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The Carpathian Mountains in Europe are a biodiversity hot spot; harbor many relatively undisturbed ecosystems; and are still rich in seminatural, traditional landscapes. Since the fall of the Iron Curtain, the Carpathians have experienced widespread land use change, affecting biodiversity and ecosystem services. Climate change, as an additional driver, may increase the effect of such changes in the future. Based on a workshop organized by the Science for the Carpathians network, this paper reviews the current status of global change research in the Carpathians, identifies knowledge gaps, and suggests avenues for future research.

Introduction

The Carpathians are Europe's largest mountain range, spanning Austria, Slovakia, the Czech Republic, Hungary, Poland, Ukraine, Romania, and Serbia (Ruffini et al 2006). They hold tributaries of four main European watersheds and, although not glaciated, include distinctly alpine regions (eg Tatra Mountains, Fagaras). The region is important for biodiversity, hosting the largest unmanaged old-growth ("virgin") forests of Western and Central Europe, many endemic species, and Europe's largest wolf and brown bear populations (Csagoly 2007). Diverse cultural landscapes offer important ecosystem services to both local and national economies, including agriculture, timber production, and tourism.

The fall of the Iron Curtain in 1989 profoundly changed Carpathian societies and economies (Turnock 2002). The complexity of recent history; the coexistence of rapidly developing and marginal areas; emerging conflicts between nature conservation and tourism, industry, and transportation; and drastic changes in governance systems challenge the region's sustainable development, especially in view of increasing vulnerability due to climate change (Hostert et al 2008).

In response to these challenges, the Carpathian countries issued the Framework Convention on the Protection and Sustainable Development of the Carpathians (Carpathian Convention) in Kiev, Ukraine, on 22 May 2003, to promote the region's sustainable development. Research needs to provide the scientific foundation for stakeholders and policy-makers to facilitate this development. The Interim Secretariat for the Carpathian Convention therefore encouraged scientists from within and outside the Carpathians at the Forum Alpinum 2007 to lead research efforts, which brought forth the regional science network Science for the Carpathians (S4C) at a follow-up meeting at the European Academy (EURAC) in Bolzano, Italy. S4C was officially launched during a workshop at the Institute of Geography and Spatial Management (IG&SM), Jagiellonian University, Kraków, Poland, in May 2008.

This paper summarizes the outcomes of this workshop by reviewing the current status of global change research in the Carpathians in the fields of (1) climate, (2) water, (3) land use and land cover change (LUCC) and forestry, (4) biodiversity and conservation, (5) tourism, and (6) ecosystem services. By identifying main research gaps, it also provides a basis for developing a Carpathian research strategy similar to the Research Strategy for Global Change in Mountain Regions (Björnsen Gurung 2005).

Current status of global change research

Climate

The majority of the mainly national climatological projects have focused on single countries and areas not representative of the Carpathians as a whole. Bilateral projects implemented between Poland and

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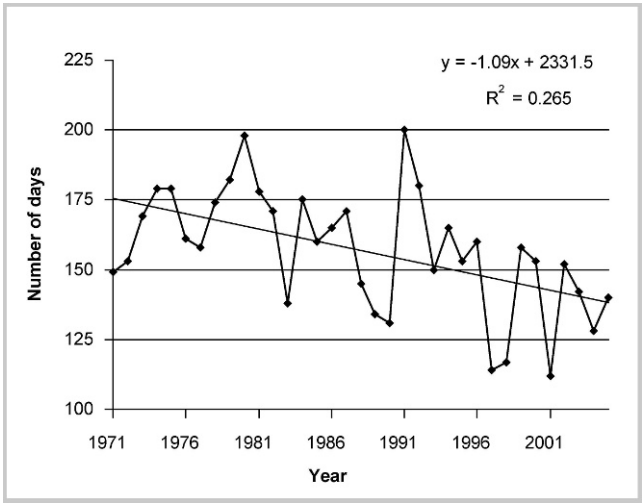
the former Czechoslovakia resulted in a climatic monograph on the Tatra Mountains (Koncek 1974; Niedźwiedź 1992). In 1981–1982, the Polish–Czechoslovakian research program TATREX investigated the influence of mountains on the atmosphere. After 1994, the national meteorological services of both countries continued these studies within the project Climate Changes and Variability in the Western Carpathians. International cooperation during that time was often limited to cyclic conferences on Carpathian meteorology organized in parallel with the International Conferences on Alpine Meteorology (Obrebska-Starkel 1983).

At the European scale, regions of the Carpathians have been included in projects dealing with mountain climates. Various studies showed warming in the annual temperature variability from 1962 to 2000 (eg 0.3–0.5°C in the Bucegi Mountains, 0.5–0.7°C in the Semenic Mountains, and 0.8–0.9°C in the southern Carpathians and Apuseni Mountains; Csagoly 2007). However, a pan-Carpathian research program is lacking. Climatological maps for the whole Carpathians are not available, as no complete, international climatological database with long-term monitoring results exists. The Carpathians Environment Outlook characterizes the Carpathian climate on the basis of few nonrepresentative case studies (Csagoly 2007).

Given the geographical extent and climate variability, there is a great need to (1) establish a joint, international climatological database of long-term data; (2) set up additional meteorological stations at higher altitudes; and (3) make data freely available for scientists (in post-Socialist countries meteorological data are still not publicly available). In parallel, existing case studies should be coordinated at the international level to establish common research protocols. This approach would provide a more comprehensive understanding of Carpathian climate, which is necessary for developing and verifying regional climate models.

FIGURE 1 Trend in ice cover duration in the Morskie Oko Lake, High Tatra Mountains, 1971–2005. (Graph by A. Choiński and J. Pociask-Karteczka)



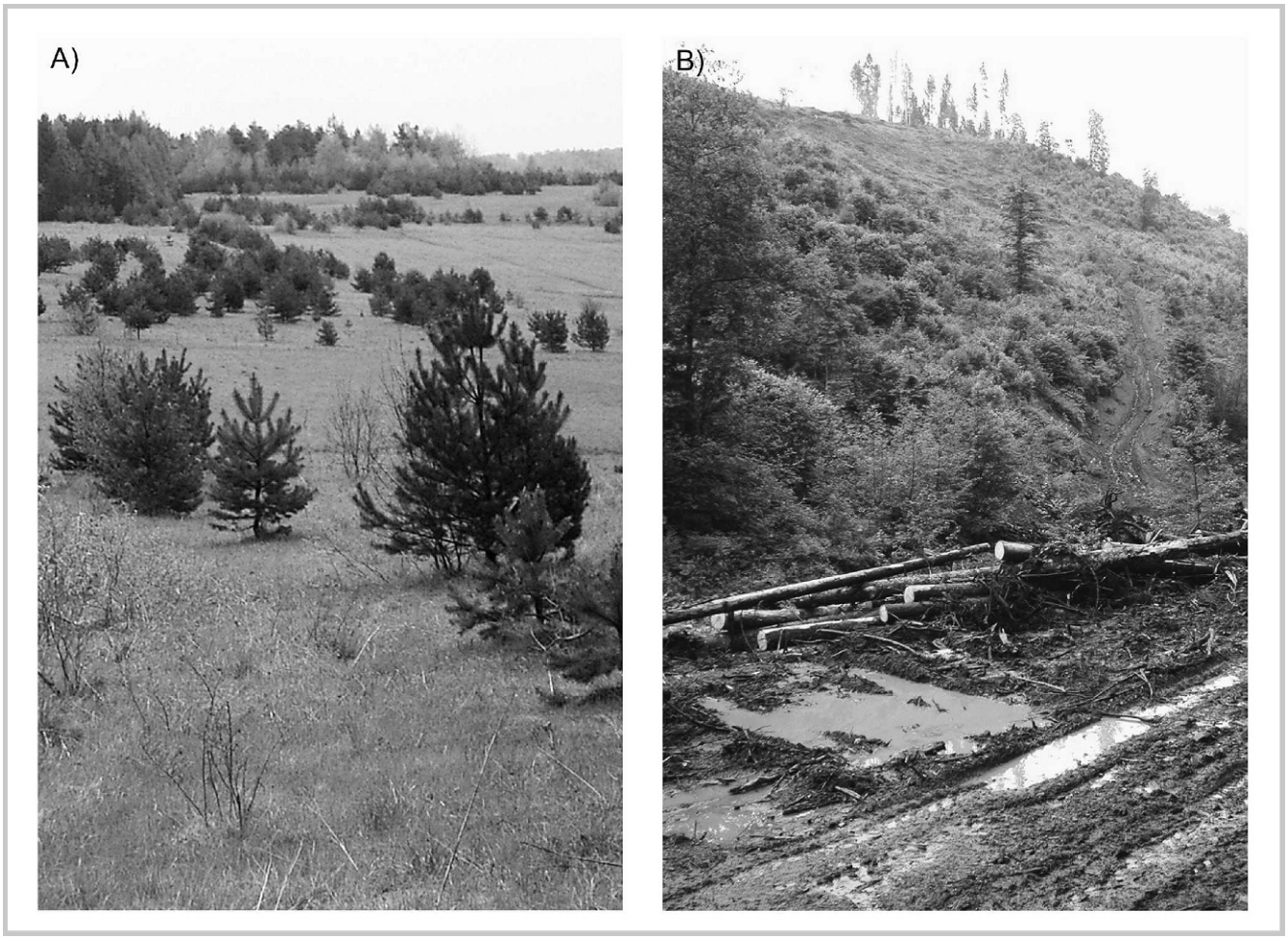
Water systems

The frequency of extreme hydrological events in the Carpathians has been increasing over the last decades and is likely connected to recent climate changes. Floods often jeopardize people's safety and cause economic loss (eg in agriculture or infrastructure). Compared to floods, environmental and economic consequences of droughts are more substantial, but also difficult to mitigate (Tallaksen and van Lanen 2004). Snowmelt during spring and summer is an important component of the hydrological cycle, but snow depth has decreased in the eastern and southwestern Carpathians (related to the tendency toward the positive phase of the North Atlantic Oscillation, resulting in warmer winters; Bojariu and Dinu 2007). Snow-cover analysis in the southeastern part of the Carpathians from 1962 to 2001 does not reveal significant trends in snow-water equivalents. However, differences between snow-rich and snow-poor winters were more extreme in the period 1982–2001 than in 1962–1981. Furthermore, duration of ice cover and ice thickness have recently been reported as decreasing in the High Tatra mountain lakes (Figure 1).

Average annual precipitation increased slightly in the Romanian and Czech Carpathians from 1991 to 2005, while winter precipitation decreased in the mountains after 1970 (Busuioc and von Storch 1996). Despite positive precipitation trends, maximum runoff in the Carpathian basins in Poland remained relatively stable (Pociask-Karteczka and Nieckarz 2006), although greater variability in extreme precipitation events was observed in the period 1995–2006 than previously (Niedźwiedź et al 2006).

To better understand hydrological systems in the Carpathians, research should first focus on precipitation and runoff (amount, variability, intensity, frequency, temporal and spatial distribution), taking into account data from the entire Carpathian range. Furthermore, research needs to develop adaptation and mitigation strategies for potential changes in water resources. Such strategies will be required at regional and national levels.

FIGURE 2 (A) Large-scale clear-cutting in Rakchiv district, Ukraine; (B) forest expansion on former farmland in the Polish Bieszczady Mountains. (Photos by P. Ibisch and T. Kuemmerle, respectively)



Land use and land cover change and forestry

LUCC is widespread in the Carpathians, mainly due to transformations of land use systems after 1990 (eg land reforms, policy changes, socioeconomic transformation, accession to the European Union [EU], international agreements) and land use legacies from Austro-Hungarian and Socialist times. Main processes include farmland abandonment (and forest expansion; Figure 2A) and agricultural parcelization (Turnock 2002; Kuemmerle et al 2008). In some parts, forest cover has been reduced due to logging (Figure 2B), infrastructure development, or urban sprawl (Turnock 2002; Kozak et al 2007b; Kuemmerle et al 2007).

LUCC research in the Carpathians has so far mainly focused on local and regional scales. Contemporary statistical data from standard surveys are available for all Carpathians within the EU, but consistent data for Ukraine and Serbia and pre-1990 data are largely lacking. More importantly, pan-Carpathian studies are missing. Short-term LUCC research (<10 years) mostly focused on land cover conversions, especially concerning forest disturbance. Extreme events such as windstorms and pests appear especially widespread in spruce monocultures established during the last 100 to 200 years. Pollution has resulted in a deterioration of forest health (Badea et al 2004), sometimes resulting in forest dieback (Grodzki 2007). Excessive forest exploitation occurred under Socialism and continued in some places after 1989, and illegal logging increased in the Ukrainian Carpathians (Kuemmerle et al 2007). At medium term time scales (10–50 years), remote sensing helped to map farmland abandonment and forest expansion (Kozak et al 2007b; Kuemmerle et al 2008). Long-term studies of LUCC suggest a slow forest transition in the

FIGURE 3 The endemic Carpathian blue slug, *Bielzia coerulans*. (Photo by P. Ibisch)

Carpathians (Kozak et al 2007a); for such studies, access to historic Austro-Hungarian maps is crucial.

It is essential to improve communication and collaboration between scientists studying the spatial patterns and rates of LUCC and those searching for its underlying drivers. Therefore, the most urgent challenges in LUCC research in the Carpathian Mountains are (1) the integration of disciplines, themes, and scientific communities and (2) an increase in the reliability of LUCC models and their value for stakeholders, especially at the pan-Carpathian scale.

Biodiversity and conservation

The Carpathians' exceptional biodiversity results from high geodiversity, marked environmental gradients, and historical climate variations. While Carpathian ecosystem diversity is relatively well understood (Perzanowski and Jerzy 2001), species inventories are incomplete. Still, new species—mainly invertebrates and microorganisms—are being added to the endemic taxa list (Figure 3). Biodiversity research refers mainly to faunistics, floristics, or phytosociology (eg Liana 2007; Minář et al 2007). Applied biodiversity conservation research has so far mostly been promoted by nongovernmental organizations. Most importantly, the WWF Danube Carpathian Programme helped establish the Natura 2000 protected area network, and the Carpathian EcoRegion Initiative compiled the first comprehensive assessment of the region's biodiversity, endangered species, and their conservation (CERI 2001; Witkowski et al 2003).

So far research has paid little attention to global change processes, including climate change. This is unfortunate because the latter is particularly threatening for montane habitats and their biodiversity (Csagoly 2007). For example, alpine species, often occurring in small, isolated populations, are highly vulnerable to climate change (eg Thuiller et al 2005), while invasives often benefit from changing conditions. Concerning plant diversity, some efforts to assess climate threat, such as the EUROMONT initiative and the Global Observation Research Initiative in Alpine Environments (GLORIA), are underway. A future activity could also be the extension of the Global Mountain Biodiversity Assessment network (GMBA) to the Carpathians. Last, future research activities should address the adaptation of conservation strategies to anticipated global and regional changes related to biodiversity threats in the Carpathians, specifically including emerging topics such as increasing biofuel demand.

FIGURE 4 The village of Volosyanka in Ukraine, 2007: ecosystem services in the Carpathians are a basis for traditional cultural landscapes. (Photo by M. Elbakidze)

Tourism

During Socialist times, tourism was politically promoted throughout the region, particularly focusing on health, social, and mass tourism. Yet tourism was poorly diversified, and related research was conducted at the national level. After 1990, ecotourism, winter sports, and rural tourism emerged in the Carpathians (Kurek 1996). Mountain communities often considered tourism as the first option for development, provided that environmental impacts are minimized and tourism enterprises are accessible to local investors and communities. Today, numerous businesses are registered in mountain resorts, and tourism's contribution to EU gross domestic product is expected to rise to 10.2% in 2008 (compared to 9.9% globally, 12.6% in Slovakia, or 5.8% in Romania; WTTC 2008).

Tourism research should contribute to the development of national and international tourism strategies (Mika and Pawlusiański 2003). After 1989, most Carpathian countries had common research interests in the field of ecotourism, tourism potentials, and the relationship between tourism and the environment, and important cross-border research projects have emerged (Ptaszycka-Jackowska and Baranowska 2003). Central research issues related to tourism in the Carpathians include defining how sustainable tourism can be achieved and how negative environmental and sociocultural impacts of tourist infrastructure can be avoided. As a precondition, social processes in transboundary areas have to be analyzed and adequate steering measures identified. Future research also needs to focus on the protection of natural and cultural values, the integration of tourism in mountain economies, and joint research protocols.

Ecosystem services

Ecosystem services are the benefits humans receive, directly or indirectly, from ecosystems (Millennium Ecosystem Assessment 2005). The post-Socialist Carpathian countries need to adapt their "societal system of values" to new political and socioeconomic conditions. This societal system includes the value attributed to ecosystem services as defined for each nation. Assessments of ecosystem services require estimates of changes in ecosystem processes and structures and in the resulting flows of services. Studying the relationship between ecosystem services and human wellbeing has recently received increased attention in the Carpathians; however, until now there have been no examples of ecosystem service research in the region.

Concerning ecosystem services, research needs include (1) disciplinary research on water quantity and quality, hazard and erosion regulations, biodiversity conservation and creation of functional networks of protected

areas, and local inventories of natural resources and (2) interdisciplinary research on the role of traditional village systems in sustainable forest landscapes (Figure 4), resilience of natural ecosystems to natural hazards, gaps in sustainable forest management implementation, and trends and drivers of land use changes. An ecosystem assessment specifically targeted at the Carpathian ecoregion has not been carried out. The Millennium Ecosystem Assessment (2005), the largest study ever conducted on the linkages between ecosystems and human wellbeing, highlights the importance of incorporating an understanding of ecosystem dynamics into governance systems when managing ecosystem services. Research on governance of natural resources is thus an important basis on which to evaluate ecosystem services, but only a few projects focusing on local stakeholder involvement in natural resources management and forest governance have been conducted. Due to the ongoing radical changes in the political, social, and ecological environments in all Carpathian countries, there is an urgent need to develop an ecosystem services approach for the entire ecoregion, by both scientific communities and governmental organizations.

Outlook

The Carpathian region today faces manifold challenges arising from socioeconomic transformation; institutional change; shifting policy frameworks; demographic change; dynamics in land use systems; and, increasingly, climate change and globalization. Meeting these challenges and identifying possible future pathways to sustainability require better knowledge about how socioecological systems react to these transformations, how they affect ecosystems services and biodiversity, and how they link to human wellbeing. Carpathian research has so far been mostly disciplinary and has studied socioecological systems at a single scale. What is urgently needed is interdisciplinary and transdisciplinary research that:

1. Studies complex and nested human–environment systems as such, not merely their constituents;
2. Assesses the entire Carpathian ecoregion by synthesizing from a multitude of local case studies;
3. Links knowledge about ecological and economic systems across multiple scales;
4. Addresses multiple ecosystem services, human wellbeing, and biodiversity conservation simultaneously;
5. Produces scenarios for different future climate, land use, and socioeconomic trajectories; and
6. Bridges the gap between researchers, policy-makers, and stakeholders.

Only if global change research in the Carpathians starts addressing these issues will policy-makers and stakeholders be able to evaluate the trade-offs and synergies connected to future pathways. Much is at stake, because the Carpathians harbor exceptional natural and social treasures. The formation of the network initiatives such as S4C is a first step in the direction outlined by this agenda, and we hope it will grow further and facilitate productive cooperation.

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