MBR and the surrounding landscapes. An example of the expanded scale is the BIOME–BGC model that has been used to more closely examine spatial variability in climate, vegetation production, water budgets, and carbon stocks across several MBRs in the northwestern United States (Fagre et al 2005). Maps showing cell-by-cell evapotranspiration vs precipitation, temperature, and incident shortwave radiation dramatize how differently climate controls ecosystem function of the 3 MBRs that were examined by Fagre et al (2005) when compared to the northwestern US as a whole (Figure 5). Under a future climate scenario, most of the region becomes drier and the MBRs may be even more critical than today in providing ecosystem services to people as the regional "water towers." Results such as these (Figure 5) become useful for regional policy formulation and provide MBR managers with better appreciation of the importance of ecosystem functions to society.

The role of remote sensing

Remote sensing provides a powerful set of tools for observing environmental changes in MBRs. Given the difficult access to most mountain regions, remote sensing is often the only way to investigate large areas. Thereby, remote sensing provides data

FIGURE 6 Oblique view from the north towards the Himalaya main ridge in Bhutan. The terrain section shown is approximately 40 km wide. The synthetic perspective was computed by the authors using the digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM; lower figure); a satellite image from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) was draped over this DEM (upper figure). Similar base data are potentially available for most MBRs.



required for modeling climate change impacts (terrain elevation, land cover data) and data to calibrate or validate such models (land cover/land use change) (Lillesand and Kieffer 2000; Bishop and Shroder 2004).

The extent to which remote sensing systems can provide such data, the costs, and the required expertise and types of analyses depend largely on:

- The type of platform: spaceborne (high acquisition frequency, large areas covered, medium resolution, low costs), airborne (low acquisition frequency, medium-size areas covered, high resolution, high costs for new acquisitions), and terrestrial (high acquisition frequency possible, small areas covered, wide range of costs);
- The section of the electromagnetic spectrum exploited: visible and near infrared, short-wave infrared (both very useful for land cover mapping and monitoring), thermal infrared (helpful for energy balance studies), microwaves (all-weather and day-and-night capabilities);
- The spatial resolution of remote sensing data: resolutions useful for MBRs range from low resolution (100–1000 m per image pixel; eg for large-scale vegetation and snow cover mapping), to medium resolution (5–100 m per pixel; eg for large-scale base mapping, vegetation mapping, monitoring of glacier and vegetation changes), and high resolution (<5 m per pixel; eg for mapping detailed land cover and land use studies).

Three types of data that can be derived from remote sensing are of major interest for MBRs: 1) data on terrain elevation; 2) data on land cover, land use, and their changes over time; and 3) data on mass movements. The following paragraphs provide more detail about remote sensing of these data types.

(1) Digital elevation models (DEMs) form the base data for virtually any mountain geoinformation system and spatial model. If not readily available (digitized from topographic maps), satellite-derived DEMs can be computed from optical satellite stereo and interferometric synthetic aperture radar (InSAR; Toutin and Gray 2000; Kääb 2005). A unique DEM that is available at no costs for the continents between 60° N and 54° S was computed from the Shuttle Radar Topography Mission (SRTM). The SRTM DEM has a spatial resolution of about 90 m and a vertical accuracy in the order of meters to a few tens of meters (Figure 6). Another group of DEMs with finer spatial resolution and better vertical accuracy (meters to decimeters) is derived from aero-photogrammetry (based on analogue or digital imagery), airborne InSAR, and airborne laser scanning (LIDAR). InSAR and laser scanning provide not only terrain elevation, but can also be used to derive vertical forest structure, which is important for forest and fire management (Lefsky et al 1999).

(2) One of the best-established applications of remote sensing is mapping and characterizing of the surface cover. Multi-spectral remote sensing offers the opportunity for automatic classification of surface cover utilizing the variation in reflectivity with wavelength,

which differs for most surface types. Besides purely spectral classification methods, spectral–spatial methods are particularly promising, involving also DEMs or spatial relations. Multispectral analysis techniques are particularly powerful and of special interest for MBRs if applied to repeat imagery (change detection) (Lillesand and Kieffer 2000; Kääb 2004). Utilizing hundreds of different, very narrow spectral bands (hyperspectral remote sensing) instead of some broad bands in multi-spectral imaging allows for a much more detailed, but also more complicated surface characterization (vegetation, lithology, etc).

Thus, remote sensing is an invaluable tool in ecosystem research, for instance for mapping vegetation (Frank 1988) or as additional predictors in species distribution models (Guisan et al 1998). Recent progress in both data acquisition and analysis has made remote sensing data at higher temporal, spatial, and spectral resolution increasingly available and applicable to ecosystem research (Schwarz and Zimmermann 2005).

(3) Mass movements are particularly effective in mountains and thus form important drivers of mountain landscape evolution and related processes. Vertical changes, such as glacier thickness changes or different types of accumulation/erosion, can often be derived as differences between repeat high-accuracy DEMs. Slow horizontal terrain movements can be measured from the matching of repeat optical imagery (Kääb 2004). The surface movement of dry and open terrain can be determined with millimeter accuracy through spaceborne differential InSAR (Strozzi et al 2004).

In view of the manifold possible applications of remote sensing, the selection of specific tools depends largely on the specific questions being asked, the human, technical, and financial resources, and the knowledge level available in a specific MBR. To establish a standardized and thus compatible set of data, the focus should be on a minimum but global set of data, methods, and expertise with respect to remote sensing application in/to MBRs. Such a research strategy facilitates inter-MBR knowledge sharing and support, and it can help to make remote sensing a sustainable part of MBR mapping, monitoring, and modeling efforts. Thus the first steps in a GLOCHAMORE research strategy are 1) a representative set of pilot studies, 2) a survey of needs and particularly the GIS and remote sensing resources existing in the MBRs, 3) selection of sophistication levels, and 4) selection of related sets of data and methods.

Summary and conclusions

From the present review, the following conclusions emerge:

First, a methodology is available to guide the development of land use and land cover (LULC) change scenarios for MBRs and associated monitoring. LULC scenarios are closely related to tourism and associated infrastructure, urban development and migration, forest use, pastoralism, and hazards affecting the livelihoods of many mountain people. Therefore, the same attention needs to be paid to socioeconomic factors such as the supply and demand of certain goods and services as to biophysical changes that are triggered by climate change.

Second, a wide range of methods exists to derive scenarios in the biophysical environment such as climatic change. Given the amount of expertise and resources at hand, the appropriate level of sophistication can be chosen to determine scenarios essential for driving impact assessments, in concert with other driving forces such as land use change, atmospheric CO_2 concentration, and others.

Third, a variety of simple to complex models can provide basic to detailed information about the physical characteristics, the spatial distribution and the changes in presence of snow and surface/subsurface ice in complex topography. Model calculations at the essential level should be applied in all MBRs to enable large-scale comparison of present-day conditions and climate-related impacts. A primary challenge consists in combining models for investigating interactions, feedbacks and the increasing system deviations that are affecting snow, glaciers, permafrost, and related phenomena in cold mountain areas.

Fourth, progress in predictive modeling of species and community distribution and dynamics, together with increasing GIS data availability, make these techniques increasingly applicable by non-specialists, ranging from questions of single species to community and ecosystem management. Initiating comparative modeling exercises within and across the MBRs would provide valuable tools for future management as well as for advancing science itself. A comparative study of species distribution modeling across many MBRs is proposed and should take place in the coming years.

Fifth, MBRs will play an increasingly important role in providing water to surrounding landscapes as demand for water grows, and in storing and sequestering carbon. Ecosystem modeling will be critical to achieve a better understanding of how climate change will alter MBR ecosystems and the functions of these (as well as other) ecosystems.

The integrated research strategy for mountain regions proposed here can be achieved only by establishing research partnerships among MBRs, scientists, and MBRs and research agencies. While the participating agencies share the cost of generating and analyzing the data, the benefits received from such a research network will be much greater than the inputs.

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AUTHORS

Harald Bugmann
Forest Ecology, Department of Environmental Sciences, Swiss Federal Institute of Technology (ETHZ), 8092 Zurich, Switzerland.
harald.bugmann@ethz.ch

Astrid Björnsen Gurung
Mountain Research Initiative, Coordination Office, Swiss Academy of Natural Sciences, Schwarztorstrasse 9, 3007 Berne, Switzerland.
bjoernsen@env.ethz.ch

Frank Ewert
Department of Plant Sciences, Group Plant Production Systems, Wageningen University, PO Box 430, 6700 AK Wageningen, The Netherlands.
frank.ewert@wur.nl

Wilfried Haeberli
Geography Department, University of Zurich, 8057 Zurich, Switzerland.
haeberli@geo.unizh.ch

Antoine Guisan
Department of Ecology and Evolution, University of Lausanne, 1015 Lausanne, Switzerland.
antoine.guisan@unil.ch

Dan Fagre
USGS Science Center, Glacier National Park, West Glacier, MT 59936, USA.
dan_fagre@usgs.gov

Andreas Kääb
Department of Geosciences, University of Oslo, 0316 Oslo, Norway.
kaeaeb@geo.uio.no

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