# DISSERTATION

Titel der Dissertation

“Combining participatory and geospatial modelling to generate spatially explicit land change scenarios applied to European mountain areas: Italian Alps and Romanian Carpathians”


Verfasser

Žiga Malek


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*The optimal model is one that contains sufficient complexity to explain phenomena, but no more.*

John Wainwright and Mark Mulligan
Environmental Modelling: Finding Simplicity in Complexity

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# Declaration

This is a cumulative dissertation, divided into a framework and publications part. The framework part presents how different publications are following common research objectives on development of future land change scenarios. It presents the objectives, theory, methodology and the description of both study areas. This part focuses on the background of the research and study areas, with the methods, results and discussion mostly being summarized. A more detailed description of the methodology, results and discussion is provided in the publications part, where different publications and manuscripts are attached as appendices to the dissertation.

The research presented in this dissertation is my own original work. I was the lead author on all publications, where it was carried out in collaboration with co-authors. The role and work performed by each co-author is summarized in the Appendix section.

All figures (maps, schemes, photographs) in this dissertation were produced by the author of the thesis, unless stated otherwise. I endeavoured to ascertain the copyright holders of all illustrations cited and secure their consent to the utilisation of their illustrations in the present paper. If, in spite of my efforts, a copyright infringement should have occurred, I kindly request the relevant parties to contact me.

# 1 Rationale

## 1.1 Land changes

Land use and land cover have always been subject to change in response to evolving human needs. They were driven either by gradual trends or abrupt changes in the economy, society, technology, governance structures, and environmental conditions (Lambin and Geist, 2006; Turner et al. 2007). Changes in land use and land cover - land changes (Box 1.1) - have often been seen as improvements and are not a new process. Many of the world's most productive areas have long histories of continuous settlement, agricultural activities and forest exploitation (Meyer and Turner, 1994). Over the past 50 years however, humans have converted and modified natural ecosystems more rapidly and over larger areas than in any comparable period of human history (Metzger et al. 2006; Steffen et al. 2005). These changes have been a consequence of outstanding economic growth and technological advancement, caused by the rapidly growing demands for food, freshwater, timber, fuel, and energy which has led to our planet being almost completely human-dominated (Vitousek et al. 1997). Human activities grew into a driving force of environmental change, outcompeting natural processes, and leading to the term "the Anthropocene" being used to describe the current, human dominated geological epoch. This term suggests, that human activities have become so pervasive that they rival the great forces of nature and are transforming the Earth into a less biologically diverse, less forested, and probably less habitable planet (Steffen et al. 2007).

**Box 1.1: Land change – Land use change – Land cover change (Turner et al. 2007)**

Land change is a general term for land use and land cover change - human modification of the terrestrial surface. Land changes address the complex dynamics of land use and land cover as a coupled human-environment system. In order to improve the understanding and management of the terrestrial surface as a resource, land changes are being investigated by developing new concepts and methods in the field of observation, modelling, and understanding the impacts and consequences of these changes.

Intensive land changes have contributed to substantial net gains in human well-being and economic development. On the other side, they lead to a substantial and largely irreversible loss of biodiversity and degradation in ecosystems and their services (Fischlin et al. 2007; Millenium Ecosystem Assessment, 2005). This can have strong feedback effects on several human activities, e.g. agriculture, forestry, fishery and also on our health and well-being and traditional assets such as cultural landscape (Metzger et al. 2006). What is more, it seems that the current development trajectories are not delivering human benefits in the way they should. There is numerous evidence that conversions and degradation of the environment are eroding overall human well-being for short term private gain (Balmford et al. 2002).

The future capability of ecosystems to provide us with services is therefore under threat by land changes caused by socio-economic development (Metzger et al. 2006). Land changes are considered to have the largest effect on terrestrial ecosystems in this century, followed by climate change (EASAC, 2009; Sala et al. 2000). This convincing link between land changes and human well-being has resulted in an increased attention of policy makers and planners in driving forces and consequences of these changes (Schneeberger et al. 2007). Therefore, studying how the human-environment interactions might result to future land changes is essential (Rounsevell et al. 2006).

## 1.2 Land changes in mountain areas

Researchers promote to increase efforts to monitor, analyse and project land changes in areas experiencing or expecting high rates of socio-economic changes, as well as areas where land changes can have most significant environmental consequences (Lambin and Geist, 2006). European mountain are among areas that have been experiencing significant land changes, as a consequence of drastic socio-economic transformation since the beginning of the 20th century. Consequently, the land use and land cover have changed intensely on spatial and temporal terms unknown before, presenting a break to the gradualism of long term landscape evolution (Olsson et al. 2000). Thus, we could observe a significant decline in agricultural activities, improved accessibility due to new infrastructure, and the emergence of recreational areas (Körner et al. 2005; MacDonald et al. 2000; Tasser et al. 2007). Moreover, mountain areas have proved to be particularly vulnerable to future socio-economic development and consequent land change on a European scale (Schröter et al. 2005). Therefore, this research focuses on two case study areas undergoing a socio-economic transition in two major European mountain areas: the Alps and the Carpathians. More precisely, it focuses on two local to regional scale study areas: The Mountain community of Gemona, Canal del Ferro and Val Canale in the Italian Alps, and the Carpathians of Buzau County in Romania. The study areas are described in more detail later as well as in the appendices (Appendices A, B, C).

Mountains and their ecosystems provide many key resources and services to European societies: freshwater and energy supply, maintenance of biological diversity, carbon storage, forest and agricultural products, protection from natural hazards, and tourism and recreation related services such as an aesthetic landscape (Körner et al. 2005; Schröter et al. 2005). Mountain land use and land cover changes can therefore result in negative impacts on human well-being on a larger scale (Körner et al. 2005; Tasser et al. 2003).

Complex topography and altitudinal gradients are among the reasons why mountain ecosystems are particularly sensitive to environmental change in comparison with lowlands (Koellner, 2009). Land changes in mountains can result in consequences for vegetation composition, water balance, soil structure and productivity, and changes in microclimate (Tasser et al. 2005). They can also have numerous other consequences, such as changes to biodiversity levels and the landscape image. The abandoning of meadows and pastures in the uphills, and elimination of hedges and banks with natural vegetation in the lowland plains have led to loss and fragmentation of habitats and lowering of biodiversity levels (Chemini and Rizzoli, 2003; Giupponi et al. 2006). Moreover, land changes as the result of agricultural abandonment have led to overgrowth and spread of subalpine woodlands, and a raised treeline. The former mountain landscape patterns, resulting from the diverse land use, have so been transformed into a more homogenous landscape (Olsson et al. 2000).

Changes to the land use and land cover are thus among most significant factors of changes to hydro-meteorological risks, such as floods and landslides. They can affect the spatial-temporal characteristics, magnitude and occurrence of natural hazards, as well as the spatial distribution of elements at risk (Figure 1.1). Land changes affect erosion levels that can lead to increased environmental risks in both mountains and adjacent lowlands and can have strong impacts on the human well-being in affected areas (Körner et al. 2005). Changes to the land use and land cover such as deforestation (Figure 1.1a) or an increase of impervious urban areas can therefore impact predisposing factors of the occurrence of natural hazards (Glade, 2003; Glade and Crozier, 2005).

For example, landslides in topsoils are caused by a set of factors, which determine the probability of such landslides. Besides bedrock, relief and climate, the geomorphological changes in connection with land changes, vegetation and soil changes may influence landslides in alpine regions (Tasser et al. 2003). Also, runoff has often become more rapid due to land change, including deforestation, and replacement of diverse natural and semi-natural ecosystems by intensively managed lands and urban areas (Glade, 2003; Tasser et al. 2003). Additionaly, urban expansion can result in new built up areas on hazard prone areas, therefore increasing the number of elements at risk and exposure (Figure 1.1b). Many of those impacts are likely to be amplified by climate change, which will result in different patterns of water movement both spatially and temporally, including a greater frequency of extreme events and long-term trends in precipitation and evaporation (EASAC, 2009).

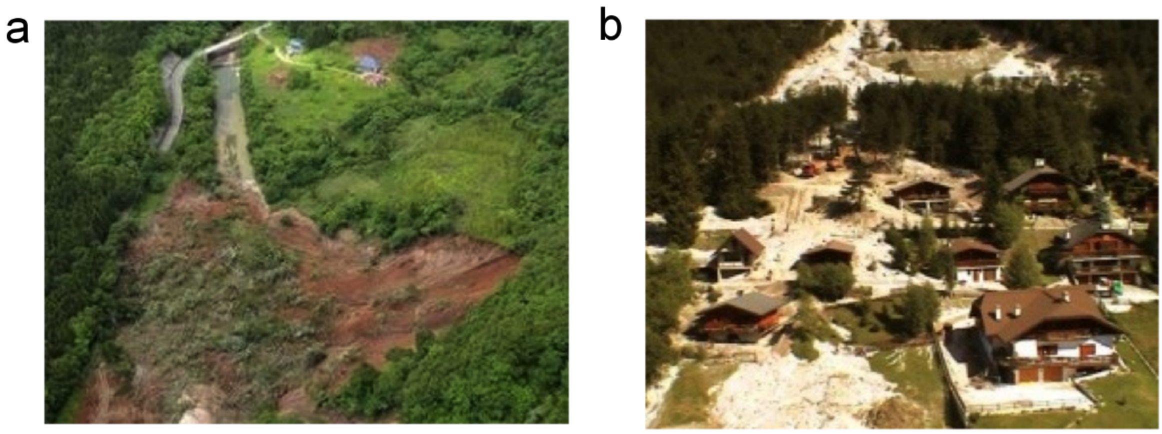


Figure 1.1 Land use and land cover changes affecting hydro-meteorological risk. a) deforestation influencing the occurrence of landslide hazard in the Romanian Carpathians (Ziare.com, 2011), b) urban expansion resulting in an increase of elements at risk in the Italian Alps (Protezione Civile, 2009).

# 2 Scenarios of land change

## 2.1 Scenarios as a tool to address uncertainty

Projecting future environmental changes remains a difficult task, as the driving forces shaping the future can be uncontrollable and characterized by a high level of uncertainty (Peterson et al. 2003). Uncertainties related particularly to simulating future land change scenarios are characterised among others by (Brown et al. 2013; Verburg et al. 1999):

- “unknown” knowledge about a system
- indescribable relationships between factors within the system
- deficiencies in spatial and statistical data
- difficulties to recognize and quantify driving forces
- the failure to effectively relate possible future changes to a spatial pattern

Scenarios offer exploring possible futures and the corresponding environmental consequences, and enable to analyse possible decision options (Kriegler, 2010). This way, they are a creative, visionary tool, providing support for planning a desired future, or preparing for possible undesirable events (Deshler, 1987; Wollenberg et al. 2000). Scenarios are not predictions or exact forecasts, but images of likely, plausible futures (Abildtrup et al. 2006). All this has led to an increased interest of decision makers and researchers to propose scenarios for studying future land changes (Rounsevell et al. 2006; Schneeberger et al. 2007).

Scenarios can either be generated only by researchers, or involving stakeholders. Researcher can generate scenarios by themselves by using quantitative data and models (Barredo and Engelen, 2010; Breuer et al. 2009; Santelmann et al. 2004), or management plans (Kooistra et al. 2008). However, in order to bridge the gap between research and decision making, stakeholders are being involved into scenario generation. Even though, this can be time consuming, it can improve the transparency and credibility of the research and result in more plausible scenarios (Kepner et al. 2012). Moreover, it can also have multiple benefits on decision making, among others improved communication among participants, higher diversity of options in decision-making and a higher likelihood that a certain decision will take into account possible environmental consequences (Jacobs et al. 2010; Kooistra et al. 2008; Metcalf et al. 2010).

Any scenario is based on a qualitative storyline, a narrative describing the future (O’Neill and Schweizer, 2011; Swart et al. 2004; Wright et al. 2013). Storylines can range from short visions of the future, to long and detailed description combined with quantitative models (Trutnevyte et al. 2014). Besides being a scenario generation step, they are vital for communicating the results of the scenarios, as they are based on assumptions and value judgements from the involved experts and other stakeholders (Trutnevyte, 2014). As opposed to quantitative models, storylines portray a broader picture and consider numerous other aspects that might have been ignored otherwise. Combined with quantitative models, storylines can thus influence the input assumptions, and put the models into a wider context (Hughes, 2013; Hughes and Strachan, 2010; Trutnevyte et al. 2014).

Being a well-acknowledged tool in environmental science, scenarios have been applied on a variety of issues on different spatial scales. These range from municipality scale (Briner et al. 2012; Schirpke et al. 2012; Walz et al. 2007), regional or national scale (Barredo and Engelen, 2010; Teixeira et al. 2009), subcontinental or continental scale (Reginster and Rounsevell, 2006; Rounsevell et al. 2006; Sleeter et al. 2012; Sohl et al. 2012), or global scale (Kriegler et al. 2012; Nakicenovic et al. 2000; Sala et al. 2000).

## 2.2 Participatory modelling

To address the issue of data unavailability and the tangibility of the driving forces, numerous studies have applied participatory modelling techniques to develop future scenarios (Castella et al. 2005; Walz et al. 2007; Wollenberg et al. 2000). Unlike “one way” scientist-stakeholder communication, the more interactive “two way” participatory approaches provide the opportunity for discussion, deliberation, negotiation and consensus building (Patel et al. 2007). There are several reasons in favour of participatory scenario development.

First, involving stakeholders in scenario development process leads to incorporating a broader spectrum of professional values and experience. Stakeholders can provide additional or missing data, more detailed information, uncover mistakes in the model, or lead to alternative clarifications (Beierle and Cayford, 2002). Moreover, through participation the involved stakeholders can consider the developed scenarios as more reliable and relevant (Von Korff et al. 2010). Finally, participatory modelling promotes learning for and from all involved stakeholders, and can thus be considered as a means for learning and communication (Mendoza and Prabhu, 2006). All these arguments lead to a higher level of acceptability of the developed scenarios among stakeholders (Stach et al. 2005).

In land systems science, participatory scenario development has been applied among others to study:

- management of community forests (Wollenberg et al. 2000),
- rural funding policies affecting mountain landscapes (Bayfield et al. 2008),
- deforestation in the Brazilian Amazon (Kok, 2009),

- livelihood consequences of forest management (Kassa et al. 2009),
- understanding future environmental changes (Odada et al. 2009),
- natural park management (Daconto and Sherpa, 2010),
- possible changes to freshwater resources (van Vliet et al. 2010),

Generally, participatory scenario development results in more plausible (likely) scenarios, as they are backed by the insights from the stakeholders (Castella et al. 2005). Nevertheless, these approaches rarely generate spatially explicit results.

## 2.3 Spatially explicit modelling

Identification of critical areas of land change, together with improving the understanding on the changes to the land use and land cover pattern, poses a need for spatially explicit modelling of land change scenarios (Verburg et al. 1999). Spatially explicit models can help to explain the patterns and locations of future land changes at a certain level of detail (Verburg et al. 2006).

The majority of spatially explicit models are based on geostatistical methods, such as regression analysis or other multivariate techniques to capture the significance of the driving forces of land change (Lesschen et al. 2005). When allocating future land changes, these models usually take into account both biophysical factors (terrain, hydrology, soil, geology, etc.) together with socio-economic spatial factors (distance to cities, accessibility, population and employment density, etc.) joined in a geographic information system (GIS) (Agarwal et al. 2002; Koomen and Stillwell, 2007). This way the land changes are distributed across the landscape simulating human decisions (van Vliet et al. 2013), for example from the perspective of a spatial planner, forester, farmer, etc. Moreover, spatially explicit models are able to simulate a more realistic spatial pattern of change, which may or may not be based on past observations (Engelen et al. 1995).

Spatially explicit land change scenarios have been applied for studying numerous environmental issues:

- soil erosion analysis as a consequence of land changes (Hessel et al. 2003),
- assessment of wildlife habitats due to increased human influence (Falcucci et al. 2008),
- analysing the changes to flood risk due to urban expansion (Barredo and Engelen, 2010),
- expansion of rural agricultural activities (Maeda et al. 2010),
- agricultural expansion and forest protection (Koh and Ghazoul, 2010),
- changes to mountain land use patterns (Schirpke et al. 2012),

- future forest harvesting (Kamusoko et al. 2013).

These models, usually consisting of spatial simulation techniques and GIS, however often lack the involvement of stakeholders (Castella et al. 2005). Scenarios analysed using these models are mostly extrapolations of observed past trends, changes to model parameters as defined by the researchers, or changes to growth/decrease rates of a particular land change process. This way, they fail to capture the relationship between different driving forces, the role of decision making and cannot explain land change beyond the accessible data (Parker et al. 2003; Verburg et al. 2006). Therefore, when using these approaches, the reflections of stakeholders' values in scenarios are not clear, posing questions on the likelihood and relevance of the scenarios.

## 2.4 Combining participatory scenario development with geospatial modelling

Projecting possible future scenarios demands in-depth understanding of driving forces of the observed (past) land changes. These can either be proximate or distant, tangible or intangible, supported by abundant numerical data, or difficult to quantify (Bürgi et al. 2004; Campbell et al. 2005; Schneeberger et al. 2007). This is one of the reasons why developing future land change scenarios in terms of amount of change and its location, remains a challenging task. Nevertheless, the integration of social and natural scientific disciplines can lead to a development of participatory geo-simulation models, that are able to address these issues and are already being used in decision making (EEA, 2007).

Different disciplines address land changes using different approaches: socio-economic researchers focus on individual agents of land change on a very detailed level, whereas researchers in natural sciences tend to work on a wider areas with an emphasis on spatially explicit results (Verburg et al. 2004). This divide can also be translated into:

- Studies behind the driving forces and amounts of future land changes: How many changes might occur in the future?
- Studies in possible future spatial distributions of these changes: Where might changes occur in the future?

However, in order to develop spatially explicit future land change scenarios, both approaches should be combined. Studying the driving forces of quantity of land use and land cover change contributes to the knowledge of possible future amount of land changes. Spatially explicit land change models on the other hand help to identify locations that are more susceptible to driving forces of change and resulting land changes with consequences on the environment and human activities (Verburg et al. 2004). Often, these two approaches are dealt with separately when modelling future land changes.

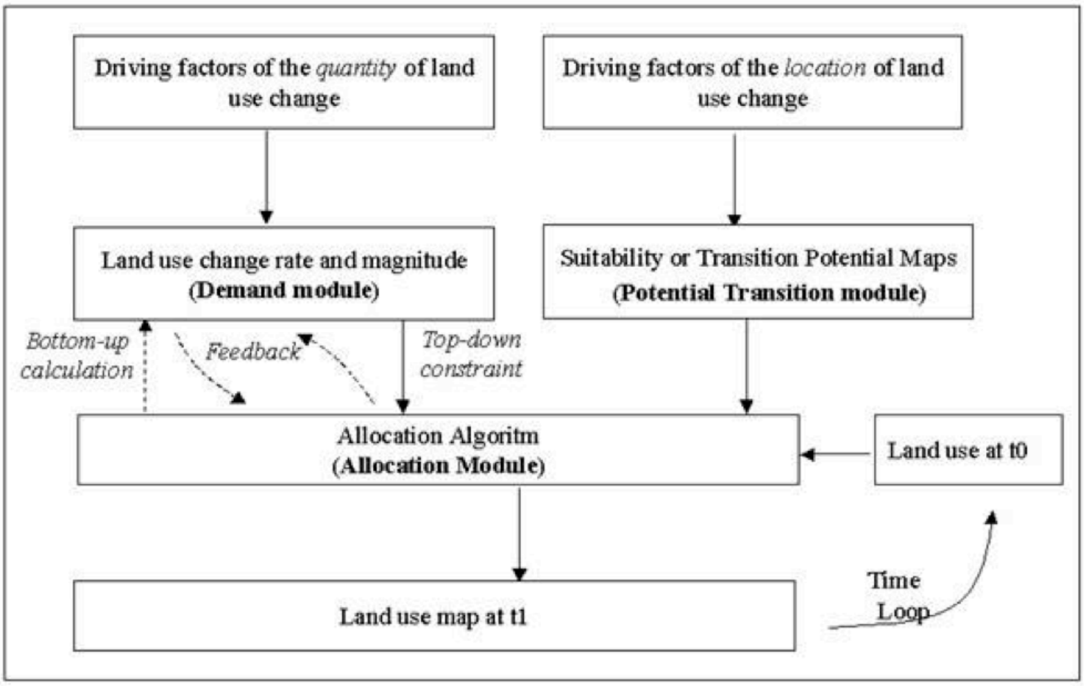


Figure 2.1 General framework for land use and land cover change modelling (Verburg et al. 2006)

In the case of spatially explicit models (Figure 2.1), the amounts of future land use changes (Driving factors of the quantity of land use change) can be provided by stakeholders. Often, this is only in the form of the stakeholders' vision on future land use change trends, with no or limited involvement of stakeholders in the development of the spatially explicit model (Barredo and Engelen, 2010; Giupponi et al. 2006; Promper et al. 2014; Schirpke et al. 2012). However, in order to improve the ability of the model to support decision making, efficient stakeholder communication, and encourage the discourse about different options for land use planning, a higher level of stakeholder participation is suggested (van Vliet et al. 2010; Voinov and Bousquet, 2010; Wainwright and Mulligan, 2013; Wollenberg et al. 2000). Therefore, this research will focus on the involvement of stakeholders both in the form of potential future visions of land change, as well as the development of the simulation model itself. This means that the knowledge of the local system of land change will need to be derived from the stakeholders, shaping the conceptual model of future land changes and their consequences.

# 3 Research objectives

This research aims to contribute towards increasing the knowledge on future land change processes in European mountain areas, their driving forces, and their consequences. More precisely, it aims at developing a methodology for combining participatory scenario development with geospatial techniques like geographic information systems and environmental simulation to generate future environmental conditions of mountain areas. The focus is on possible future land changes as a result of socio-economic development, taking into account the uncertainties and limitations related to local scales and mountain environments: inaccessibility of data, and relationships between external driving forces and local environmental consequences. Moreover, another aim is to identify additional uncertainties related to future land change modelling, such as accuracy of the data and model performance.

Capturing the complexity of relationships in the human-environment system, incorporating human decisions, feedbacks to land change demands, and spatial limitations is a necessity for more accurate and details land change modelling (Veldkamp and Lambin, 2001). Approaches integrating expert knowledge with geo-simulation, probability techniques or artificial intelligence are therefore becoming more significant in the field of spatially explicit land change models (Parker et al. 2003). Therefore, this research will focus on the integration of semi-quantitative methods to develop the future scenarios in terms of demand for land change, and traditional geo-simulation techniques to spatially allocate these changes simulating the observed patterns of change.

Even though, there are numerous studies on future land change scenarios on a local and regional scale in European mountain regions, it often remains unclear how these scenarios were developed. These studies range from a spatially explicit economic analysis (Gellrich et al. 2007), statistical models (Rutherford et al. 2008) to landscape dynamics evaluation (Schirpke et al. 2012), to generate spatially explicit land change scenarios. Most of the approaches have been calibrated and validated in particular case study area with a finite data set, thus their transferability to other case study areas remains unknown. Moreover, addressing the issue of inaccessible data, and more importantly external driving forces of land change remains difficult to quantify and relate to spatial patterns (Messerli et al. 2013). These are especially significant in case of prevailing external driving forces such as changes to policy occurring on national or global scale (Michetti, 2012).

The specific objectives of the dissertation are summarized below. The methodology for development of future scenarios of land change is described in more detail in the following sections and research papers serving as appendices of this thesis.

1. The research will study past land changes in two selected study areas, focusing on the spatial pattern of these changes, as well as their driving forces. A special emphasis will be given to study the influence of different spatial factors, and the uncertainty related to these observations. The research will investigate local and external driving forces of land change. It will address their tangibility and possibility of quantification. (Appendix A)

2. The research will develop plausible (where plausible is defined as likely to occur) scenarios of future land change. To achieve this, it will need to overcome the limitations in data and knowledge, and difficulties when identifying driving forces of change. This will be done by applying participatory modelling techniques. Participatory modelling however needs to be flexible and able to use proxy data or indicators in case of missing data. (Appendix B, C, F)

3. The developed future socio-economic scenarios will be translated into spatial demands and spatial patterns for particular land change processes. Moreover, the approach will identify potential deficiencies of this approach for decision support, such as assessing the performance of the model and the accuracy of the data. (Appendix B, C, D, E)

4. The research will demonstrate the applicability of the proposed methodology and generated scenarios in decision support. The potential consequences of the developed land changes will be analysed, such as changes to hydro-meteorological risk and the landscape. Moreover, the research will evaluate the effect of implementing a policy for reducing potential negative consequences of land changes (e.g. risk reduction policy). (Appendix B, C, D, E)

5. The methodology will be transferrable to different study areas; different areas with different land change processes and their consequences. Nevertheless, the methodology needs to take into account specific characteristics of the observed study area, and is consistent with past and future trends as defined by decision makers (Appendix B, C, E)

# 4 Study areas

## 4.1 General research on land changes in the Alps and Carpathians

The Alps and the Carpathians are two major mountain areas in Europe. Main European rivers originate in these two mountain ranges, providing freshwater and energy to a large share of the European population. Both are recognised as major biodiversity hotspots in Europe (Cremene et al. 2005; Kräuchi et al. 2000). The Alps are considered one of the first tourist destinations, with tourism being a major economic activity (Bätzing, 2005). Even though in the Romanian Carpathians tourism is still underdeveloped, it has major potential (Erdeli and Dinca, 2011). The two regional scale study areas were selected due to their representativeness in terms of biophysical and socio-economic characteristics for the Alps and Carpathians respectively.

Comparing the two mountain ranges, there is more research on land changes in the Alps than in the Carpathians. When focusing only on the Italian Alps, the research ranges from investigating the changes to the forest cover (Dalla Valle et al. 2009), agricultural abandonment (Cocca et al. 2012), impact of agri-environmental measures (Giupponi et al. 2006), the role of socio-economic and natural variables (Tasser et al. 2007), and the impact of land changes on biodiversity (Chemini and Rizzoli, 2003). Nevertheless, there is a lack of research investigating the link between socio-economic changes (post-industrialization in Europe, migrations, tourism, and expansion of transport routes), and land changes (Bätzing, 2005; Bender et al. 2011).

Research on the Carpathian region focuses on most widespread land changes: abandonment of grasslands and cropland, and the consequent expansion of forests (Baumann et al. 2011; Kuemmerle et al. 2008; Müller et al. 2009; Taff et al. 2009; Turnock, 2002). Though more drastic on the spatial and temporal scale in nature, these changes are in line with the long term trends for European mountain areas, including the Alps (Kozak et al. 2007). However, there is a significant process particular to the Carpathian region: the increase in the quantity of forest disturbances in form of deforestation as well as changes in spatial pattern of the logging (Griffiths et al. 2012; Knorn et al. 2012a, 2012b; Kuemmerle et al. 2009, 2007). Processes like this are linked to the fall of Communism since 1989, and the expansion of the European Union in the years after 2000. Numerous research on past and ongoing processes of land changes in the Carpathian region investigates ownership changes, land abandonment, changes to the forest policy, and the influence of private forestry and wood processing industry (Griffiths et al. 2014, 2012; Ioras and Abrudan, 2006; Munteanu et al. 2014). Despite well understood processes of past and current land change in the Carpathian region, there is however still a lack on how possible future socio-economic changes can result in changes to the land cover.

## 4.2 Mountain community of Gemona, Canal del Ferro and Val Canale

The Alpine case study area lies in the Autonomous Region of Friuli Venezia Giulia in north-eastern Italy on the border with Austria and Slovenia (46°30’25’’ N, 13°26’25’’ E, Figure 4.1). The 15 municipalities in the area form a mountain community, a sub-regional administration unit specific for Italian mountainous area. These administrative units were designated by the Italian government as a measure to confront demographic and economic issues of mountain areas, and are usually based on logical geographic units (UNCEM, 2014). The Mountain community of Gemona, Canal del Ferro and Val Canale covers 1148 $km^2$ including the mountain area and adjacent plain near Gemona del Friuli, the catchment of the Fella river flowing through Canal del Ferro and Val Canale, and the surroundings of Tarvisio in the north-east.

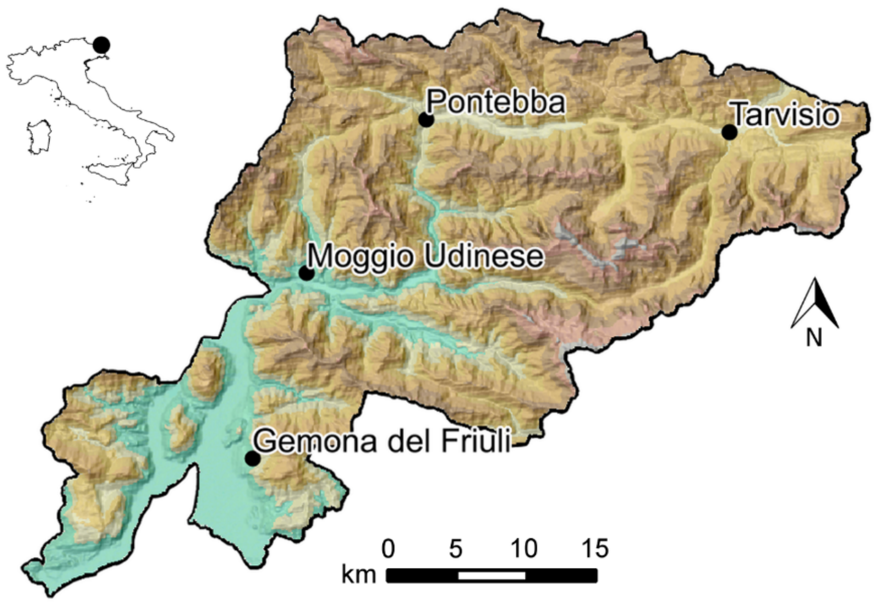


Figure 4.1 Location of the study area (modified from Malek et al. 2014)

High elevation, steep slopes, and high precipitation levels characterize the area; the Carnian and Julian Alps rise up to 2754 m with the relative relief in the upland area being more than 1500 m, a mean altitude of 1140 m, and the average mean precipitation of 1920 mm (Sangati, 2009). As rainfall is concentrated mainly in intense and erosive showers, it determines the torrential regime of the rivers in the area. Moreover, in the higher altitude areas the annual precipitation can reach up to 3000 mm and frequent extreme daily rainfall exceeding 300 mm have been recorded in the area in 20-30 years time span (Ceschia et al. 1991). The majority of the area consists of limestone (Cucchi et al. 2000). The area is subject to frequent seismically activity landslides (among them debris flows) and flash floods (Borga et al. 2007). In the last two decades, extreme flash flood, landslides and debris flows affected settled areas, resulting in several hundreds of millions Euros of damage to the area, evacuation of 600 people and 2 casualties (Borga et al. 2007; Tropeano et al. 2004).

a b

Figure 4.2 Contrast between the (a) traditional alpine landscape (own photograph) and the (b) urbanised valley floor (Schabus, 2005), both near Pontebba

The total population is 33286 inhabitants, and only two settlements have more than 4000 inhabitants: Tarvisio and Gemona del Friuli. The area has been experiencing one of the highest depopulation rates and decreases in economic activities in the whole Alpine region in the last three decades (Instituto Nazionale della Montagna, 2007). Due to difficult physical geographic characteristics and sparse population density the area appears remote, however important traffic and other infrastructural connections along the river valley (National Road No. 13, Highway A-23, railroad, gas pipeline, high-voltage power line) act as a vital link to the neighbouring Austria and Slovenia. There are four ethnic groups living in the area; Italian, Friulian, German (Austrian) and Slovenian; thus making it an area with a diverse social and cultural background. Important economic activities in the area are forest harvesting, transport, agriculture (mainly extensive on pastures) and tourism (both summer and winter); but also water and gravel extraction. Being a significant international energetic and communication corridor, the area is subject to numerous efforts of the regional and national government to further development of infrastructure and risk mitigation. Also, due to the growing tourism development, the interest for maintaining the population and the traditional cultural landscape which is being degraded by the dense infrastructural network (Figure 4.2b) in the area is high.

The river Fella, which flows through the area, is a major left-hand tributary of the Tagliamento river. It is considered among the last morphologically intact rivers in the Alps, although it is not completely without human influence (Ward et al. 1999; Arscott et al. 2002; Lintzmeyer 2005). The Fella is the largest tributary of the Tagliamento and is still mostly characterised by a natural flow regime, although in some segments it is subject to water abstraction, gravel exploitation and drop structures in order to restrain erosion and channel incision. The natural flow regime of the Fella river has raised questions about hazard mitigation involving technical and infrastructural solutions on one side, and sustainable catchment management involving suitable land use planning on the other (Scolobig et al. 2008). This discourse on sustainable hydro-meteorological hazard management strategies is a challenge particularly for land change science, making this study area suitable for the application of future land change scenarios.

## 4.3 Subcarpathians and Carpathians in Buzau County, Romania

The Carpathians and Subcarpathians of Buzău County in Romania are a suitable study area for studying land changes due to its physical-geographic characteristics affected by hilly terrain and hydro-meteorological hazards occurrence on one side, and its complex socio-economic background, as a result of the recent policy and economic changes. It lies in Buzau County in the south-east of Romania, bordering Brasov, Covasna, Prahova and Vrancea counties (45°25’18’’ N, 26°17’46’’ E, Figure 4.3). It covers 3500 $km^2$ from the lower Subcarpathians to the higher Carpathians surrounding the Buzau river valley. The Carpathians rise from up to 1772 m, with the relative relief being 500 to 800 m. The mean altitude of the area is 896 m, with the geology being characterised mainly by deposits of Neogene molasse (Micu and Bălteanu, 2013). The yearly amount of precipitation is between 630-700 mm, with torrential heavy summer rainfalls and spring showers overlapping snow melt in the Carpathians. Landslides, as seen in Figure 4.4a cover large areas in the case study site, in some parts more than two-thirds of the total local area (Muică and Turnock, 2008). The dense river network and spatial distribution of landslides pose questions on possible consequences of future land use and land cover management, such as future forest harvesting and urban expansion.

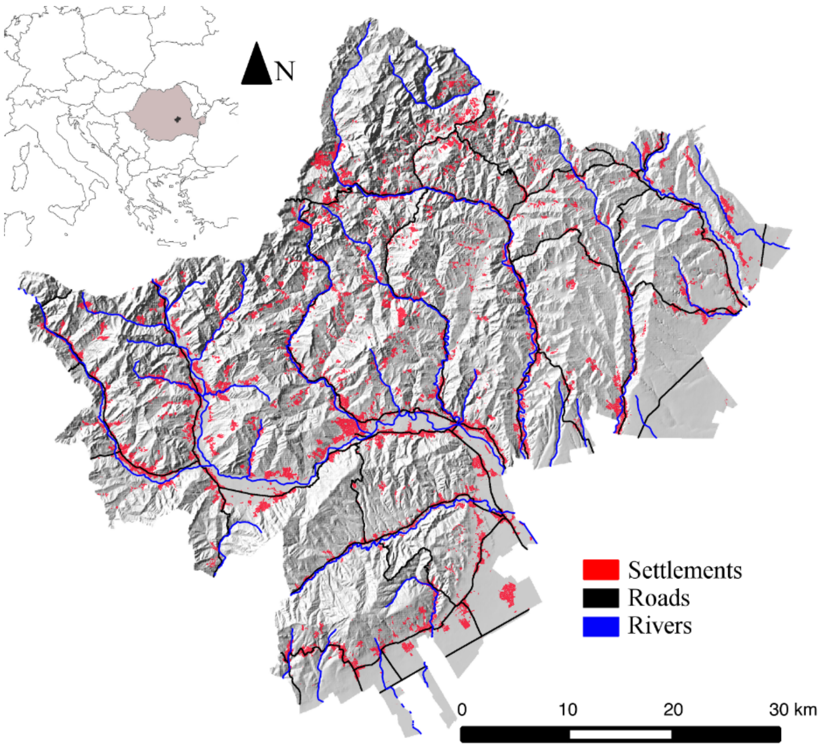


Figure 4.3 Location of the Romanian study area (Malek et al. Under review)

The settlement pattern is characterized by longitudinal settlements along the main Buzau river valley, also extending to side catchments. The total population is around 170000 inhabitants; Nehoiu (11355 inhabitants) and Patarlagele (7831 inhabitants) are the largest settlements. With a share of up to 40% locally, agriculture is an important part of the economy; however its share is declining (Ministry of Agriculture and Rural Development of Romania, 2012). Wood harvesting is also very important, not only for processing, but also for fuel, as also mineral extraction such as mineral deposits (sulfids, iron…) near Nehoiu and Siriu upstream the Buzau river (Institutul Naţional de Statistică, 2011) and energy production (reservoir in Siriu).

One of the important characteristics of the case study area is the long history of intensely populated (from 90-150 pers/ km$^2$) and used areas, including large deforested areas. Hill slopes offered support for the spread of subsistence communities, as they are covered with relatively fertile landslide material. On the other side, more intensive agriculture has developed on the Buzău river terraces, as well as more dense urban areas and important communication and transportation corridors (national road and railroad) (Muică and Turnock 2008).


Figure 4.4 a) Landslide hazard, b) forested landscape and c) deforestation in the Carpathian study area (modified from Appendix C)

Main drivers of land change are connected with the collapse of socialism, following profound changes in policy, economy and land management. These changes were exacerbated by Romania’s entry into the European Union, and the implementation of new agricultural and environmental policies, and the access to European markets. One of the most significant changes in the period of transition was the extension of private property over agricultural land and forests, which followed decollectivisation (Bălteanu and Popovici, 2010). Land reforms restituted forests and agricultural lands in three phases, where the last one (subsequent to the 247/2005 restitution law) potentially enables to returning all the collectivized land to former owners – while the agricultural land has mostly found its former owners (95.3% of all agricultural land in private ownership), the restitution of forests is still in progress (34.1% of all forests are private). Decollectivisation resulted in the emergence of numerous small holdings, over 4,25 million farms nationwide with an average size of an private owned farm of 2,15 ha (Ministry of Agriculture and Rural Development of Romania 2010).

The majority of the study area, around 40 % is covered with forests, as seen in Figure 6b (INSSE, 2013). Forests in private ownership are characterized by fragmented small plots. Together with illegal logging (Figure 6c) it is the cause of difficulties in realising the economic potential of forests (Ministry of Agriculture and Rural Development of Romania, 2012). Romanian Carpathians are not only providing numerous valuable ecosystems to the local and regional population, but are also important on the European scale, as they are one of the last shelters for large carnivores and herbivores (van Maanen et al. 2006). Although the ecosystems in the Carpathians are in a well preserved state, they are very vulnerable to anthropogenic change, due to severe natural conditions such as high altitude, steep slopes, large temperature amplitudes, poor soils, precipitation, etc. (Körner et al. 2005; Ministry of Agriculture and Rural Development of Romania, 2012; van Maanen et al. 2006). For example, forest recovery and expansion after disturbances in the Romanian Carpathians occur relatively slow, or do not occur at all (Jacek Kozak et al. 2007; Kuemmerle et al. 2008).

The transition era in Romania (like in most of post-socialist countries) was characterized by poor socio-economic conditions. Together with forest restitution and weakened authorities this has resulted in the increase of pressure to forest, also in the form of illegal logging, especially with the aim of collecting wood for fuel (David Turnock 2002; Kuemmerle et al. 2008; Dutcă and Abrudan 2010). Large-scale clear-cutting is present, although the government defines harvesting limits and the 1996 forest code promoting multifunctional forestry. Illegal logging takes place mainly in privately owned forests, as the control there is not as successful as in the forest owned by the state (Kuemmerle et al. 2008). Moreover, Romania's European Union membership resulted in rise of pressure to the forests, due to their well-preserved state and a large economic potential (Ministry of Agriculture and Rural Development of Romania 2010). Studying how the increase in the demand for wood supply will result in deforestation and possible environmental consequences is therefore of high importance and the main research topic of this study area.

# 5 Overview of methods

The development of spatially explicit scenarios of land change combining participatory modelling and geospatial modelling involves numerous steps focusing on particular objectives:

1. objective: Investigation of land changes and their driving forces

   This step includes the generation and preparation of land change data, such as past land use and land cover maps, their accuracy, and the identified significance of driving forces of land change. Both the amount and location of past land changes were studied using classification of remote sensing imagery. Using GIS and geostatistical methods, the significance of spatial factors such as elevation, slopes, distance to roads, etc. was investigated as well. Finally, the driving forces such as socio-economic changes were studied by interviewing local and regional experts and decision makers.

2. objective: Participatory scenario modelling

   Expert knowledge on land changes was used to develop cognitive maps of land change. These maps, representing expert based system knowledge on land change were then used to develop a conceptual model of land change. The conceptual model was later used to identify future driving forces of land change, recognize suitable indicators in case of data unavailability, generate future storylines, and identify the focus of potential consequences of future land changes.

3. objective: Spatial allocation of land change scenarios

   First, the scenarios were translated to spatial demands, by analysing the relationship between driving forces of land change and observed past changes to the land use and land cover. Then, a spatially explicit allocation model was developed. The allocation model was calibrated with past observations and spatial factors using the weights of evidence method. The resulting land change potential map was then used to allocate the scenarios across the landscape applying a cellular automata (CA) model. The CA model simulated local scale land changes on a 30 m resolution. Additional scenarios simulating the implementation of a risk policy were also modelled. Finally, the spatially explicit model was validated, thus providing information on the uncertainty of the model.

4. objective: Investigating consequences of land changes

   A GIS based assessment of future land change scenarios was performed. This enabled an analysis of potential changes to the landscape and hydro-meteorological risk. Moreover, it demonstrated the potential of spatially explicit land change scenarios for decision making.

The methodological framework of this research was applied in two different study areas. In the Italian Alps, future urban expansion due to tourism and its consequences in terms of changes to the landscape and hydro-meteorological risk were studied (Appendix B). Two studies were performed in the Romanian Carpathians, both focusing on changes to landslide risk: future deforestation and forest expansion (Appendix C), and future expansion of built up areas (Appendix E).

The following sections give a summary on the methodology developed and applied in this research. A more detailed description of the methodology is provided in the publications (Appendices).

## 5.1 Investigation of land changes and their driving forces

This section focuses on the first objective of the research. It describes how past land changes in two selected study areas were studied, focusing on their spatial, and their driving forces. The influence of different spatial factors was investigated, together with the uncertainty related to these observations. Local and external driving forces of land change were studied, and their tangibility and possibility of quantification were addressed.

### 5.1.1 Land change data generation

Two different methods were applied to generate past maps of land use and land cover, as there were less data available for the Romanian study area compared to the Italian one. The land use and land cover maps were generated for the years 1989, 2000 and 2010 on a spatial resolution of 30 m. The aim was to study and model local changes, which is why a very detailed spatial resolution was used. Using accessible data, 30 m was the most detailed resolution possible to achieve.

For the Italian study area, accessible data was characterised by a detailed spatial and temporal resolution, with some of the land use and land cover maps already available. The procedure therefore combined the methods of mapping land changes by manual interpretation of images, and integration of different data sources (spatial plans, forestry maps). In the Romanian study area, almost no local data was available, which is why global remote sensing datasets have been used (LANDSAT satellite imagery). To map the land use and land cover maps for Romania, a semi-automatic classification was performed (Kuemmerle et al. 2008). This consisted of the combination of the automatic ISODATA clustering algorithm, and manual digitisation of urban areas, due to the resolution of used data. A full description of the data used is in Appendix A.

Later, I performed a post-classification change analysis - the past maps were overlaid in a GIS to generate maps of land change (Pontius et al. 2004). This enabled a spatially explicit analysis of changes, as well an analysis of driving factors of change of location, such as terrain and distance to roads. The influence of terrain and distance was studied by performing a statistical analysis of the incidence of land changes in different classes of elevation, slope and distance to roads. These spatial factors were chosen to represent the accessibility of the selected mountain areas. Moreover, they were later used for calibration of the spatially explicit model.

### 5.1.2 Estimating the uncertainty of land change data

The standard accuracy assessment procedure consists only of providing the information on the accuracy of the individual land use and land cover maps in the form of the overall, user's and producer's accuracy (Foody, 2002). Therefore, I applied a post-classification accuracy assessment proposed by Olofsson et al. (2013). Besides the overall, user's and producer's accuracy this approach also provides information on the error-adjusted area of each land change process and its 95 % confidence interval (Olofsson et al. 2013). Thus, it informs the user of the final maps on the uncertainty of the data in form of the possible interval of exact areas subject to land change. This information is especially useful when modelling land changes, as the model's error rate is aggregated with the errors of the data. The assessment was based on an independent stratified random sample of 9 pixel sample units, visually interpreted using remote sensing imagery. In each study area 325 reference units were used to estimate the uncertainty of the classified maps.

### 5.1.3 Identifying driving forces of land change

In order to understand the causes behind the observed land changes, 24 interviews with local and regional experts, stakeholders and researchers were conducted. In the Italian study area, 11 interviews were performed in October and November 2012 in three languages: Italian, German and Slovenian. In the Romanian area, 13 interviews were performed in July and September 2012 in English and Romanian (with a translator). The roles of interviewees and the purpose of their involvement are described in Table 5.1 and Appendix A. The influence of following aspects of land change was investigated: demography, agriculture and forestry, economy, tourism, role of decision making, external driving forces such as global political changes… The concepts gathered in the interviews served as a basis of the preparation of a conceptual model described in later section.

Table 5.1 List of stakeholders interviewed (Malek et al. 2014)

| Level | Stakeholder | Aspect of Change |
|---|---|---|
| Municipal | Mayor, Vice Mayor (2, I, R) | a, b, d |
| | Local historian (2, I, R) | a, b |
| | Forestry technician (3, I, R) | c, e |
| | Spatial planner (2, I, R) | c, d, e |
| | Officer for environmental protection (1, R) | c, e |
| | Technical officer, local emergency or fire department (2, I, R) | e |
| | Farmers (10, R) | b, e |
| | Researchers on human and physical geography (2, I, R) | a, d, e |
| Regional | Forestry officials (3, I, R) | b, c |
| | Geologist (1, I) | c, d |
| | Officials at regional civil protection agency (2, I, R) | e |
| | Officials at regional environmental agency (1, R) | c, e |
| | Researchers on rural economy and land cover change (2, I, R) | a, b, d, e |
| National | Statistical officials (1, R) | a, b, d |

Notes: I, Italian area; R, Romanian area; a, demographic changes; b, changes to agriculture, forestry; c, environmental (agriculture, forestry, risk) policy; d, economic development; e, consequences of land cover change.

## 5.2 Participatory modelling of land change scenarios

In this section, the second objective of the research is addressed: the development of scenarios of future land change. This was performed by applying participatory modelling techniques. These were applied in order to overcome the limitations in data and knowledge, and difficulties when identifying driving forces of change.

### 5.2.1 Elicitation of expert based knowledge

Expert opinions and concepts of land change collected through interviews were used to develop Cognitive Maps (CM) of land change. This qualitative (or semi-quantitative) methodology consists of numerous concepts of a particular issue connected to each other in a form of a graph, depicting an expert based mental model (Axelrod, 1976). The resulting graph provides information on the relationships between different concepts of land change. Constructing CMs with experts can help to encode and visualize knowledge on a particular system. Thus, the issues of inaccessible data and driving forces difficult to identify can be solved (Eden, 1992). The development of a CM starts with identifying the concepts forming a particular system, and later identifying the relationships between them by visually connecting the concepts. These relationships are later visualized in the form of a directional graph (Figure 5.1).

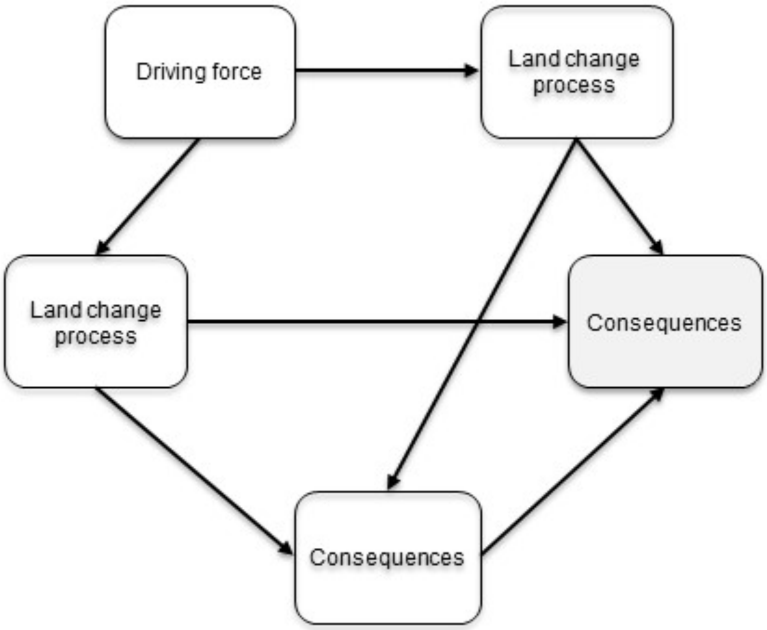


Figure 5.1 A graphical representation of a conceptual Cognitive Map. Nodes represent concepts of a particular issue, in this case land changes. The arrows of the causal relationships represent the influences between the concepts.

### 5.2.2 Developing a conceptual model of future land change

The CM models are however unstructured and can be difficult to read by non-experts. Moreover, they cannot be used for advanced simulation and cannot operate on a temporal scale (Kok, 2009). Therefore, the CMs were only used as an intermediate step in the development of the final model. To structure the relationships of the CMs we applied the Driving forces – Pressures – State – Impact – Response (DPSIR) framework (EEA, 1999). This way, the relationships between different concepts of land change were organised in a cause-response framework together with the stakeholders (Figure 5.2). This enabled the derivation of indicators that can be translated into quantitative terms and spatial demands for future land change. Moreover, it enabled the definition of management objectives and served as a framework behind scenario development, with the possibility to evaluate different options that were identified by the stakeholders. Concepts identified as Driving forces (D) in the DPSIR framework have been defined as key scenario concepts. In the case of the Romanian study area (Appendix C), this was the forest harvesting demand. In the Italian study area (Appendix B), this was the demand for tourist accommodation. The future trends of these driving forces were discussed with the stakeholders and backed by their development plans and policy. The values for concepts PSI in the DPSIR framework were subsequently generated by the researcher through GIS and spatial allocation, as described in Appendix B and C. The response (R) concepts were again defined together with the stakeholders representing their options to manage potential land changes. The indicators for each part of the conceptual DPSIR model have been chosen based on the following criteria: (1) significance and understanding by the stakeholders, (2) relevance for land change processes, (3) data accessibility, and (4) possibility of expressing and modelling in terms of spatial demands.

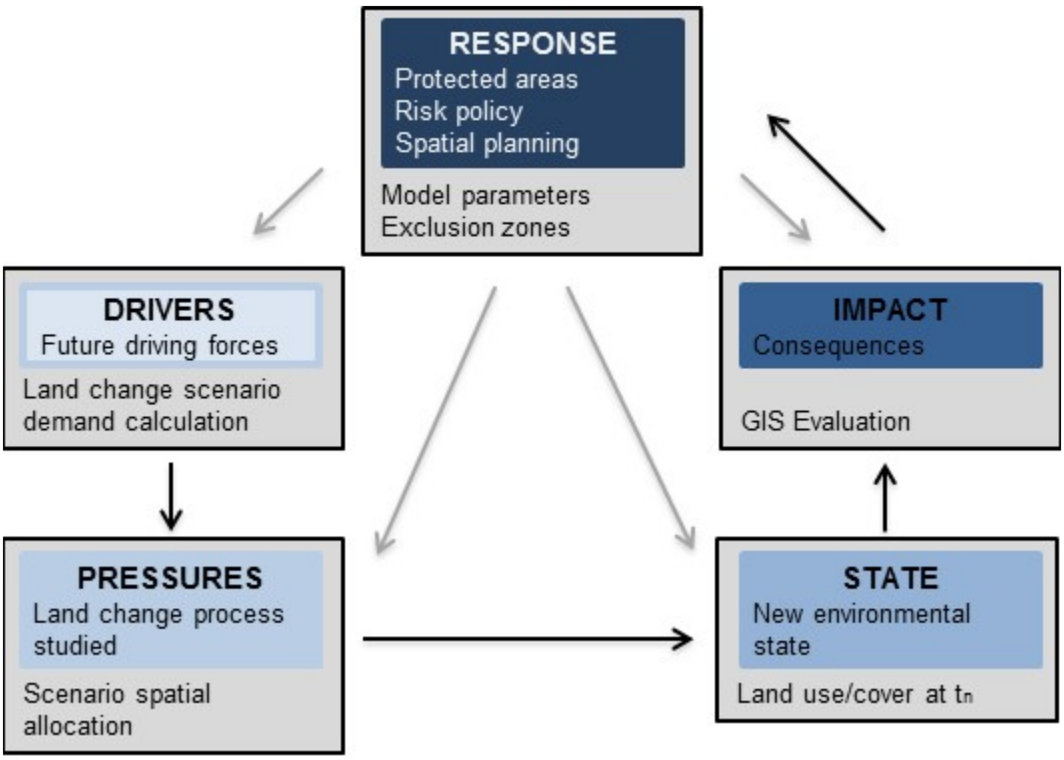


Figure 5.2 Drivers – Pressures – State – Impact – Response framework

The development of the conceptual land change model enabled the identification and development of future scenarios, described by plausible storylines and accompanied quantified futures. Storylines are descriptions of possible future states of concepts categorized as Driving forces (D) as the future visions of the involved stakeholders and available development plans. By using the DPSIR model, it was more straightforward for the stakeholders to develop future storylines, describing future socio-economic development. The storylines were based on different logic and assumptions (e.g. different tourism strategies or forest harvesting pattern), instead of the commonly applied approach of defining different scenarios as merely low, normal and high growth or decrease rates of a particular process (Ogilvy and Schwartz, 1998).

## 5.3 Spatial allocation of land change scenarios

This section focuses on the third objective: how the developed future socio-economic scenarios can be translated into spatial demands and spatial patterns for particular land change processes. The focus was also on identifying potential deficiencies of a spatially explicit approach for decision support, such as the performance of the model and the accuracy of the data.

### 5.3.1 Translating the scenarios to spatial demands

After the DPSIR models were developed, the relationships between the different parts of the DPSIR model were further investigated. Here, accessible data on the identified socio-economic driving forces was used, and the statistical relationships between the different constituents of the DPSIR were identified.

In the Italian study area, the relationship between tourism accommodation trends and the demand for tourism related built up areas was investigated. The proxy for tourism accommodation was used, as associating future tourism development directly to urban areas was considered as too abstract to the stakeholders (Appendix B).

In the Romanian area, the relationship between the demand for forest cover change and allowed amount of forest harvesting was studied. Here, the spatial demand for forests was easily comprehensible to the stakeholders, however it was difficult to relate it only to deforestation without considering other forest management options. A model for estimating deforestation as a function of forest harvesting, clear felling and biophysical characteristics of regional forests was developed and is described in more detail in Appendix C.

### 5.3.2 Simulating future land change using geospatial modelling

This section describes the development of a spatially explicit model of future land change. It was developed in Dinamica EGO, software for raster-based simulation of environmental changes (Soares-Filho et al. 2002). This software was chosen as it enables modelling on detailed spatial and temporal resolution, and has a transparent interface for building and displaying models, avoiding the use of black box solutions.

Dinamica EGO combines traditional GIS functions with geostatistical methods and complex algorithms for analysis and geospatial simulation of numerous environmental issues. It has already been applied to simulating urban, agricultural and forest changes (de Almeida et al. 2003; Kamusoko et al. 2013; Maeda et al. 2010). It enables the development of variety of environmental models: from simple static spatial models, spatial multi-criteria evaluation, to complex dynamic models. Dynamic models can be built as it enables nested iterations, multi-transitions of land change and dynamic feedbacks. Moreover, it supports multi-scale simulation as it can operate on numerous regions at the same time (e.g. regional scale to catchment scale). All this leads to a more clear and faster development, calibration, validation and execution of spatially explicit environmental models compared to other approaches (Pérez-Vega et al. 2012). Dinamica EGO is freely available at http://www.csr.ufmg.br/dinamica/.

The land change scenarios were allocated using two geospatial modelling techniques: weights of evidence (WoE) and cellular automata (CA). The WoE method is a bayesian geostatistical method used to generate a land change transition potential map (Bonham-Carter, 1994). Using WoE, the probability of future changes is calculated for each pixel of the map using past observations on land changes and predefined spatial factors, such as elevation, slopes, distance to roads, etc. The result is a land change probability map. The probability map shows where particular changes are more or less likely to occur based on defined spatial driving forces and restrictions. Each pixel in the probability map is so defined with a probability value, in this case between 0 and 1.

The CA model is used to spatially allocate the changes to the specific land use and land cover classes across the probability map. CA are dynamic, bottom-up models that are able to model land changes simulating decision making from the point of view of a spatial planner (White and Engelen, 2000). The landscape in a CA model is defined as a grid of cells with a particular land use and land cover type (Engelen et al. 1995). The cells change their step in a predefined time step, according to their neighborhood, previously calculated potential map, and cell transition rates (Mitsova et al. 2011). The neighborhood effect promotes changes to a particular land use and land cover class near existing cells of that class (Figure 5.3). This for example simulates realistic urban expansion, as new urban areas usually mostly emerge adjacent or near to existing urban areas and not as completely new patches. The transition rates are defined by spatial demands of scenarios, divided into time steps. Decision making time steps can be adjusted manually, such as a 5-year development plan instead of simulating the land use each year. By training the spatial pattern of future land changes using landscape metrics of past observations, the future changes result in a more realistic spatial pattern for a specific study area (Gustafson, 1998). The model can so be calibrated to promote more changes in the neighbourhood when modelling urban expansion. On the example of modelling deforestation, the model can be calibrated to form new deforestation patches in the middle of an existing forest patch and not nearby existing deforestation.

The methodology behind calibration of the whole allocation model, as well as the parameters is described in more detail in Appendices B and C.

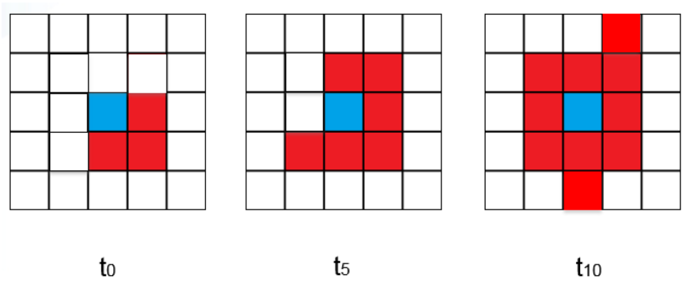


Figure 5.3 A simplified Cellular Automata simulation. The example shows a simulation in the neighbourhood of a reference urban cell (blue). New cells of urban land use (red) are more likely to be simulated in the neighbourhood, thus adjacent to existing urban areas.

### 5.3.3 Estimating the performance of the geospatial model

To estimate the success rate of the allocation model, I applied a multi-resolution approach (Hagen, 2003). The difference map of the initial (e.g. 1989) and reference (2010) map, was compared to the difference map of the initial (1989) and simulated (2010) map. I evaluated the cell agreement using windows with different spatial resolutions: from one cell to the agreement in a defined neighbourhood of the observed cell (Figure 5.4). This way, the ability of the model in capturing the spatial pattern can be tested, as the simulated and reference maps usually do not match on a single cell resolution. The result is a fuzzy similarity index, based on the agreement of change cells between both difference maps.

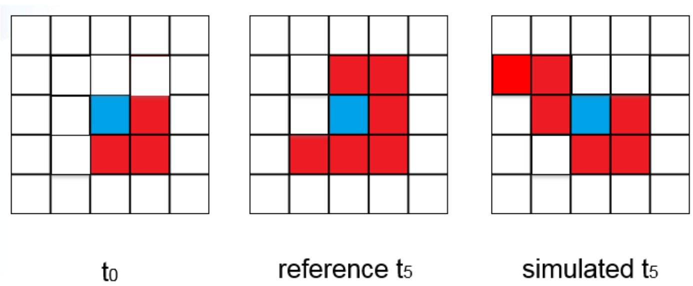


Figure 5.4 A multi window performance estimation. The model failed to simulate the exact locations of new urban areas (red) when comparing it to a defined cell neighbourhood. Nevertheless, the model simulated the same amount of urban expansion in the neighbourhood, of the reference cell (blue).

## 5.4 Investigating consequences of land changes

Following objective 4, the research aimed at demonstrating the applicability of the proposed methodology and generated scenarios in decision support. The potential impact of the land change scenario to risk and landscape were analysed.

In order to demonstrate the applicability of the developed land change scenarios for decision support, an assessment of potential impacts of these changes has been performed. All the results are spatially explicit, therefore enabling an analysis of changes to the landscape, and more importantly, hydro-meteorological risk. The assessment was performed using a GIS based approach.

To identify the potential changes to the landscape, the future changes were analysed by investigating lost natural and semi-natural areas, such as grasslands, agricultural areas, forests and other vegetation. The performed analysis of potential changes to hydro-meteorological risk was more complex, and differed for each of the study areas. Whereas it consisted of a spatial overlay of risk related data in the Italian study area (Appendix B), an external landslide susceptibility model needed to be applied in the Romanian area (Hussin et al. 2013; Zumpano et al. 2014). The landslide susceptibility map was used to identify the extent of projected deforestation and forest expansion on areas with high landslide susceptibility. This way, I investigated how much deforestation was projected on areas where landslides are more likely to occur (high susceptibility).

## 5.5 Transferability of the approach

The final objective of the research aimed at a methodology that is transferrable to other study areas.

The methodology was applied in two study areas described in the Study areas section. In the Italian study area, the effects of potential future tourism development on the land use and land cover was studied. In the Romanian area, potential future changes to the forest cover as a consequence of changing forest policy were investigated. Moreover, the methodology was applied for studying future expansion of built up areas in the Romanian area.

# 6 Results

The results of the dissertation are presented in detail in the publications (Appendices). In this section, the main results are summarized.

## 6.1 Analysis of past land changes

The results of the first objective are the spatial extent of land changes, the influence of spatial factors and possible driving forces behind the observed land changes. First, land cover maps for 1989, 2000 and 2010 were generated. A subsequent post classification change detection of these maps (Figure 6.1) revealed the most significant land changes in the areas. The amounts of land change processes in spatial terms are presented in Table 6.1. The post-classification accuracy assessment revealed the uncertainty of the classified land change maps in terms of the range of land change quantities (Table 6.2).

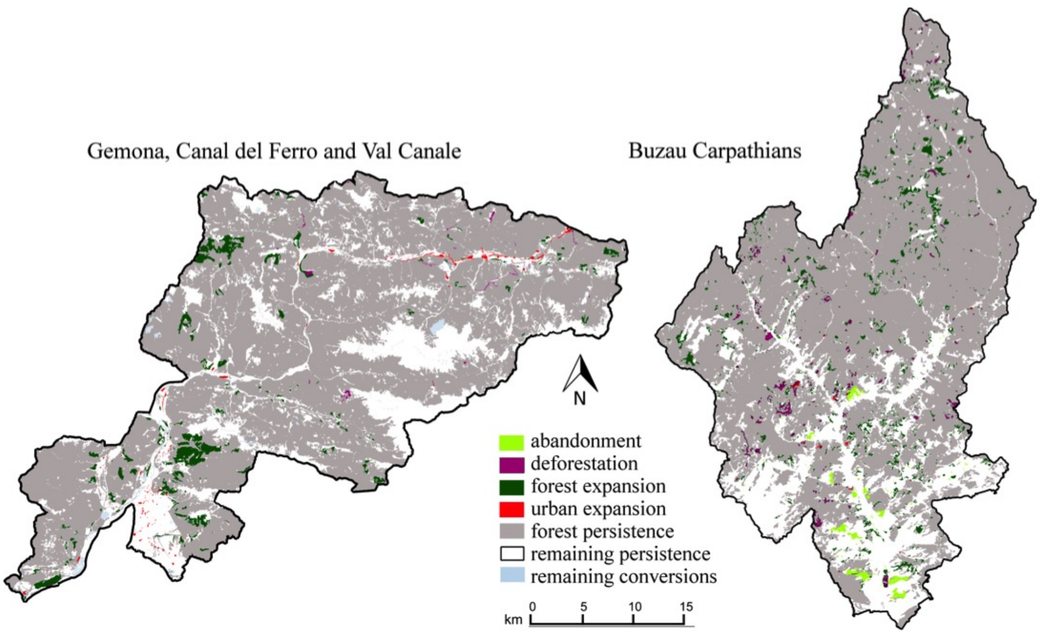


Figure 6.1 Spatial distribution of land cover conversions between 1989 and 2010. (Malek et al. 2014)

In the Italian study area, most striking changes between 1989 and 2010 were forest expansion and the consequent 22.6 % loss of grasslands, and a 14.9 % urban expansion (Table 6.1). Urban expansion occurred mainly in the main valley and in the lowlands, whereas forest expansion occurred on slopes and higher altitudes (Figure 6.1). The overall accuracy for the post classification change map is 91.7%, with high accuracies for each land cover change category (Table 6.2). Nonetheless, urban expansion and deforestation might have been overestimated - they are not within the margin of error (at a 95% confidence interval). Additionally, the area subject to forest expansion is characterized by a large uncertainty, due to the wide confidence interval of almost 45% of the adjusted area of forest expansion (Table 6.2).

In the Romanian study area, reforestation, deforestation and the abandonment of agricultural areas were most significant (Figure 6.1). The majority of forest expansions occurred in higher altitudes, a consequence of grassland abandonment in these areas after 1989. One the other side, most of the deforestation occurred near the main Buzau river valley (Figure 6.1). In spite of the high level of accuracy of the change map (89.2 %), the adjusted areas of forest expansion, deforestation and abandonment have high uncertainties, as reflected by the wide margins of error. Considering these uncertainties, forest expansion varied between 2,714.8 and 5,247.8 ha, deforestation between 610.8 and 1,329 ha and abandonment between 516.7 and 928.7 ha (Table 6.2). Furthermore, due to the lack of high-detail multi-temporal data and the nature of the data used (the spatial and temporal resolution of Landsat satellite imagery), the results might ignore all land cover processes in the area. For example, substantial small-scale deforestation could have been unaccounted for.

Table 6.1 Land changes in both case study areas. Changes are expressed as net increases or decreases in the percent of areas covered by the particular land cover type (Malek et al. 2014).

| **Class** | **Gemona, Canal del Ferro and Val Canale** | | | **Buzau Carpathians** | | |
|---|---|---|---|---|---|---|
| | **Land Cover ($km^2$)** | | **Land Cover Change (%)** | **Land Cover ($km^2$)** | | **Land Cover Change (%)** |
| | **1989** | **2010** | **Change** | **1989** | **2010** | **Change** |
| Urban | 23.9 | 27.4 | 14.9 | 36.7 | 37.5 | 2.1 |
| Cultivated | 27.7 | 26.9 | −2.9 | 17.2 | 10.8 | −37.4 |
| Forest | 829.8 | 857.8 | 3.4 | 818.4 | 840.9 | 2.8 |
| Grassland | 119.5 | 92.5 | −22.6 | 234.7 | 218.9 | −6.7 |
| Other | 24.7 | 20.4 | −17.4 | 8.7 | 7.8 | −9.9 |

Table 6.2 Accuracy assessment and estimation of areas with a margin of error at a 95% confidence interval (CI) for both land change maps (Figure 9) (Malek et al. 2014)

| Change category | Classified Area (ha) | Adjusted Area (ha) | 95% CI (ha) | 95% CI (%) | User's Accuracy (%) | Producer's Accuracy (%) |
|---|---|---|---|---|---|---|
| **Gemona, Canal del Ferro and Val Canale** | | | | | | |
| Forest expansion | 3,234.3 | 3,736.8 | 1,674.2 | 44.8 | 88.0 | 97.8 |
| Deforestation | 112.5 | 99.0 | 10.5 | 10.6 | 88.0 | 95.7 |
| Urban expansion | 350.2 | 309.8 | 21.2 | 6.8 | 86.0 | 100.0 |
| **Buzau Carpathians** | | | | | | |
| Forest expansion | 3,435.8 | 3,981.3 | 1,266.5 | 31.8 | 84.0 | 85.7 |
| Deforestation | 1,085.0 | 970.0 | 359.2 | 37.0 | 86.0 | 93.5 |
| Abandonment | 715.0 | 722.7 | 206.0 | 28.5 | 82.0 | 95.3 |

## 6.2 Future scenarios of land change

### 6.2.1 Conceptual land change models

Interviews and stakeholder discussion resulted in Cognitive Maps (CM). These unstructured expert based systems were not used for simulation or analysis, however lead to the consequent development of the conceptual scenario model. Moreover, investigating a CM example (Figure 6.2) already provided information on potential feedbacks in terms of driving forces, land changes and their consequences. For example, forest management difficulties can lead to illegal logging, which often occurs in the form of clear cutting. This can result in exposed slopes that might increase the landslide risk, due to increased water runoff. The increase in landslide risk results in a rise in forest management difficulties, thus closing the feedback loop.

In order to enable the generation of scenarios and their subsequent quantification and spatial simulation, the CM were structured using the DPSIR approach (Figures 6.3 and 6.4). The DPSIR conceptual models present a clear cause response chain of the local system of land change based on expert knowledge.

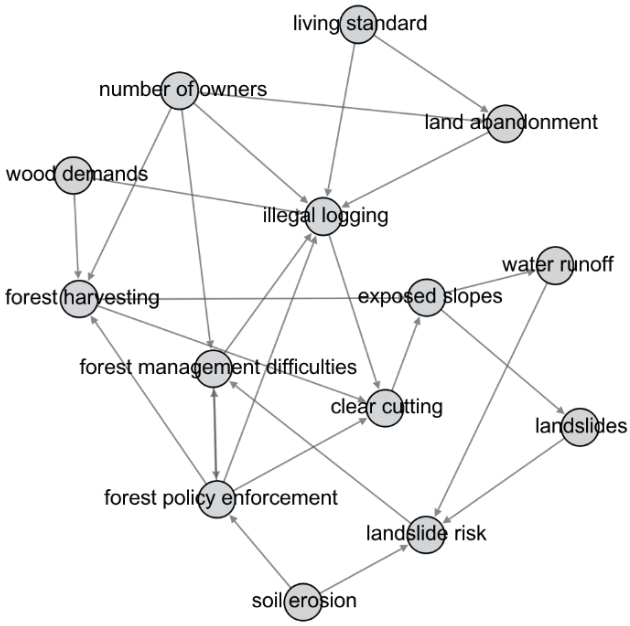


Figure 6.2 An example of a cognitive map for the Romanian study area

In the Italian study area the main identified driver of future urban expansion was tourism development (Figure 6.3). A changed landscape and new elements at risk were identified as the consequences of new built up areas. The response options of the decision makers were also identified limiting further landscape degradation or risk increase, as well as promoting a particular spatial pattern of urban expansion (e.g. promoting small scale tourism).

Forest policy and the pressures of the wood processing industry were identified as the main drivers of allowed forest clear cutting in the Romanian study area (Figure 6.4). Deforestation resulted in a changed landscape and exposed slopes, with implications for landslide risk and nature degradation. Enforcement of forest policy, together with nature conservation and risk zoning were identified as response options.

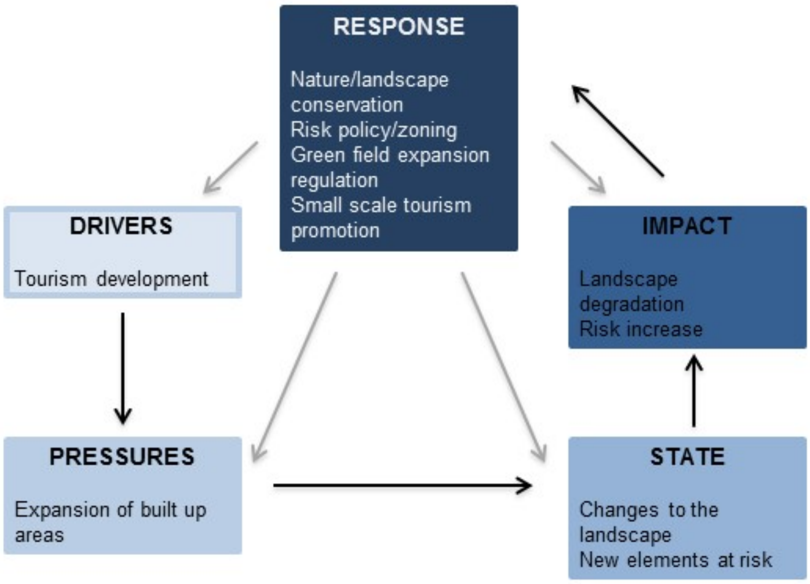


Figure 6.3 Drivers – Pressures – State – Impact – Response conceptual model of future urban expansion due to tourism development in the Italian study area (Appendix B).

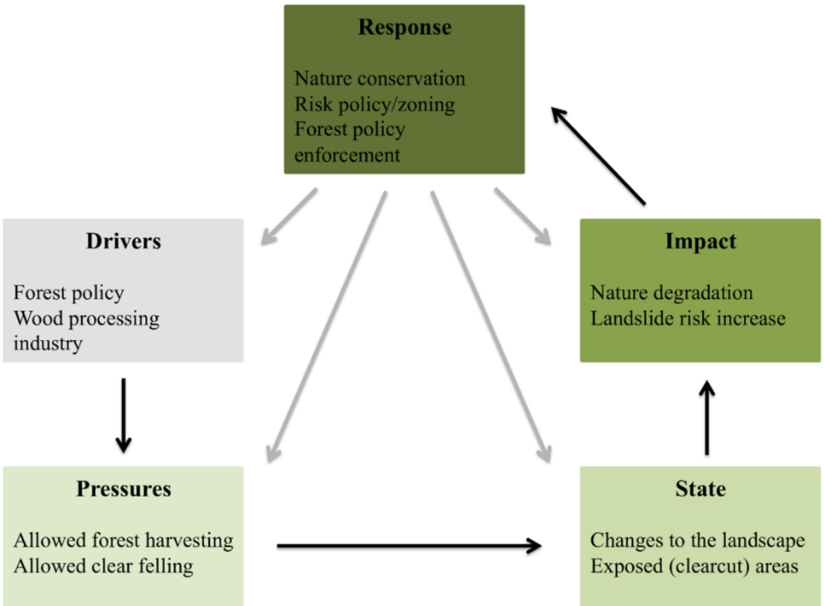


Figure 6.4 Drivers – Pressures – State – Impact – Response conceptual model of the forest harvesting system for the Romanian study area (Appendix C).

### 6.2.2 Scenario storylines

Based on the identified parts of the DPSIR conceptual model, future storylines were developed for both study areas, based on stakeholders' involvement and available data on future development. The temporal resolution was decided together with the stakeholders, and was representing medium term development of the areas. The storylines for each study area are summarized in this section.

Two scenarios were developed in the Italian study area, both aiming at the same 30 % increase of tourism accommodation facilities until 2035 (Appendix B). They were however based on two different tourism expansion strategies. The first scenario was described as a small-scale tourism pathway. It was based on increasing tourist accommodation facilities in individual objects, similar to the tourism development trajectory of the last decades, therefore this scenarios was defined as Business As Usual (BAU). The BAU scenario was promoting new urban expansion in the form of smaller individual patches of new urban areas. The second strategy (the Alternative scenario) of the increase of tourist accommodation was based on new hotel resorts. This scenario promoted larger patches of new urban areas. The BAU scenario was characterised by a lower density of accommodation per hectare (180 beds per ha) as compared to the Alternative scenario (281 beds per ha). These densities were based on the observed accommodation densities from the last 20 years. The different spatial demands and spatial pattern of the scenarios were later investigated in terms of quantity of new urban land, as well as changes to the landscape and risk.

Two scenarios focusing on future changes to the forest cover until 2040 were developed in the Romanian study area (Appendix C). The Business as usual scenario followed existing policy that was identified as sustainable by the stakeholders. The limits of clear cutting thus remained the same, as well as the size of allowed clear cuts (2 ha). The Alternative scenario was oriented towards the aims of investors in the forestry and wood processing industry. Thus, in the Alternative scenario, the clear cutting limits increased by 66 %. Moreover, the scenario had a larger size of allowed clear cuts (2.5 ha). Two additional scenarios were developed: both scenarios with an implemented risk policy. Following this policy, all high landslide risk areas were excluded from the model. This way, the effects and costs of a possible risk policy were investigated.

## 6.3 Spatially explicit scenarios

### 6.3.1 Urban expansion scenarios

The results of the geospatial simulation in the Italian study area focused on the simulation of urban expansion due to two future tourism development scenarios. The BAU and Alternative scenario differed both in terms of the total urban expansion (Table 4), as well as in the spatial pattern and distribution of these changes (Figure 6.5). A higher increase of urban areas was projected in the BAU scenario, following the fact that the observed accommodation density (beds per ha) was lower than in the Alternative scenario.

The areas experiencing most urban expansion were near the existing settlements on the valley floor. The areas at higher elevations and steeper slopes were not excluded manually, but recognized with low probability of land changes by analysing past observations (Appendix B). Urban expansion varied among different areas in the whole study area. Even though the rate of projected urban expansion might seem insignificant on the regional scale (2.7 % in the BAU and 2 % in the Alternative scenario), this is not the case when investigating the changes at the local level. For example, the area surrounding the major tourism centre of Tarvisio, experienced several times higher urban expansion when compared to the regional average (Table 6.3). In the BAU scenario it experienced 3.6 times higher and in the alternative a 3.3 times higher urban expansion.

Table 6.3 Urban expansion scenarios (increase in %) in the Italian study area (Appendix B)

| | **BAU** | **Alternative** |
|---|---|---|
| New urban areas | 2.7 | 2.0 |
| Local relative increase in the main tourism area (Tarvisio) | 9.9 | 6.6 |

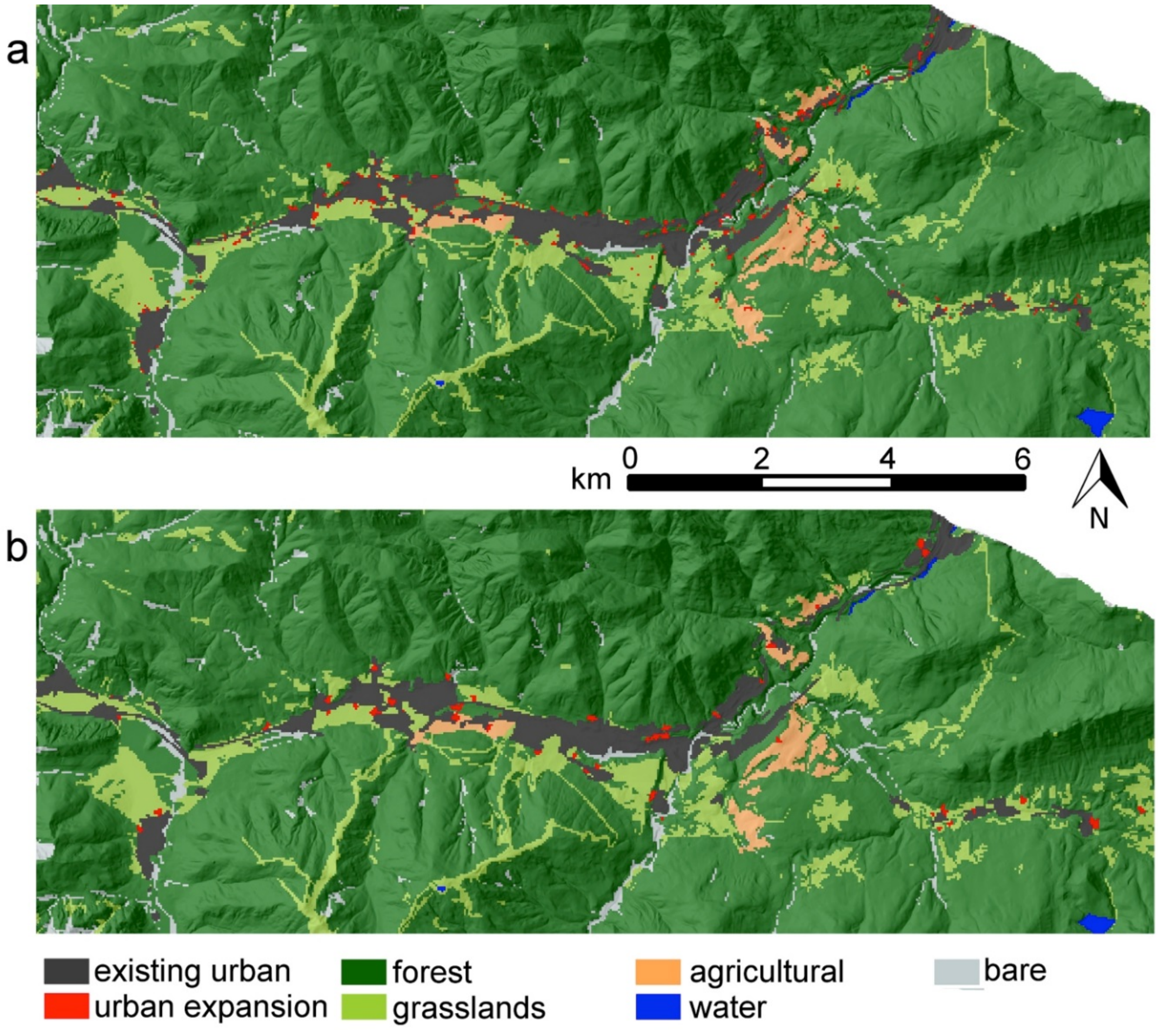


Figure 6.5 Detailed example of the 2035 scenarios for the Italian study area. The figure shows the spatial distribution of future changes in the BAU (a) and Alternative (b) scenario. The red patches show the simulated urban expansion (Appendix B).

### 6.3.2 Scenarios of forest cover change

This section presents possible future changes to the forest cover as a consequence of forest expansion and forest harvesting policy. Scenarios for the Romanian study area show the locations, where deforestation was projected to occur in the 30 year model run. There were no significant differences in the spatial distribution between the two scenarios (Figure 6.6). This is because they were both based on identical spatial factors spatial allocation rules, except the size of clear cuts. The two scenarios did however vary in the % of 2010 forest areas subject to deforestation until 2040: 2.2 % in the Alternative and 1.3 % in the BAU scenario (Table 6.4). Forest expansion was also modelled for both scenarios, resulting in an 8 % increase of forest cover in the

Alternative, and an 8.8 % increase in the BAU scenario. For both scenarios this meant a 14.3 % decrease in grasslands. An additional analysis considering landslide susceptibility was also performed. It showed, that the majority of deforestation occurred on areas with lower susceptibility in both scenarios. Nevertheless, the Alternative scenario projected significantly more deforestation on areas with high susceptibility compared to the BAU deforestation scenario. According to both scenarios, on a regional scale most of forest expansion is projected to occur on areas with higher likelihood of landslide occurrence.

Table 6.4 Distribution of forest cover change scenarios and baseline among landslide susceptibility classes. The values for the scenarios are in ha and % of the total forest cover change process. (Appendix C)

| | **Scenarios – ha (%)** | | |
|---|---|---|---|
| **Landslide susceptibility (%)** | **Deforestation Alternative** | **Deforestation BAU** | **Forest expansion** |
| 0 – 20 | 980.7 (45.9) | 607.7 (47.4) | 1844.7 (18.5) |
| 20 – 40 | 673.8 (31.5) | 399.5 (31.1) | 1407.0 (14.1) |
| 40 – 60 | 374.7 (17.5) | 219.8 (17.1) | 1839.7 (18.4) |
| 60 – 80 | 105.7 (4.9) | 53.8 (4.2) | 2344.4 (23.4) |
| 80 – 100 | 2.9 (0.1) | 1.9 (0.1) | 2558.2 (25.6) |
| Total | 2138 | 1283 | 9993 |

### 6.3.3 Estimating the model performance

The Fuzzy similarity index shows the spatial agreement of change cells between the actual and modelled difference maps (Figure 6.7). On the example of the Romanian study area, this agreement ranged from 51.5 % at the windows size of 30 m (single cell) to 83.9 % at the windows size of 450 m (15 cells neighbourhood).

This result shows how difficult it is to simulate spatially explicit land changes on a cell basis. On the other side, it also shows that the model is able to capture the spatial pattern of changes, as the agreement becomes much higher when looking at a neighbourhood larger than 3 cells.

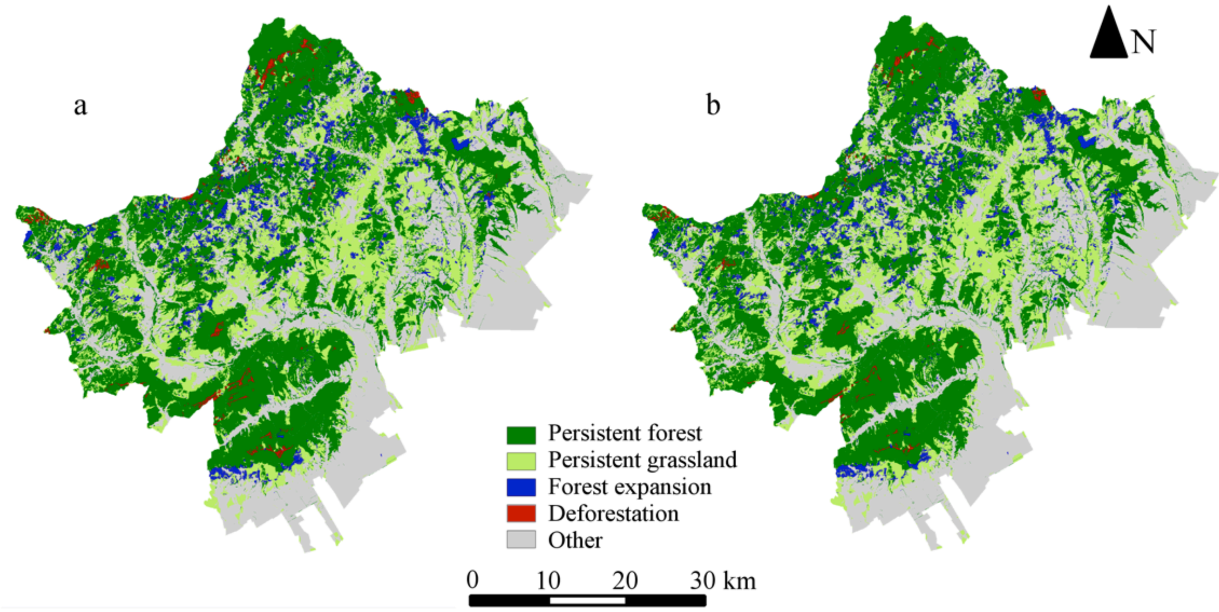


Figure 6.6 2040 scenarios of forest cover change in the Romanian study area: (a) Alternative, (b) BAU. (Appendix C)

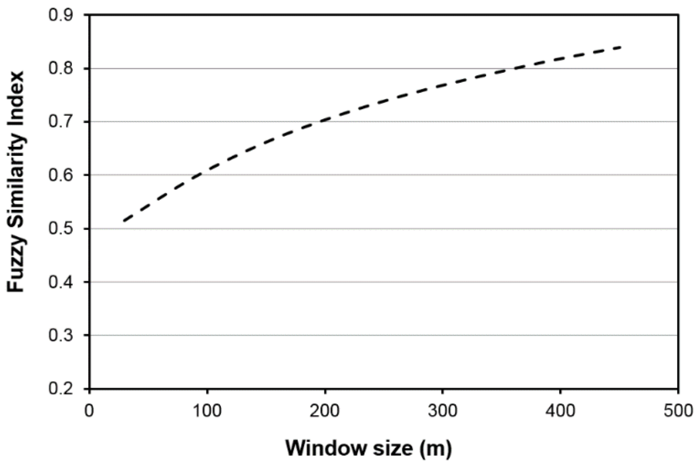


Figure 6.7 Fuzzy similarity index, describing the agreement of change cells between the actual and modelled difference map using multiple resolution windows

## 6.4 Potential consequences of land changes

### 6.4.1 Consequences of urban expansion scenarios

It is difficult to quantify the impact on the environment by only analysing the total land use and land cover classes subject to change. The impact was assessed among others by measuring the loss of natural and semi-natural land cover types due to urban expansion (Figure 6.8). The BAU scenario results in a higher loss of natural and semi-natural areas (Table 6.5). This scenario also projected more urban expansion on areas with possible geological risk. The Alternative scenario resulted in more urban expansion on areas with moderate flood risk. The simulated urban expansion in this scenario is defined by larger homogeneous areas. If projected to occur on areas with moderate flood hazard, these larger urban patches covered more areas, than smaller urban patches of the BAU scenario that are more evenly scattered across the landscape.

Table 6.5 Evaluation of impact of the urban expansion scenarios in the Italian study area

| | BAU | Alternative |
|---|---|---|
| **Landscape degradation (ha)** | | |
| Forest loss | 28.9 | 22.4 |
| Grassland loss | 29.3 | 18.2 |
| Agricultural loss | 13.9 | 11.5 |
| **Risk increase (ha)** | | |
| Expansion on areas with high geological risk | 18.0 | 13.9 |
| Expansion on areas with moderate flood risk | 4.4 | 5.9 |

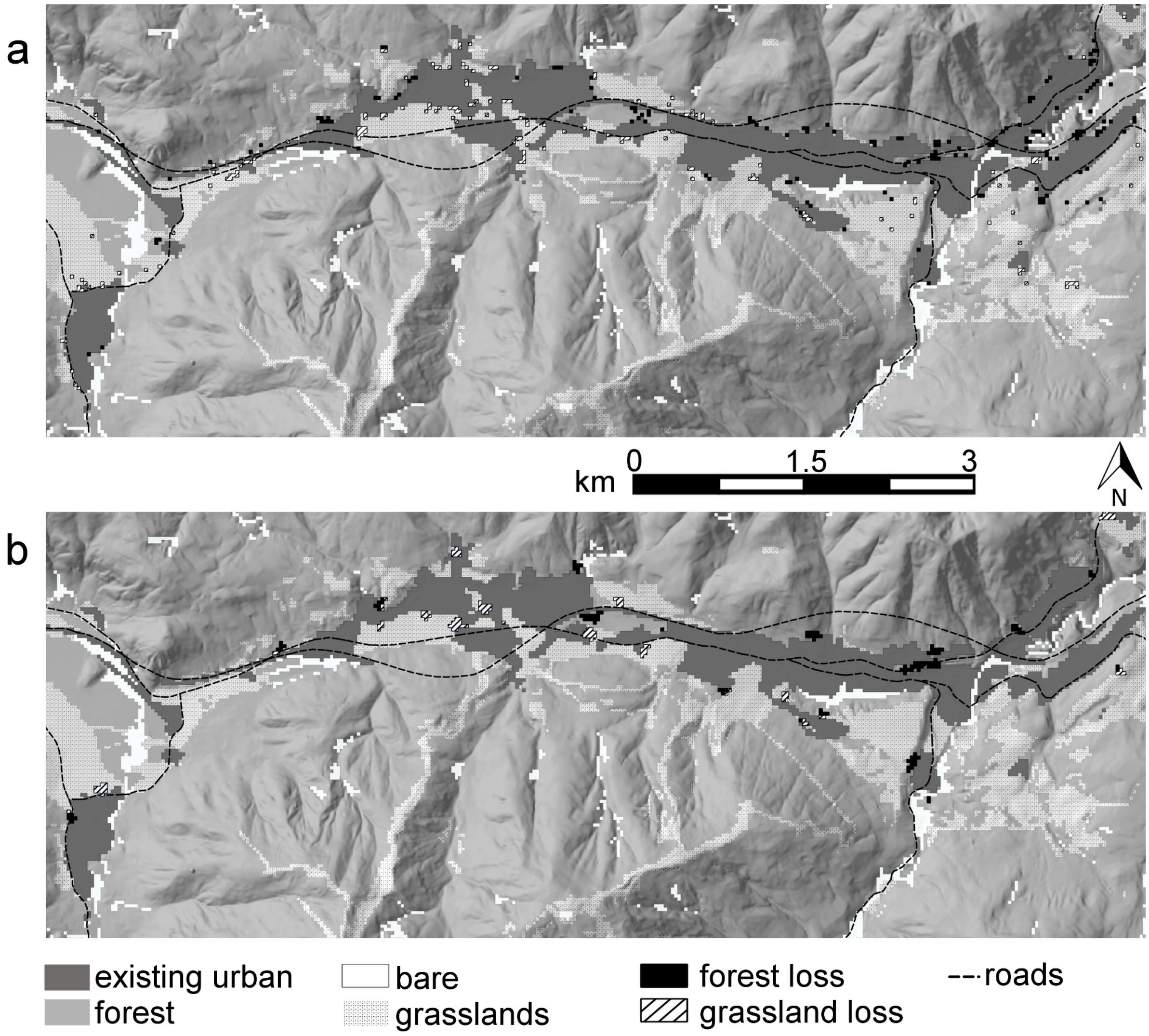


Figure 6.8 Impact of the 2035 scenarios on the landscape, in the main tourism area near Tarvisio. The maps show the projected losses of particular land cover types for the (a) BAU and (B) Alternative scenario (Appendix B)

### 6.4.2 Consequences of deforestation

The 2040 deforestation and forest expansion scenarios in the Romanian study area were analysed using GIS and geostatistical modelling to identify potential changes to landslide susceptibility (Figure 6.9). Both the increases and decreases to landslide susceptibility were analysed. A decrease means a lower likelihood that a landslide would occur, whereas an increase leads to a higher likelihood.

The two scenarios differ slightly in terms of the decrease in landslide susceptibility: 6.1% of the whole area in the Alternative, and 6.2% in the BAU scenario are projected to experience a decrease in the level of landslide susceptibility. The difference between the scenarios was higher when investigating the areas subject to an increased level of landslide susceptibility (Table 6.6). Here, 4.4% of the total study area in the alternative and 4.1% in the BAU scenario experienced an increase of the level of landslide susceptibility. When looking at regional changes, the alternative scenario resulted in 4068 ha, and the BAU in 5228 ha of net decrease in landslide susceptibility.

Table 6.6 Areas experiencing changes to landslide susceptibility in ha under two 2040 scenarios of forest cover change (Appendix D)

| | Alternative scenario | Business as usual |
|---|---|---|
| Decrease in landslide susceptibility | 14744 | 15060 |
| Increase of landslide susceptibility | 10676 | 9835 |

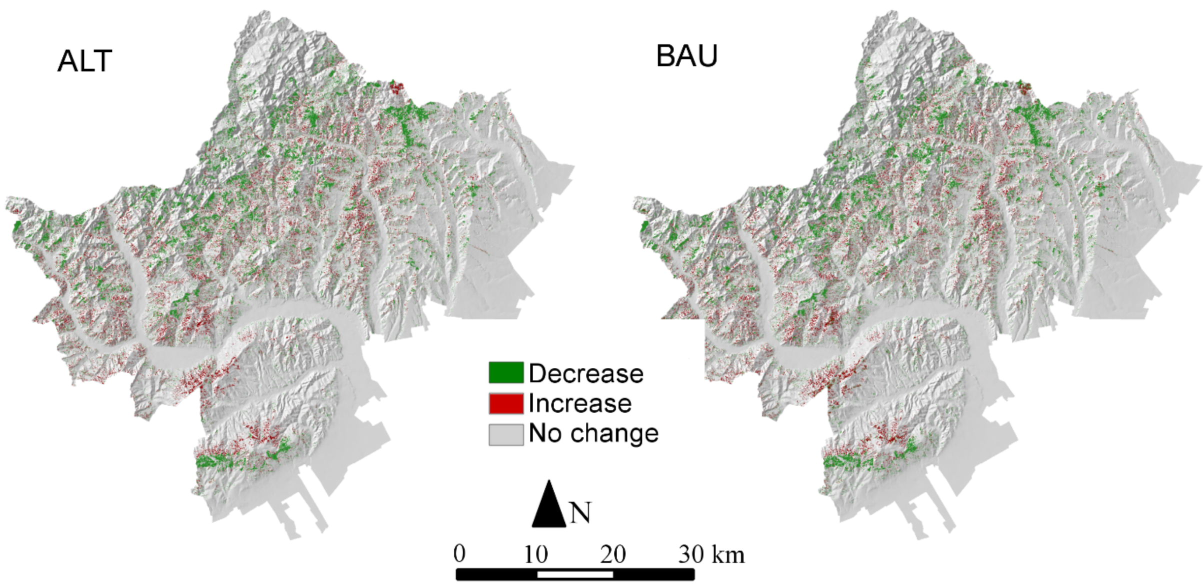


Figure 6.9 Spatial pattern of changes to landslide susceptibility under the 2040 scenarios of future forest cover change (Appendix D)

# 7 Discussion and future perspectives

Individual studies forming this dissertation address different aspects of future land change scenarios: preparation and generation of spatial data, elicitation of stakeholders' knowledge and identification of main driving forces of change, modelling expert based systems of future land change, developing future development scenarios, geospatial modelling of developed scenarios and analysis of potential changes of land changes. The main results are discussed briefly in this section, with a more detailed discussion on each part of the dissertation in the Appendices. The methodology and results are discussed in the context of analysing land changes in European mountain areas. Possible limitations of the proposed methodology, as well as suggested future steps are discussed as well.

The methodology was influenced by the characteristics of the study areas and available data. Both study areas are remote, mountain areas, where most significant driving forces of land change are external and difficult to quantify. Focusing on a single study area could simplify the task or result in a more detailed statistical or agent based model of land change, as these approaches demand more data, time and involvement of stakeholders. Working on two different study areas however enabled the development of a transferrable framework for the development of land change scenarios. Particular approaches (steps of the proposed methodology) could therefore be changed when investigating land changes in additional study areas, depending on the available data, stakeholders involved, or land change processes studied. The focus on meaningful and relevant future scenarios is necessary to generate results that could inform decision making. As this research has shown, such scenarios demand combining participatory and geospatial modelling approaches. This combined approach however results in assumptions and uncertainties deriving from the stakeholders' bias, and the errors in data and the models themselves as discussed in the following sections.

## 7.1 Analysis of land changes and their driving forces

I applied a set of quantitative and qualitative methods in order to understand land changes in two European mountain areas: Italian Alps and Romanian Carpathians. The findings provide new knowledge on the past land changes, their driving forces and consequences of land changes in mountain areas in transition. The results revealed how some processes in the Italian and Romania study areas are in line with other mountainous areas in Europe. The spatial and temporal rate of forest expansion on the account of abandoned grasslands in both study areas is similar to trends of other European mountain areas (Giupponi et al. 2006; J. Kozak et al. 2007; Kuemmerle et al.

2008). Other land change processes can however differ significantly, especially in the observed 20-year period. The Italian study area so witnessed a drastic expansion of urban areas, whereas the Romanian area was subject to local-scale deforestation (Malek et al. 2014).

The qualitative part of the analysis of past changes shows the complexity of the relationship between socio-economic changes as driving forces, and land changes as consequences. The research revealed a mismatch between the perception of stakeholders and the results of the spatial analysis carried out by the researcher (Malek et al. 2014). This mismatch however presented an added value to the spatial result, especially when focusing on the possible causes between land changes in mountain environments.

The methodology for the spatial analysis of past land changes using the available remote sensing data is well acknowledged and has already been applied in numerous other studies (Cocca et al. 2012; Kuemmerle et al. 2008; Václavík and Rogan, 2009; Van Eetvelde and Antrop, 2004). This was due to necessity of generating high-resolution spatial data on land changes, and as well the data provided. Still, the data such as LANDSAT have its deficiencies, especially in terms of mapping built up areas in rural regions and deforestation below the pixel size of 30 m.

The accuracy assessment in this study goes beyond the usual approach of only providing the information on the overall accuracy. It also estimates the errors and provides the information on adjusted areas of land change (Foody, 2002; Olofsson et al. 2013; Stehman, 2009). Thus, the user of the data is informed about the uncertainty in the amount and spatial pattern of land change.

In order to highlight possible causes behind these changes, interviews were performed in both study areas. This way, the issues of unavailable data and external driving forces were addressed in a interdisciplinary manner, as opposed to performing standard statistical tests using available data (Diogo and Koomen, 2010; Giupponi et al. 2006; Millington et al. 2007; Monteiro et al. 2011). By combining different methodologies, the influence of national and European scale policy, and the linkage between external driving forces and local consequences in form of land changes could be addressed. Moreover, the findings demonstrate the necessity of involving stakeholders as experts on local land changes, the driving forces behind them, and their consequences. Studying these changes with only available data might lead to contrasting or unanticipated results. For instance, whereas the relationship between depopulation and land abandonment in the Italian study area could be considered as expected, the parallel significant increase in urban areas needed additional explanation. Also, involving stakeholders provides knowledge on the limitations the stakeholders face when managing land changes and coping with external pressures for land development

(Michetti, 2012; Thapa et al. 2013; Wollenberg et al. 2000). Finally, the findings serve as data on driving forces of land change, and the spatial extent of land changes together with the related uncertainties for both study areas.

The analysis of past changes could be improved by comibing remote sensing with crowd sourcing (or citizen science). Despite usually being applied on a different spatial scale, crowd-sourcing approaches could lead to a generation of a more detailed map of regional land change. Crowd-sourcing has proven to be succesful in mapping land changes, as well as identifying the uncertainties of global data sets (Fritz et al. 2009). It could especially contribute to the identification of local changes such as illegal logging or settlement expansion.

### 7.2 Participatory scenarios of land change

The participatory scenario development methodology started with organising data from stakeholder interviews into conceptual models. These conceptual models were based on the belief system of the involved experts. The participation of stakeholders is so well beyond only providing their vision on future development or estimations on future land changes. In the study, the stakeholders' knowledge was applied in the development of the conceptual model of future land change. Thus, this approach exhibits a higher level of stakeholder participation compared to similar studies on mountain land changes (Giupponi et al. 2006; Promper et al. 2014; Schirpke et al. 2012).

By involving stakeholders and experts from the local and regional spatial planning, development, environment and forestry sector, the methodology behind developing future deforestation rates and spatial demand differs significantly from other similar scale studies on land change. Often, scenarios on future land change are based on statistical extrapolation of past observations (Fuller et al. 2011; Kamusoko et al. 2013; Yanai et al. 2012). In this study, the scenarios were developed using different logic on possible future tourism and forest policy pathways. Tourism scenarios in the Italian Alps were based on regional plans on improving the accommodation infrastructure. In the Carpathians, the scenarios were defined by governmental plans in terms of wood demands and biophysical characteristics of the managed forests.

The scenarios in both study areas focused on a limited set of land change processes. Therefore, they did not address other possible, additional and parallel changes to the land use and land cover (e.g. agricultural changes). Other studies on land change scenarios on mountain areas did study multiple changes at the same time (Balbi et al. 2012; Bayfield et al. 2008). On the other side, my approach enabled a more thorough study of possible plans, desires and options related to identify most significant processes of land change in both study areas. Studies have shown how difficult it is to analyse multiple land use changes in mountain areas, due to the complexity of numerous driving forces (Rutherford et al. 2008).

Moreover, the scenarios developed where considered as plausible by the stakeholders. While this can be considered as a higher degree of likelihood on one side, it prevented the study of more extreme changes to the regional land use and land cover on the other. Possible extreme scenarios are numerous and could be related to sudden policy changes, economic shocks, or disturbances to the local socio-ecological system. For example, the scenarios could only model market demands for forest management, resulting in large scale clear-cutting (Thapa et al. 2013). The influence on new transport infrastructure on future land changes could also be studied (Kamusoko et al. 2013; Maeda et al. 2011). Moreover, this research did not model land changes due to illegal activities such as illegal logging and illegal settlements (Aguilar, 2008; Griffiths et al. 2012). The scenarios could also address sudden political changes, such as the events in Eastern Europe after 1989 (ownership reforms, introduction of a market economy). Possible shocks such as a dramatic wood demand increase or increased migration to mountain regions due to heat waves could also be investigated. The differences between the scenarios were not dramatic, or might seem insignificant from a regional scale due to the high likelihood. Still, the scenarios developed showed, how a set of similar decisions and corresponding futures can lead to different consequences in terms of changes to the risk. Therefore, I believe this approach is particularly significant in providing information on possible changes to hydro-meteorological risk, and the effect of risk related policies.

## 7.3 Geospatial modelling of land change scenarios

The main results of this research are the spatially explicit scenarios for both study areas. The scenarios are presented as possible future changes to the land use and land cover. Past observations, the transition probability map and the cellular automata allocation model enabled the modelling of a realistic pattern of future land changes. Moreover, the approach considered environmental and other spatial characteristics of both study areas such as elevation, slopes, distance to roads… The spatial pattern parameters of all developed scenarios could thus be characterised by a high level of likelihood as also shown by the validation of the model.

CA models however have their limitations. They do not integrate human behaviour and human-environment interactions. CA models do however exhibit a certain degree of randomness and can be integrated with biophysical and spatial factors in order to estimate the location of future land change. Moreover, the neighbourhood effect - allocating future changes near existing cells of a particular land use and land cover class - is considered among the most suitable approaches to model likely changes

(Jokar Arsanjani et al. 2013). Instead of the CA allocation model, other spatially explicit approaches could also be applied, such as logistic regression, agent-based modelling (ABM) or neural networks (Jokar Arsanjani et al. 2013). These approaches however demand more and better data, and can have issues with multi-temporal spatial simulation. Nevertheless, ABM could upgrade the DPSIR model, as it can model agent (human) behaviour. Combining the CA approach with ABM could still result in spatially explicit results, thus further improving this research.

The research also provides information on uncertainty, where the uncertainties of both the land use and land cover data, as well on the allocation model are addressed. This is especially useful when using future land change scenarios for decision support (Veldkamp and Lambin, 2001; Verburg et al. 2004). Improving the model with better data (higher spatial and temporal resolution) would indeed result in lowering the uncertainties of this scenario-based approach. On the example of the Romanian study area, detailed data on the biological characteristics of the forest could improve the model significantly. In this case, the spatial allocation model could be combined with a more elaborate biomass or wood increment model. In the Italian study area, the success rate of the model could be improved with additional data on exact tourism related urban expansion. This data would differentiate more between residential, and tourism and recreation infrastructure. Also, due to lack of data, only two type of tourism accommodation were addressed: hotel resorts and individual tourism objects. These two categories could have been differentiated into more categories with different spatial demands: lower and higher class hotel resorts, lodges and chalets, spa, sport and conference centres, etc. Considering the uncertainty of the approach, it should not be used for predicting or projecting exact locations of future land change. The uncertainties when simulating land changes on a pixel basis (exact location) are too high, also due to the uncertainty of the data applied. The approach is however useful to compare spatial consequences of different scenarios, which are based on the same environmental and spatial conditions.

### 7.4 Assessment of changes

This study expands the applicability of land change modelling in hydro-meteorological risk and ecosystem services studies. Moreover, it provides new insight on potential future changes to Carpathian and Alpine socio-ecological systems.

Potential consequences due to future land changes in the Carpathian and Alpine region are understudied. Also, general approaches on spatially explicit analysis of changes to ecosystem provision area rare (Burkhard et al. 2012, 2010). The values of the changes are based on expert opinion, remote sensing or geostatistical modelling. This study does not model the past, current and future state of hydro-meteorological risk, the landscape or provision of ecosystem services. Instead of this, it focuses only on potential changes to risk, landscape and ecosystem services provision. These changes were quantified either as the amount of land changes occurring in risk areas, or as losses or gains to a particular ecosystem service (Appendices C, D). This differs from the usual assessment of the existing risk or the ability of the landscape to provide ecosystem services (Burkhard et al. 2012; Egoh et al. 2008; Grêt-Regamey et al. 2008; Nedkov and Burkhard, 2012; Troy and Wilson, 2006).

The spatially explicit approach applied however has its deficiencies. On the example of the Romanian study area, the values of ecosystem services are considered as homogeneous across the landscape. This means there are no areas where the forest could provide more wood, or grasslands more biodiversity compared to any other area in the study region. This assumption on the evenly distributed provision of ecosystem services is due to the lack of spatially distributed data. The data on risk (landslide risk in Romania and hydro-meteorological risk in Italy) was spatially distributed, thus providing information on the location of areas where changes could result in a risk increase. Using a spatially explicit approach, this research suggests hot-spots of potential degradation of risk, landscape or ecosystem services. Moreover, maps have been recognized as an effective way of communication environmental changes (Sui and Maggio, 1999).

Additional research involving climate changes, hazard and ecosystem modelling could result in more detailed results in terms of consequences of land change scenarios. On the example of hydro-meteorological risk, an analysis of the financial aspects of the projected increase in elements at risk due to urban expansion is also suggested. This way the changes to the elements at risk would be studied more thoroughly, as changes to the financial values are also an important part when investigating risk.

# 8 Key innovations of the research

This section presents the contribution of this dissertation to land change / land systems science and research on mountain areas.

The first step of the research was the analysis of past land changes and driving forces in the two study areas. It contributed to the knowledge of how socio-economic changes in regions in transition can influence land changes. The novelty of the approach lies in the combined quantitative and qualitative approach. Using remote sensing and GIS techniques to observe past changes is an established approach, which however usually does not address the reasons behind these changes. The driving forces of land changes in areas in a socio-economic transition are difficult to study due to the lack of data and complexity of these issues. Besides, mountain areas are regions where the prevailing driving forces of land change can be external, and therefore not obvious when investigating them with available statistical data. The qualitative part of the research (interviews) therefore helped to understand the causes behind land changes in these two areas in more detail. Moreover, the research showed the differences between the observations on land changes by the researcher and the perceptions of the stakeholders – these differences are usually not addressed. It also revealed the driving forces of land change, which cannot be handled by the local decision makers and can thus result in land management difficulties.

The second step was the participatory development of scenarios. Involving stakeholders by performing interviews, discussions and workshops has become an established method in scenario development. Their involvement is however usually limited with providing their visions on future plans or amounts of land change. This research aimed at a higher level of stakeholder involvement. By developing expert based belief systems – cognitive maps – stakeholders' knowledge shaped the conceptual models and the individual components of the spatial allocation models developed in the subsequent steps. Supported by local knowledge, the whole modelling procedure and the resulting scenarios could therefore be considered as more plausible and relevant for the stakeholders. Moreover, the approach identified the possible set of options the local and regional stakeholders have to manage potential future land changes and their consequences.

The spatial allocation of scenarios using GIS and geosimulation followed. The spatial simulation approach applied in this research was embedded in the participatory-geosimulation framework. This way, the developed future storylines were translated to spatially explicit scenarios that took into account local scale specific environmental and spatial characteristics. The approach can be replaced by a different spatial allocation procedure in case different data (more or less data available) or processes are studied.

The cellular automata allocation algorithm calibrated with past observations and physical-geographic characteristics also resulted in a study area specific and more realistic spatial pattern of change. Pure CA models fail to capture the amount of future land change as a consequence of future human decision and socio-economic development. Combining spatial simulation models such as CA with participatory scenario development can however improve the relevancy and likelihood of the simulation. The applied approach also provides the information on the uncertainty of the model. When modelling future scenarios, this information is often omitted. Scenarios are based on future assumptions and are usually presented as creative visions of the future. Still, providing the information on the success rate of the model taking into account both the uncertainty of the data and the model, improves the transparency of the simulation. This way, it is clear that spatial simulation (at this stage) cannot be used for prediction of exact locations of land change. Due to the relatively high likelihood of capturing the spatial pattern of future changes, it can however be applied for identifying hot-spots of change (e.g. particular catchments or slope classes) or comparing different future scenarios and evaluating decisions.

The GIS assessment part of the dissertation presents both the possible consequences of future land changes as well as the applicability of the proposed scenario development framework. As discussed in the previous section spatially explicit studies of environmental consequences of future development are rare. Like the spatial allocation step, the assessment part was also shaped by the characteristics of the study areas and data available. This way it demonstrated the possibility to evaluate different scenarios in terms of consequences for the provision of ecosystem services, or changes to landscape and hydro-meteorological risk. Moreover, the resulting maps of future distributions of consequences of land changes can help to communicate the potential consequences of future land changes.

Finally, the methodology presented in this dissertation is novel in the way that it was developed and applied in two different study areas. Both are mountain areas with complex socio-economic and physical geographic characteristics, and are subject to hydro-meteorological risk. They are however experiencing different processes of land change and are characterised by different data availability. Other studies on future land change in the mountains have developed approaches with better estimated performance of the spatial simulation (Schirpke et al. 2012). Still, those approaches are usually tailor made for specific study areas and thus not transferable to other regions.

# 9 German and English Summary

## 9.1 Zusammenfassung

Diese Studie präsentiert die Methodik und Ergebnisse hinter der Entwicklung von räumlich-expliziten Zukunftsszenarien für Landnutzungs- und Bodenbedeckungs-Änderungen. Um die Übertragbarkeit auf andere Untersuchungsgebiete zu demonstrieren, wurde die Methode auf zwei Gebirgsregionen angewendet: die Italienischen Alpen und die Rumänischen Karpathen.

Aufgrund der großen Unsicherheiten in Bezug auf die Verfügbarkeit von Daten und der Modellierung in die Zukunft wurde eine partizipative Modellierung unter Einbeziehung der lokalen Akteure und Experten für die Entwicklung von Szenarien vorgeschlagen. Darüber hinaus, um das Potenzial der Landnutzungsänderungs-Szenarien bei der Entscheidungsfindung zu nutzen, wurde diese mit einem räumlich-expliziten Landnutzungsänderung-Modell kombiniert. Somit wurde eine Vielzahl von verschiedenen Methoden aus verschiedenen Bereichen angewandt: qualitative Methoden wie Interviews, Analysen der Wahrnehmung von Stakeholdern und kognitive Kartierung (Cognitive Mapping), in Kombination mit quantitativen Methoden wie Klassifizierung von Fernerkundungsdaten, Raumanalyse mit geografischen Informationssystemen (GIS) und geostatistischen Methoden mit zellulare Automaten Algorithmen. Auf diese Weise konnten Bereiche mit signifikanten Landnutzungsänderungen und deren möglichen negativen Auswirkungen identifiziert werden. Darüber hinaus wurde eine Kombination aus partizipativer Szenario-Entwicklung und räumlich expliziter Modellierung als eine Möglichkeit identifiziert, plausible räumlich explizite Szenarien mit höherer Wahrscheinlichkeit und Relevanz für die Stakeholder zu generieren.

Die Ergebnisse liefern Informationen über mögliche Zukunftsszenarien in den europäischen Gebirgsregionen. Im Fall des italienischen Untersuchungsgebietes wurde eine Zunahme bebauter Gebiete durch Tourismus als wahrscheinlich projiziert. Diese kann zu einer Erhöhung des Risikos führen. Zwei Szenarien - mit Schwerpunkt auf kleinen Tourismus- und Hotelanlagen - wurden modelliert. Die Szenarien zeigen, dass eine mehr zufällige und im Raum verstreute Expansion städtischer Gebiete einen größeren Einfluss auf die Landschaft und das Risiko auf regionaler Ebene hat, während die größeren Tourismus Resorts einen größeren Einfluss auf lokaler Ebene haben. In Rumänien wurde eine Zunahme der Abholzung projiziert. Obwohl räumlich nicht signifikant (prozentualer Anteil der entwaldeten Fläche), deuten die Ergebnisse auf wesentliche Änderungen der Erdrutschgefahr auf lokaler Ebene hin. Obwohl das Modell nicht die exakten Lokationen der zukünftigen Landänderungen projizieren kann, kann es Entscheidungsträgern durch Informationen über mögliche Umweltschäden oder

Änderungen des Risikos aus den verschiedenen Szenarien unterstützen.

Diese Arbeit hat Interessengruppen bei der Entwicklung eines Landnutzungsänderungsmodells involviert, speziell im Hinblick auf die Identifizierung der Ursachen dieses Wandels. Somit präsentiert die Arbeit einen neuen Ansatz, um die Mängel der räumlich expliziten Modelle zu überwinden und um die Beziehung zwischen diesen Ursachen und der räumlichen Muster der Änderungen zu erfassen.

## 9.2 Summary

This study presents the methodology and results for the development of spatially explicit future scenarios of land use and land cover change. In order to demonstrate its transferability to other study areas, the method was applied in two mountainous study areas: Italian Alps and Romanian Carpathians.

Due to large uncertainties regarding data availability and future modelling, participatory modelling involving local stakeholders and experts was proposed for the development of scenarios. Moreover, to utilise the potential of land change scenarios in decision making, participatory modelling was combined with a spatially explicit land change model. Thus, a variety of different methods from different domains were applied: qualitative methods such as interviews, analysis of stakeholders' perception, and cognitive mapping, combined with quantitative methods such as classification of remote sensing imagery, spatial analysis using geographic information systems (GIS), and geostatistical methods with a cellular automata algorithm. This way, areas expecting more land changes and potential negative consequences could be identified. Furthemore, combining participatory scenario development with spatially explicit modelling has been identified as a way to generate plausible spatially explicit scenarios with a higher degree of relevance for the stakeholders.

The results provide information on possible future development of European mountain areas. In the case of the Italian study area, a likely expansion of built up areas due to tourism development was projected. This can lead to an increase of elements at risk. Two scenarios – focusing on small scale tourism and hotel resorts – were modelled. The scenarios show that more random urban expansion scattered across the landscape has a bigger impact on landscape and risk on a regional scale, whereas bigger tourism resorts have a bigger impact on a local scale. In Romania, an increase in deforestation was projected. Though not significant in spatial terms (% of areas affected by deforestation), the results imply a significant increase to the landslide hazard on a local scale. Although the model cannot project exact locations of future land changes, it can inform decision makers with potential environmental degradation or changes to risk of different scenarios.

This research involved stakeholders in the development of a land change model, especially in terms of the identification of driving forces of change. Thus, it presents a novel approach to overcome the shortcomings of spatially explicit models to capture the relationships between driving forces and the spatial pattern of change.

# 10 References

Abildtrup, J., Audsley, E., Fekete-Farkas, M., Giupponi, C., Gylling, M., Rosato, P., Rounsevell, M., 2006. Socio-economic scenario development for the assessment of climate change impacts on agricultural land use: a pairwise comparison approach. Environmental Science & Policy 9, 101–115. doi:10.1016/j.envsci.2005.11.002

Agarwal, C., Green, G.M., Grove, J.M., Evans, T.P., Schweik, C., 2002. A review and assessment of land-use change models: dynamics of space, time, and human choice. Gen. Tech. Rep. NE-297. Newton Square, PA: US Department of Agriculture, Northeastern Research Station 61.

Aguilar, A.G., 2008. Peri-urbanization, illegal settlements and environmental impact in Mexico City. Cities 25, 133–145. doi:10.1016/j.cities.2008.02.003

Arscott, D.B., Tockner, K., Nat, D. van der, Ward, J.V., 2002. Aquatic Habitat Dynamics along a Braided Alpine River Ecosystem (Tagliamento River, Northeast Italy). Ecosystems 5, 802–814.

Axelrod, R.M., 1976. Structure of Decision: The Cognitive Maps of Political Elites, 1st Paperback Edition edition. ed. Princeton University Press, Princeton, N.J.

Balbi, S., Giupponi, C., Perez, P., Alberti, M., 2012. A spatial agent-based model for assessing strategies of adaptation to climate and tourism demand changes in an alpine tourism destination. Environmental Modelling & Software 45, 29–51. doi:10.1016/j.envsoft.2012.10.004

Balmford, A., Bruner, A., Cooper, P., Costanza, R., Farber, S., Green, R.E., Jenkins, M., Jefferiss, P., Jessamy, V., Madden, J., Munro, K., Myers, N., Naeem, S., Paavola, J., Rayment, M., Rosendo, S., Roughgarden, J., Trumper, K., Turner, R.K., 2002. Economic Reasons for Conserving Wild Nature. Science 297, 950 – 953. doi:10.1126/science.1073947

Bălteanu, D., Popovici, E.A., 2010. Land use changes and land degradation in post-socialist Romania. Romanian Journal of Geography 54, 95–105.

Barredo, J.I., Engelen, G., 2010. Land Use Scenario Modeling for Flood Risk Mitigation. Sustainability 2, 1327–1344. doi:10.3390/su2051327

Bätzing, W., 2005. Die Alpen: Geschichte und Zukunft einer europäischen Kulturlandschaft. C.H.Beck, München.

Baumann, M., Kuemmerle, T., Elbakidze, M., Ozdogan, M., Radeloff, V.C., Keuler, N.S., Prishchepov, A.V., Kruhlov, I., Hostert, P., 2011. Patterns and drivers of post-socialist farmland abandonment in Western Ukraine. Land Use Policy 28, 552–562. doi:10.1016/j.landusepol.2010.11.003

Bayfield, N., Barancok, P., Furger, M., Sebastià, M.T., Domínguez, G., Lapka, M., Cudlinova, E., Vescovo, L., Ganielle, D., Cernusca, A., Tappeiner, U., Drösler, M., 2008. Stakeholder Perceptions of the Impacts of Rural Funding Scenarios on Mountain Landscapes Across Europe. Ecosystems 11, 1368–1382. doi:10.1007/s10021-008-9197-1

Beierle, T.C., Cayford, J., 2002. Democracy in Practice: Public Participation in Environmental Decisions. Resources for the Future, Washington, DC.

Bender, O., Borsdorf, A., Fischer, A., Stotter, J., 2011. Mountains Under Climate and Global Change Conditions – Research Results in the Alps, in: Blanco, J.A. (Ed.), Climate Change - Geophysical Foundations and Ecological Effects. InTech, Rijeka.

Bonham-Carter, G., 1994. Geographic information systems for geoscientists: modelling with GIS. Pergamon, Oxford; New York.

Borga, M., Boscolo, P., Zanon, F., Sangati, M., 2007. Hydrometeorological Analysis of the 29 August 2003 Flash Flood in the Eastern Italian Alps. Journal of Hydrometeorology 8, 1049–1067. doi:10.1175/JHM593.1

Breuer, L., Huisman, J.A., Willems, P., Bormann, H., Bronstert, A., Croke, B.F.W., Frede, H.-G., Gräff, T., Hubrechts, L., Jakeman, A.J., Kite, G., Lanini, J., Leavesley, G., Lettenmaier, D.P., Lindström, G., Seibert, J., Sivapalan, M., Viney, N.R., 2009. Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM). I: Model intercomparison with current land use. Advances in Water Resources 32, 129–146. doi:10.1016/j.advwatres.2008.10.003

Briner, S., Elkin, C., Huber, R., Grêt-Regamey, A., 2012. Assessing the impacts of economic and climate changes on land-use in mountain regions: A spatial dynamic modeling approach. Agriculture, Ecosystems & Environment 149, 50–63. doi:10.1016/j.agee.2011.12.011

Brown, D.G., Verburg, P.H., Pontius Jr, R.G., Lange, M.D., 2013. Opportunities to improve impact, integration, and evaluation of land change models. Current Opinion in Environmental Sustainability, Human settlements and industrial systems 5, 452–457. doi:10.1016/j.cosust.2013.07.012

Bürgi, M., Hersperger, A.M., Schneeberger, N., 2004. Driving forces of landscape change – current and new directions. Landscape Ecology 19, 857–868. doi:10.1007/s10980-004-0245-8

Burkhard, B., Kroll, F., Müller, F., 2010. Landscapes‘ Capacities to Provide Ecosystem Services – a Concept for Land-Cover Based Assessments. Landscape Online 1–22. doi:10.3097/LO.200915

Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012. Mapping ecosystem service supply, demand and budgets. Ecological Indicators 21, 17–29. doi:10.1016/j.ecolind.2011.06.019

Campbell, D.J., Lusch, D.P., Smucker, T.A., Wangui, E.E., 2005. Multiple Methods in the Study of Driving Forces of Land Use and Land Cover Change: A Case Study of SE Kajiado District, Kenya. Human Ecology 33, 763–794. doi:10.1007/s10745-005-8210-y

Castella, J.-C., Trung, T.N., Boissau, S., 2005. Participatory simulation of land-use changes in the northern mountains of Vietnam: the combined use of an agent-based model, a role-playing game, and a geographic information system. Ecol Soc 10, 27.

Ceschia, M., Micheletti, S., Carniel, R., 1991. Rainfall over Friuli-Venezia Giulia: High amounts and strong geographical gradients. Theoretical and Applied Climatology 43, 175–180.

Chemini, C., Rizzoli, A., 2003. Land use change and biodiversity conservation in the Alps. Journal of mountain ecology 7, 1–7.

Cocca, G., Sturaro, E., Gallo, L., Ramanzin, M., 2012. Is the abandonment of traditional livestock farming systems the main driver of mountain landscape change in Alpine areas? Land Use Policy 29, 878–886.

Cremene, C., Groza, G., Rakosy, L., Schileyko, A.A., Baur, A., Erhardt, A., Baur, B., 2005. Alterations of Steppe-Like Grasslands in Eastern Europe: a Threat to Regional Biodiversity Hotspots. Conservation Biology 19, 1606–1618.

Cucchi, F., Piano, C., Marinetti, E., Massari, G., Oberti, S., Zini, L., 2000. Studies For The Realization Of The Hydrogeological Map Of Friuli-Venezia Giulia. IPOGEA 3, 57 – 71.

Daconto, G., Sherpa, L.N., 2010. Applying Scenario Planning to Park and Tourism Management in Sagarmatha National Park, Khumbu, Nepal. Mountain Research and Development 30, 103–112. doi:10.1659/MRD-JOURNAL-D-09-00047.1

Dalla Valle, E., Lamedica, S., Pilli, R., Anfodillo, T., 2009. Land Use Change and Forest Carbon Sink Assessment in an Alpine Mountain Area of the Veneto Region (Northeast Italy). Mountain Research and Development 29, 161–168.

De Almeida, C.M., Batty, M., Vieira Monteiro, A.M., Câmara, G., Soares-Filho, B.S., Cerqueira, G.C., Pennachin, C.L., 2003. Stochastic cellular automata modeling of urban land use dynamics: empirical development and estimation. Computers, Environment and Urban Systems 27, 481–509. doi:10.1016/S0198-9715(02)00042-X

De Marchi, B., Scolobig, A., Delli Zotti, G., Del Zotto, M., 2007. Risk construction and social vulnerability in an Italian Alpine Region. FLOODsite Project Report.

Deshler, D., 1987. Techniques for generating futures perspectives. New Directions for Adult and Continuing Education 1987, 79–92. doi:10.1002/ace.36719873609

Diogo, V., Koomen, E., 2010. Explaining land-use changes in Portugal 1990-2000, in: Painho, M., Santos, M.Y., Pundt, H. (Eds.), Geospatial Thinking. Presented at the AGILE, Guimaraes, Portugal.

Dutcă, I., Abrudan, I., 2010. Estimation of forest land-cover change in Romania, between 1990 and 2006. Bulletin of the Transilvania University of Braşov• Vol 3, 52.

EASAC, 2009. Ecosystem services and biodiversity in Europe. European Academies Science Advisory Council, The Royal Society, London.

Eden, C., 1992. On the Nature of Cognitive Maps. Journal of Management Studies 29, 261–265. doi:10.1111/j.1467-6486.1992.tb00664.x

EEA, 1999. Environmental indicators: Typology and overview. European Environment Agency, Copenhagen.

EEA, 2007. Land-use scenarios for Europe: Qualitative and quantitative analysis on a European scale (PRELUDE). Technical report. European Environmental Agency, Copenhagen.

Egoh, B., Reyers, B., Rouget, M., Richardson, D.M., Le Maitre, D.C., van Jaarsveld, A.S., 2008. Mapping ecosystem services for planning and management. Agriculture, Ecosystems & Environment 127, 135–140. doi:10.1016/j.agee.2008.03.013

Engelen, G., White, R., Uljee, I., Drazan, P., 1995. Using cellular automata for integrated modelling of socio-environmental systems. Environmental Monitoring and Assessment 34, 203–214. doi:10.1007/BF00546036

Erdeli, G., Dinca, A.I., 2011. Tourism – A vulnerable strength in the protected areas of the Romanian Carpathians. Procedia - Social and Behavioral Sciences 19, 190–197.

Falcucci, A., Maiorano, L., Ciucci, P., Garton, E.O., Boitani, L., 2008. Land-cover change and the future of the Apennine brown bear: a perspective from the past. Journal of Mammalogy 89, 1502–1511. doi:10.1644/07-MAMM-A-229.1

Fischlin, A., Midgley, G.F., Price, J., Leemans, R., Gopal, B., Turley, C., 2007. Chapter 4: Ecosystems, their properties, Goods and Services, in: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge University Press.

Foody, G.M., 2002. Status of land cover classification accuracy assessment. Remote sensing of environment 80, 185–201.

Fritz, S., McCallum, I., Schill, C., Perger, C., Grillmayer, R., Achard, F., Kraxner, F., Obersteiner, M., 2009. Geo-Wiki.Org: The Use of Crowdsourcing to Improve Global Land Cover. Remote Sensing 1, 345–354. doi:10.3390/rs1030345

Fuller, D.O., Hardiono, M., Meijaard, E., 2011. Deforestation Projections for Carbon-Rich Peat Swamp Forests of Central Kalimantan, Indonesia. Environmental Management 48, 436–447. doi:10.1007/s00267-011-9643-2

Gellrich, M., Baur, P., Koch, B., Zimmermann, N.E., 2007. Agricultural land abandonment and natural forest re-growth in the Swiss mountains: A spatially explicit economic analysis. Agriculture, Ecosystems & Environment 118, 93–108. doi:10.1016/j.agee.2006.05.001

Giupponi, C., Ramanzin, M., Sturaro, E., Fuser, S., 2006. Climate and land use changes, biodiversity and agri-environmental measures in the Belluno province, Italy. Environmental Science & Policy 9, 163–173. doi:10.1016/j.envsci.2005.11.007

Glade, T., 2003. Landslide occurrence as a response to land use change: a review of evidence from New Zealand. Catena 51, 297–314. doi:10.1016/S0341-8162(02)00170-4

Glade, T., Crozier, M.J., 2005. The Nature of Landslide Hazard Impact, in: Glade, T., Anderson, M., Crozier, M.J. (Eds.), Landslide Hazard and Risk. John Wiley & Sons, Ltd, pp. 41–74.

Grêt-Regamey, A., Bebi, P., Bishop, I.D., Schmid, W.A., 2008. Linking GIS-based models to value ecosystem services in an Alpine region. Journal of Environmental Management 89, 197–208. doi:10.1016/j.jenvman.2007.05.019

Griffiths, P., Kuemmerle, T., Baumann, M., Radeloff, V.C., Abrudan, I.V., Lieskovsky, J., Munteanu, C., Ostapowicz, K., Hostert, P., 2014. Forest disturbances, forest recovery, and changes in forest types across the Carpathian ecoregion from 1985 to 2010 based on Landsat image composites. Remote Sensing of Environment, Special Issue on 2012 ForestSAT 151, 72–88. doi:10.1016/j.rse.2013.04.022

Griffiths, P., Kuemmerle, T., Kennedy, R.E., Abrudan, I.V., Knorn, J., Hostert, P., 2012. Using annual time-series of Landsat images to assess the effects of forest restitution in post-socialist Romania. Remote Sensing of Environment 118, 199–214. doi:10.1016/j.rse.2011.11.006

Gustafson, E.J., 1998. Quantifying Landscape Spatial Pattern: What Is the State of the Art? Ecosystems 1, 143–156. doi:10.1007/s100219900011

Hagen, A., 2003. Fuzzy set approach to assessing similarity of categorical maps. International Journal of Geographical Information Science 17, 235–249. doi:10.1080/13658810210157822

Hessel, R., Messing, I., Liding, C., Ritsema, C., Stolte, J., 2003. Soil erosion simulations of land use scenarios for a small Loess Plateau catchment. Catena 54, 289–302. doi:10.1016/S0341-8162(03)00070-5

Hughes, N., 2013. Towards improving the relevance of scenarios for public policy questions: A proposed methodological framework for policy relevant low carbon scenarios. Technological Forecasting and Social Change, Scenario Method: Current developments in theory and practice 80, 687–698. doi:10.1016/j.techfore.2012.07.009

Hughes, N., Strachan, N., 2010. Methodological review of UK and international low carbon scenarios. Energy Policy, The socio-economic transition towards a hydrogen economy - findings from European research, with regular papers 38, 6056–6065. doi:10.1016/j.enpol.2010.05.061

Hussin, H., Zumpano, V., Sterlacchini, S., Reichenbach, P., Bãlteanu, D., Micu, M., Bordogna, G., Cugini, M., 2013. Comparing the predictive capability of landslide susceptibility models in three different study areas using the Weights of Evidence technique, in: EGU General Assembly Conference Abstracts. Presented at the EGU General Assembly 2013, Vienna, p. 12701.

INSSE, 2013. Romanian National Institute of Statistics Data Portal [WWW Document]. URL http://www.insse.ro/ (accessed 5.11.13).

Instituto Nazionale della Montagna, 2007. Atlante Statistico Della Montagna Italiana. Bononia University Press, Bologna.

Institutul Naţional de Statistică, 2011. INS: Direcţia Judeţeană Buzău [WWW Document]. URL http://www.buzau.insse.ro/main.php (accessed 12.15.11).

Ioras, F., Abrudan, I.., 2006. The Romanian forestry sector: privatisation facts. International Forestry Review 8, 361–367. doi:10.1505/ifor.8.3.361

Jacobs, K., Lebel, L., Buizer, J., Addams, L., Matson, P., McCullough, E., Garden, P., Saliba, G., Finan, T., 2010. Linking knowledge with action in the pursuit of sustainable water-resources management. PNAS 200813125. doi:10.1073/pnas.0813125107

Jokar Arsanjani, J., Helbich, M., Kainz, W., Darvishi Boloorani, A., 2013. Integration of logistic regression, Markov chain and cellular automata models to simulate urban expansion. International Journal of Applied Earth Observation and Geoinformation 21, 265–275. doi:10.1016/j.jag.2011.12.014

Kamusoko, C., Wada, Y., Furuya, T., Tomimura, S., Nasu, M., Homsysavath, K., 2013. Simulating Future Forest Cover Changes in Pakxeng District, Lao People's Democratic Republic (PDR): Implications for Sustainable Forest Management. Land 2, 1–19. doi:10.3390/land2010001

Kassa, H., Campbell, B., Sandewall, M., Kebede, M., Tesfaye, Y., Dessie, G., Seifu, A., Tadesse, M., Garedew, E., Sandewall, K., 2009. Building future scenarios and uncovering persisting challenges of participatory forest management in Chilimo Forest, Central Ethiopia. Journal of Environmental Management 90, 1004–1013. doi:10.1016/j.jenvman.2008.03.009

Kepner, W.G., Ramsey, M.M., Brown, E.S., Jarchow, M.E., Dickinson, K.J.M., Mark, A.F., 2012. Hydrologic futures: using scenario analysis to evaluate impacts of forecasted land use change on hydrologic services. Ecosphere 3, art69. doi:10.1890/ES11-00367.1

Knorn, J., Kuemmerle, T., Radeloff, V.C., Keeton, W.S., Gancz, V., Biriş, I.A., Svoboda, M., Griffiths, P., Hagatis, A., Hostert, P., 2012a. Continued loss of temperate old-growth forests in the Romanian Carpathians despite an increasing protected area network. Environmental Conservation FirstView, 1–12.

Knorn, J., Kuemmerle, T., Radeloff, V.C., Szabo, A., Mindrescu, M., Keeton, W.S., Abrudan, I., Griffiths, P., Gancz, V., Hostert, P., 2012b. Forest restitution and protected area effectiveness in post-socialist Romania. Biological Conservation 146, 204–212. doi:10.1016/j.biocon.2011.12.020

Koellner, T., 2009. Supply and demand for ecosystem services in mountainous regions. Alpine Space - Man & Environment 7: Global Change and Sustainable Development in Mountain Regions, 61–70.

Koh, L.P., Ghazoul, J., 2010. Spatially explicit scenario analysis for reconciling agricultural expansion, forest protection, and carbon conservation in Indonesia. PNAS 107, 11140–11144. doi:10.1073/pnas.1000530107

Kok, K., 2009. The potential of Fuzzy Cognitive Maps for semi-quantitative scenario development, with an example from Brazil. Global Environmental Change 19, 122–133. doi:10.1016/j.gloenvcha.2008.08.003

Kooistra, L., Wamelink, W., Schaepman-Strub, G., Schaepman, M., van Dobben, H., Aduaka, U., Batelaan, O., 2008. Assessing and predicting biodiversity in a floodplain ecosystem: Assimilation of net primary production derived from imaging spectrometer data into a dynamic vegetation model. Remote Sensing of Environment 112, 2118–2130. doi:10.1016/j.rse.2007.10.010

Koomen, E., Stillwell, J., 2007. Modelling Land-Use Change, in: Koomen, E., Stillwell, J., Bakema, A., Scholten, H.J. (Eds.), Modelling Land-Use Change, GeoJournal Library. Springer Netherlands, pp. 1–22.

Körner, C., Spehn, E., Ohsawa, M., Berge, E., Bugmann, H., Groombridge, B., Hamilton, L., Hofer, T., Ives, J., Jodha, N., 2005. Mountain Systems, in: Ecosystems and Human Well-Being: Current State and Trends: Findings of the Condition and Trends Working Group of the Millennium Ecosystem Assessment. pp. 681–716.

Kozak, J., Estreguil, C., Troll, M., 2007. Forest cover changes in the northern Carpathians in the 20th century: a slow transition. Journal of Land Use Science 2, 127–146. doi:10.1080/17474230701218244

Kozak, J., Estreguil, C., Vogt, P., 2007. Forest cover and pattern changes in the Carpathians over the last decades. Eur J Forest Res 126, 77–90. doi:10.1007/s10342-006-0160-4

Kräuchi, N., Brang, P., Schönenberger, W., 2000. Forests of mountainous regions: gaps in knowledge and research needs. Forest Ecology and Management 132, 73–82.

Kriegler, E., 2010. Socioeconomic Scenario Development for Climate Change Analysis.

Kriegler, E., O'Neill, B.C., Hallegatte, S., Kram, T., Lempert, R.J., Moss, R.H., Wilbanks, T., 2012. The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. Global Environmental Change 22, 807–822. doi:10.1016/j.gloenvcha.2012.05.005

Kuemmerle, T., Chaskovskyy, O., Knorn, J., Radeloff, V.C., Kruhlov, I., Keeton, W.S., Hostert, P., 2009. Forest cover change and illegal logging in the Ukrainian Carpathians in the transition period from 1988 to 2007. Remote Sensing of Environment 113, 1194–1207.

Kuemmerle, T., Hostert, P., Radeloff, V.C., Perzanowski, K., Kruhlov, I., 2007. Post-socialist forest disturbance in the Carpathian border region of Poland, Slovakia, and Ukraine. Ecological Applications 17, 1279–1295.

Kuemmerle, T., Müller, D., Griffiths, P., Rusu, M., 2008. Land use change in Southern Romania after the collapse of socialism. Regional Environmental Change 9, 1–12. doi:10.1007/s10113-008-0050-z

Lambin, E.F., Geist, H., 2006. Land-use and land-cover change: local processes and global impacts. Springer, Berlin, Heidelberg.

Lesschen, J.P., Verburg, P.H., Staal, S.J., 2005. Statistical methods for analysing the spatial dimension of changes in land use and farming systems, LUCC Report Series No. 7. ILRI & LUCC Focus 3 Office, Nairobi, Kenya & Wageningen, The Netherlands.

MacDonald, D., Crabtree, J.., Wiesinger, G., Dax, T., Stamou, N., Fleury, P., Gutierrez Lazpita, J., Gibon, A., 2000. Agricultural abandonment in mountain areas of Europe: Environmental consequences and policy response. Journal of Environmental Management 59, 47–69. doi:10.1006/jema.1999.0335

Maeda, E.E., Clark, B.J.F., Pellikka, P., Siljander, M., 2010. Modelling agricultural expansion in Kenya's Eastern Arc Mountains biodiversity hotspot. Agricultural Systems 103, 609–620. doi:10.1016/j.agsy.2010.07.004

Maeda, E.E., de Almeida, C.M., de Carvalho Ximenes, A., Formaggio, A.R., Shimabukuro, Y.E., Pellikka, P., 2011. Dynamic modeling of forest conversion: Simulation of past and future scenarios of rural activities expansion in the fringes of the Xingu National Park, Brazilian Amazon. International Journal of Applied Earth Observation and Geoinformation 13, 435–446. doi:10.1016/j.jag.2010.09.008

Malek, Ž., Glade, T., Boerboom, L.G.J., Under review. Future forest cover change under a set of forest policy scenarios: An example from Buzau Subcarpathians, Romania. Regional Environmental Change.

Malek, Ž., Scolobig, A., Schröter, D., 2014. Understanding Land Cover Changes in the Italian Alps and Romanian Carpathians Combining Remote Sensing and Stakeholder Interviews. Land 3, 52–73. doi:10.3390/land3010052

Mendoza, G.A., Prabhu, R., 2006. Participatory modeling and analysis for sustainable forest management: Overview of soft system dynamics models and applications. Forest Policy and Economics 9, 179–196. doi:10.1016/j.forpol.2005.06.006

Messerli, P., Heinimann, A., Giger, M., Breu, T., Schönweger, O., 2013. From "land grabbing" to sustainable investments in land: potential contributions by land change science. Current Opinion in Environmental Sustainability, Human settlements and industrial systems 5, 528–534. doi:10.1016/j.cosust.2013.03.004

Metcalf, S.S., Wheeler, E., BenDor, T.K., Lubinski, K.S., Hannon, B.M., 2010. Sharing the floodplain: Mediated modeling for environmental management. Environmental Modelling & Software 25, 1282–1290. doi:10.1016/j.envsoft.2008.11.009

Metzger, M.J., Rounsevell, M.D.A., Acosta-Michlik, L., Leemans, R., Schröter, D., 2006. The vulnerability of ecosystem services to land use change. Agriculture, Ecosystems & Environment 114, 69–85. doi:10.1016/j.agee.2005.11.025

Meyer, W.B., Turner, B.L., 1994. Changes in land use and land cover: a global perspective. Cambridge University Press.

Michetti, M., 2012. Modelling Land Use, Land-Use Change, and Forestry in Climate Change: A Review of Major Approaches. SSRN Electronic Journal. doi:10.2139/ssrn.2122298

Micu, M., Bălteanu, D., 2013. A deep-seated landslide dam in the Siriu Reservoir (Curvature Carpathians, Romania). Landslides 10, 323–329. doi:10.1007/s10346-013-0382-8

Millenium Ecosystem Assessment, 2005. Ecosystems and human Well-Being: Synthesis. Island Press, Washington, DC.

Millington, J.D.A., Perry, G.L.W., Romero-Calcerrada, R., 2007. Regression Techniques for Examining Land Use/Cover Change: A Case Study of a Mediterranean Landscape. Ecosystems 10, 562–578. doi:10.1007/s10021-007-9020-4

Ministry of Agriculture and Rural Development of Romania, 2012. Programul Naţional de Dezvoltare Rurală 2007-2013. National Rural Development Program. Ministry of Agriculture and Rural Development of Romania.

Mitsova, D., Shuster, W., Wang, X., 2011. A cellular automata model of land cover change to integrate urban growth with open space conservation. Landscape and Urban Planning 99, 141–153. doi:10.1016/j.landurbplan.2010.10.001

Monteiro, A.T., Fava, F., Hiltbrunner, E., Della Marianna, G., Bocchi, S., 2011. Assessment of land cover changes and spatial drivers behind loss of permanent meadows in the lowlands of Italian Alps. Landscape and Urban Planning 100, 287–294. doi:10.1016/j.landurbplan.2010.12.015

Muică, N., Turnock, D., 2008. A Toponomical Approach to the Agrarian History of the Pătârlagele Depression (Buzău Subcarpathians, România). Human Geographies - Journal of Studies and Research in Human Geography 2.

Müller, D., Kuemmerle, T., Rusu, M., Griffiths, P., 2009. Lost in transition: determinants of post-socialist cropland abandonment in Romania. Journal of Land Use Science 4, 109–129. doi:10.1080/17474230802645881

Munteanu, C., Kuemmerle, T., Boltiziar, M., Butsic, V., Gimmi, U., Lúboš Halada, Kaim, D., Király, G., Konkoly-Gyuró, É., Kozak, J., Lieskovský, J., Mojses, M., Müller, D., Ostafin, K., Ostapowicz, K., Shandra, O., Štych, P., Walker, S., Radeloff, V.C., 2014. Forest and agricultural land change in the Carpathian region—A meta-analysis of long-term patterns and drivers of change. Land Use Policy 38, 685–697. doi:10.1016/j.landusepol.2014.01.012

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H.M., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S.J., Swart, R., van Rooijen, S., Victor, N., Dadi, Z., 2000. Special Report on Emissions Scenarios : a special report of Working Group III of the Intergovernmental Panel on Climate Change.

Nedkov, S., Burkhard, B., 2012. Flood regulating ecosystem services—Mapping supply and demand, in the Etropole municipality, Bulgaria. Ecological Indicators 21, 67–79. doi:10.1016/j.ecolind.2011.06.022

Odada, E.O., Ochola, W.O., Olago, D.O., 2009. Understanding future ecosystem changes in Lake Victoria basin using participatory local scenarios. African Journal of Ecology 47, 147–153. doi:10.1111/j.1365-2028.2008.01062.x

Ogilvy, J., Schwartz, P., 1998. Plotting your scenarios, in: Learning from the Future: Competitive Foresight Scenarios. Wiley, New York, p. 464.

Olofsson, P., Foody, G.M., Stehman, S.V., Woodcock, C.E., 2013. Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation. Remote Sensing of Environment 129, 122–131. doi:10.1016/j.rse.2012.10.031

Olsson, E.G.A., Austrheim, G., Grenne, S.N., 2000. Landscape change patterns in mountains, land use and environmental diversity, Mid-Norway 1960–1993. Landscape Ecology 15, 155–170. doi:10.1023/A:1008173628016

O'Neill, B.C., Schweizer, V., 2011. Projection and prediction: Mapping the road ahead. Nature Clim. Change 1, 352–353. doi:10.1038/nclimate1241

Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M.J., Deadman, P., 2003. Multi-agent systems for the simulation of land-use and land-cover change: a review. Annals of the Association of American Geographers 93, 314–337.

Patel, M., Kok, K., Rothman, D.S., 2007. Participatory scenario construction in land use analysis: An insight into the experiences created by stakeholder involvement in the Northern Mediterranean. Land Use Policy, Integrated Assessment of the Land System: The Future of Land Use 24, 546–561. doi:10.1016/j.landusepol.2006.02.005

Pérez-Vega, A., Mas, J.-F., Ligmann-Zielinska, A., 2012. Comparing two approaches to land use/cover change modeling and their implications for the assessment of biodiversity loss in a deciduous tropical forest. Environmental Modelling & Software 29, 11–23. doi:10.1016/j.envsoft.2011.09.011

Peterson, G.D., Cumming, G.S., Carpenter, S.R., 2003. Scenario Planning: a Tool for Conservation in an Uncertain World. Conservation Biology 17, 358–366. doi:10.1046/j.1523-1739.2003.01491.x

Pontius, R.G., Shusas, E., McEachern, M., others, 2004. Detecting important categorical land changes while accounting for persistence. Agriculture, Ecosystems & Environment 101, 251–268.

Promper, C., Puissant, A., Malet, J.-P., Glade, T., 2014. Analysis of land cover changes in the past and the future as contribution to landslide risk scenarios. Applied Geography 53, 11–19. doi:10.1016/j.apgeog.2014.05.020

Protezione Civile, 2009. Le opere di ricostruzione nella Val Canale - Canal del Ferro [WWW Document]. Web Page of the Civil Protection of Friuli Venezia Giulia, Italy. URL http://www.protezionecivile.fvg.it/ProtCiv/Default.aspx/2384-le_opere_di_ricostruzione_nella_val_canale__canal_del_ferro.htm (accessed 2.24.13).

Reginster, I., Rounsevell, M., 2006. Scenarios of future urban land use in Europe. Environment and Planning B: Planning and Design 33, 619 – 636. doi:10.1068/b31079

Rounsevell, M., Reginster, I., Araújo, M.B., Carter, T., Dendoncker, N., Ewert, F., House, J., Kankaanpaa, S., Leemans, R., Metzger, M., Schmit, C., Smith, P., Tuck, G., 2006. A coherent set of future land use change scenarios for Europe. Agriculture, Ecosystems & Environment 114, 57–68. doi:10.1016/j.agee.2005.11.027

Rutherford, G.N., Bebi, P., Edwards, P.J., Zimmermann, N.E., 2008. Assessing land-use statistics to model land cover change in a mountainous landscape in the European Alps. Ecological Modelling 212, 460–471. doi:10.1016/j.ecolmodel.2007.10.050

Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M., Wall, D.H., 2000. Global Biodiversity Scenarios for the Year 2100. Science 287, 1770 –1774. doi:10.1126/science.287.5459.1770

Sangati, M., 2009. Flash Flood Analysis and Modelling in Mountain Regions (Doctoral Thesis). University of Padova.

Santelmann, M.V., White, D., Freemark, K., Nassauer, J.I., Eilers, J.M., Vaché, K.B., Danielson, B.J., Corry, R.C., Clark, M.E., Polasky, S., Cruse, R.M., Sifneos, J., Rustigian, H., Coiner, C., Wu, J., Debinski, D., 2004. Assessing alternative futures for agriculture in Iowa, U.S.A. Landscape Ecol 19, 357–374. doi:10.1023/B:LAND.0000030459.43445.19

Schabus, H., 2005. Val Canale - Movie, Installation. Austrian contribution for the 2005 Biennale di Venezia [WWW Document]. URL http://www.unikum.ac.at/dasweite_fi/VAL_PICS/val_slike1.html (accessed 9.15.13).

Schirpke, U., Leitinger, G., Tappeiner, U., Tasser, E., 2012. SPA-LUCC: Developing land-use/cover scenarios in mountain landscapes. Ecological Informatics 12, 68–76. doi:10.1016/j.ecoinf.2012.09.002

Schneeberger, N., Bürgi, M., Hersperger, A.M., Ewald, K.C., 2007. Driving forces and rates of landscape change as a promising combination for landscape change research—An application on the northern fringe of the Swiss Alps. Land Use Policy 24, 349–361. doi:10.1016/j.landusepol.2006.04.003

Schröter, D., Cramer, W., Leemans, R., Prentice, I.C., Araújo, M.B., Arnell, N.W., Bondeau, A., Bugmann, H., Carter, T.R., Gracia, C.A., de la Vega-Leinert, A.C., Erhard, M., Ewert, F., Glendining, M., House, J.I., Kankaanpää, S., Klein, R.J.T., Lavorel, S., Lindner, M., Metzger, M.J., Meyer, J., Mitchell, T.D., Reginster, I., Rounsevell, M., Sabaté, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M.T., Thonicke, K., Thuiller, W., Tuck, G., Zaehle, S., Zierl, B., 2005. Ecosystem Service Supply and Vulnerability to Global Change in Europe. Science 310, 1333 –1337.

Scolobig, A., Castán Broto, V., Zabala, A., 2008. Integrating multiple perspectives in social multicriteria evaluation of flood-mitigation alternatives: the case of Malborghetto-Valbruna. Environment and planning C: government and policy. 26, 1143–1161.

Sleeter, B.M., Sohl, T.L., Bouchard, M.A., Reker, R.R., Soulard, C.E., Acevedo, W., Griffith, G.E., Sleeter, R.R., Auch, R.F., Sayler, K.L., Prisley, S., Zhu, Z., 2012. Scenarios of land use and land cover change in the conterminous United States: Utilizing the special report on emission scenarios at ecoregional scales. Global Environmental Change 22, 896–914. doi:10.1016/j.gloenvcha.2012.03.008

Soares-Filho, B.S., Cerqueira, G.C., Pennachin, C.L., 2002. Dinamica—a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. Ecological Modelling 154, 217–235. doi:10.1016/S0304-3800(02)00059-5

Sohl, T.L., Sleeter, B.M., Sayler, K.L., Bouchard, M.A., Reker, R.R., Bennett, S.L., Sleeter, R.R., Kanengieter, R.L., Zhu, Z., 2012. Spatially explicit land-use and land-cover scenarios for the Great Plains of the United States. Agriculture, Ecosystems & Environment 153, 1–15.

Stach, W., Kurgan, L., Pedrycz, W., Reformat, M., 2005. Genetic learning of fuzzy cognitive maps. Fuzzy Sets and Systems 153, 371–401. doi:10.1016/j.fss.2005.01.009

Steffen, W., Crutzen, P.J., McNeill, J.R., 2007. The Anthropocene: are humans now overwhelming the great forces of nature. Ambio: A Journal of the Human Environment 36, 614–621.

Steffen, W.L., Sanderson, A., Tyson, P., Jäger, J., Matson, P., Moore III, B., Oldfield, F., Richardson, K., Schnellnhuber, H.J., Turner, B.L., Wasson, R.J., 2005. Global change and the earth system: a planet under pressure. Birkhäuser.

Stehman, S.V., 2009. Sampling designs for accuracy assessment of land cover. International Journal of Remote Sensing 30, 5243–5272. doi:10.1080/01431160903131000

Sui, D.Z., Maggio, R.C., 1999. Integrating GIS with hydrological modeling: practices, problems, and prospects. Computers, Environment and Urban Systems 23, 33–51. doi:10.1016/S0198-9715(98)00052-0

Swart, R.J., Raskin, P., Robinson, J., 2004. The problem of the future: sustainability science and scenario analysis. Global Environmental Change 14, 137–146. doi:10.1016/j.gloenvcha.2003.10.002

Taff, G.N., Müller, D., Kuemmerle, T., Ozdeneral, E., Walsh, S.J., 2009. Reforestation in Central and Eastern Europe After the Breakdown of Socialism, in: Nagendra, H., Southworth, J. (Eds.), Reforesting Landscapes. Springer Netherlands, Dordrecht, pp. 121–147.

Tasser, E., Mader, M., Tappeiner, U., 2003. Effects of land use in alpine grasslands on the probability of landslides. Basic and Applied Ecology 4, 271–280. doi:10.1078/1439-1791-00153

Tasser, E., Tappeiner, U., Cernusca, A., 2005. Ecological Effects of Land-use Changes in the European Alps, in: Huber, U.M., Bugmann, H.K.M., Reasoner, M.A. (Eds.), Global Change and Mountain Regions, Advances in Global Change Research. Springer Netherlands, pp. 409–420.

Tasser, E., Walde, J., Tappeiner, U., Teutsch, A., Noggler, W., 2007. Land-use changes and natural reforestation in the Eastern Central Alps. Agriculture, ecosystems & environment 118, 115–129.

Teixeira, A.M.G., Soares-Filho, B.S., Freitas, S.R., Metzger, J.P., 2009. Modeling landscape dynamics in an Atlantic Rainforest region: Implications for conservation. Forest Ecology and Management 257, 1219–1230. doi:10.1016/j.foreco.2008.10.011

Thapa, R.B., Shimada, M., Watanabe, M., Motohka, T., Shiraishi, T., 2013. The tropical forest in south east Asia: Monitoring and scenario modeling using synthetic aperture radar data. Applied Geography 41, 168–178. doi:10.1016/j.apgeog.2013.04.009

Tockner, K., Surian, N., Toniutti, N., 2005. Geomorphologie, Ökologie und nachhaltiges Management einer Wildflusslandschaft am Beispiel des Fiume Tagliamento (Friaul, Italien) - ein Modellökosystem für den Alpenraum und ein Testfall für die EU-Wasserrahmenrichtlinie, in: Lintzmeyer, K. (Ed.), Rettet den Tagliamento - Friaul/ Italien - König der Alpenflüsse. Verein zum Schutz der Bergwelt e.V, München, Germany, pp. 3–17.

Tropeano, D., Turconi, L., Sanna, S., 2004. Debris flows triggered by the 29 August 2003 cloudburst in Val Canale, Eastern Italian Alps. Presented at the International Symposium INTERPRAEVENT 2004 - Riva/ Trient.

Troy, A., Wilson, M.A., 2006. Mapping ecosystem services: Practical challenges and opportunities in linking GIS and value transfer. Ecological Economics 60, 435–449. doi:10.1016/j.ecolecon.2006.04.007

Trutnevyte, E., 2014. The allure of energy visions: Are some visions better than others? Energy Strategy Reviews, Sustainable Energy System Changes 2, 211–219. doi:10.1016/j.esr.2013.10.001

Trutnevyte, E., Barton, J., O’Grady, Á., Ogunkunle, D., Pudjianto, D., Robertson, E., 2014. Linking a storyline with multiple models: A cross-scale study of the UK power system transition. Technological Forecasting and Social Change 89, 26–42. doi:10.1016/j.techfore.2014.08.018

Turner, B.L., Lambin, E.F., Reenberg, A., 2007. The emergence of land change science for global environmental change and sustainability. PNAS 104, 20666–20671. doi:10.1073/pnas.0704119104

Turnock, D., 2002. Ecoregion-based conservation in the Carpathians and the land-use implications. Land Use Policy 19, 47–63. doi:10.1016/S0264-8377(01)00039-4

UNCEM, 2014. The National Union of Mountain Towns and Communities [WWW Document]. URL http://www.uncem.it/english-presentation_uncem.html (accessed 1.15.14).

Václavík, T., Rogan, J., 2009. Identifying Trends in Land Use/Land Cover Changes in the Context of Post-Socialist Transformation in Central Europe: A Case Study of the Greater Olomouc Region, Czech Republic. GIScience & Remote Sensing 46, 54–76. doi:10.2747/1548-1603.46.1.54

Van Eetvelde, V., Antrop, M., 2004. Analyzing structural and functional changes of traditional landscapes—two examples from Southern France. Landscape and Urban Planning 67, 79–95. doi:10.1016/S0169-2046(03)00030-6

Van Maanen, E., Predoiu, G., Klaver, R., Soulé, M., Popa, M., Ionescu, O., Jurj, R., Negus, S., Ionescu, G., Altenburg, W., 2006. Safeguarding the Romanian Carpathian ecological network. A vision for large carnivores and biodiversity in Eastern Europe. Icas Wildlife Unit, Brasov.

Van Vliet, J., Naus, N., van Lammeren, R.J.A., Bregt, A.K., Hurkens, J., van Delden, H., 2013. Measuring the neighbourhood effect to calibrate land use models. Computers, Environment and Urban Systems 41, 55–64. doi:10.1016/j.compenvurbsys.2013.03.006

Van Vliet, M., Kok, K., Veldkamp, T., 2010. Linking stakeholders and modellers in scenario studies: The use of Fuzzy Cognitive Maps as a communication and learning tool. Futures 42, 1–14. doi:10.1016/j.futures.2009.08.005

Veldkamp, A., Lambin, E.., 2001. Predicting land-use change. Agriculture, Ecosystems & Environment 85, 1–6. doi:10.1016/S0167-8809(01)00199-2

Verburg, P.H., de Koning, G.H.J., Kok, K., Veldkamp, A., Bouma, J., 1999. A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. Ecological Modelling 116, 45–61. doi:10.1016/S0304-3800(98)00156-2

Verburg, P.H., Kok, K., Pontius, R.G., Veldkamp, A., 2006. Modeling Land-Use and Land-Cover Change, in: Lambin, E.F., Geist, H. (Eds.), Land-Use and Land-Cover Change. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 117–135.

Verburg, P.H., Schot, P.P., Dijst, M.J., Veldkamp, A., 2004. Land use change modelling: current practice and research priorities. GeoJournal 61, 309–324. doi:10.1007/s10708-004-4946-y

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human Domination of Earth’s Ecosystems. Science 277, 494 –499. doi:10.1126/science.277.5325.494

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environmental Modelling & Software, Thematic Issue - Modelling with Stakeholders 25, 1268–1281. doi:10.1016/j.envsoft.2010.03.007

Von Korff, Y., D’Aquino, P., Daniell, K.A., Bijlsma, R., 2010. Designing Participation Processes for Water Management and Beyond. Ecology and Society 15, 29.

Wainwright, J., Mulligan, M., 2013. Introduction, in: Wainwright, J., Mulligan, M. (Eds.), Environmental Modelling: Finding Simplicity in Complexity. John Wiley & Sons.

Walz, A., Lardelli, C., Behrendt, H., Grêt-Regamey, A., Lundström, C., Kytzia, S., Bebi, P., 2007. Participatory scenario analysis for integrated regional modelling. Landscape and Urban Planning 81, 114–131. doi:10.1016/j.landurbplan.2006.11.001

Ward, J.V., Tockner, K., Edwards, P.J., Kollmann, J., Bretschko, G., Gurnell, A.M., Petts, G.E., Rossaro, B., 1999. A reference river system for the Alps: the “Fiume Tagliamento.” Regulated Rivers Research & Management 15, 63–75.

White, R., Engelen, G., 2000. High-resolution integrated modelling of the spatial dynamics of urban and regional systems. Computers, Environment and Urban Systems 24, 383–400. doi:10.1016/S0198-9715(00)00012-0

Wollenberg, E., Edmunds, D., Buck, L., 2000. Using scenarios to make decisions about the future: anticipatory learning for the adaptive co-management of community forests. Landscape and Urban Planning 47, 65–77. doi:10.1016/S0169-2046(99)00071-7

Wright, G., Cairns, G., Bradfield, R., 2013. Scenario methodology: New developments in theory and practice: Introduction to the Special Issue. Technological Forecasting and Social Change, Scenario Method: Current developments in theory and practice 80, 561–565. doi:10.1016/j.techfore.2012.11.011

Yanai, A.M., Fearnside, P.M., Graça, P.M.L. de A., Nogueira, E.M., 2012. Avoided deforestation in Brazilian Amazonia: Simulating the effect of the Juma Sustainable Development Reserve. Forest Ecology and Management 282, 78–91. doi:10.1016/j.foreco.2012.06.029

Ziare.com, 2011. Trafic ingreunat din cauza alunecarilor de teren, pe mai multe drumuri nationale. [WWW Document]. URL http://www.ziare.com/stiri/trafic/trafic-ingreunat-din-cauza-alunecarilor-de-teren-pe-mai-multe-drumuri-nationale-1081001 (accessed 1.11.13).

Zumpano, V., Hussin, H.Y., Reichenbach, P., Balteanu, D., Micu, M., Sterlacchini, S., 2014. A landslide susceptibility analysis for Buzau County, Romania. Romanian Journal of Geography 58, 9–16.

# Description of Appendices

This PhD thesis is a cumulative dissertation. It consists of one published and one accepted research paper, one submitted research paper, one research paper in preparation, one published conference proceeding and one accepted book chapter. The articles are structured chronologically, and are referred to in the thesis as a particular Appendix.

### Journal Articles and Manuscripts

### Appendix A: Understanding Land Cover Changes in the Italian Alps and Romanian Carpathians Combining Remote Sensing and Stakeholder Interviews

Malek Ž, Scolobig A, Schröter D. 2014. Understanding Land Cover Changes in the Italian Alps and Romanian Carpathians Combining Remote Sensing and Stakeholder Interviews. Land: 3(1): 52–73.

Status: Released publication

This paper analyses land use and land cover changes in both study areas (Italy and Romania) between 1989 and 2010. It is significant for this PhD research, as it presents the methodology for data gathering and generation. It describes the methodology to classify remote sensing imagery in order to map land use and land cover changes. Moreover, it assesses the accuracy of land use/land cover maps, needed to identify the uncertainty defined by the accuracy of data. It identifies the most significant spatial driving forces of land use/land cover change. Finally, through expert interviews, it describes socio-economic driving forces of land use/land cover change. Due to lack of data and prevailing external driving forces, this was not possible through applied statistical methods. Also, the paper highlights the need for integrating qualitative and quantitative research when studying land use/land cover changes.

The manuscript was written by Žiga Malek, supported by the co-authors. Žiga Malek was involved in all stages of the research, and coordinated the design and writing of the research: data gathering and interpretation, field visits, land cover classification, GIS and statistical analysis, designing the interview protocol, performing the majority of interviews, and the stakeholder perception analysis. Anna Scolobig was involved in the design of the interview protocol, performing interviews, and stakeholder perception analysis. Dagmar Schröter was involved in the design of interview protocol and stakeholder perception analysis.

## Appendix B: The impact of future land use change under tourism development scenarios: an example from the Italian Alps

Malek Ž, Boerboom L. The impact of future land use change under tourism development scenarios: an example from the Italian Alps. Submitted to Mountain Research and Development on 12.9.2014.

Status: Accepted on 1.12.2014

This paper deals with future land use changes due to tourism development in order to study changes to hydro-meteorological risk in an area in the Italian Alps. It describes the methodology behind constructing Cognitive Maps, conceptual Drivers-Pressures-State-Impact-Response model and development of future development scenarios. The conceptual model and the scenarios are developed in a participatory way, which is later combined with geospatial technologies, such as cellular automata land use change modelling and GIS. Spatially explicit results are generated, and later their impact on potential changes to the landscape and hydro-meteorological risk is assessed. This way the paper promotes the use of future land use scenarios when studying possible changes to future hydro-meteorological risk.

The manuscript was written by Žiga Malek, supported by the co-author. The author designed the research and performed the majority of the research: field visits, interviews, data analysis (GIS and statistical), Cognitive Map construction, development of the urban expansion model, developing future tourism scenarios and simulating future urban expansion. Luc Boerboom supported the construction of the Cognitive Map of future land use changes and the design of the conceptual model of future urban expansion.

## Appendix C: Future forest cover change under a set of forest policy scenarios: An example from Buzau Subcarpathians, Romania

Malek Ž, Glade T, Boerboom L. Future forest cover change under a set of forest policy scenarios: An example from Buzau Subcarpathians, Romania. Submitted to Environmental Management on 3.11.2014.

Status: Under review

In this manuscript future changes to the forest cover in the Buzau Subcarpathians in Romania are simulated. The manuscript describes the methodology behind scenario development, calculation of spatial demand for deforestation, and the allocation of future changes to the forest cover. It assesses the accuracy of the allocation model, needed to identify the uncertainty defined by the performance of the model. In the course of scenario development, this study involves experts and decision makers from the local and regional forestry sector, thus generating plausible scenarios despite lacks of data. Moreover, the paper results in spatially explicit scenarios of forest cover change, identifying hot-spots of potential future deforestation. Finally, this paper analyses potential consequences to landslide risk due to deforestation, and also analyses the impact of a potential risk mitigation policy.

The manuscript was written by Žiga Malek, supported by the co-authors. Žiga Malek was designed the research and performed the majority of the research: data analysis, field visits, development of a forest cover change model, developing future scenarios and simulating future forest cover changes. Thomas Glade and Luc Boerboom were involved in the design of the conceptual model of future forest cover change.

**Appendix D: Spatial assessment of future changes to the provision of ecosystem services in Buzau Subcarpathians, Romania**

Malek Ž, Zumpano V, Hussin HY. Spatial assessment of future changes to the provision of ecosystem services in Buzau Subcarpathians, Romania.

Status: In preparation for submission to Environmental Earth Sciences.

This paper analyses the potential consequences of future land changes. More precisely, it studies the consequences of future changes to the forest cover in an area in the Romanian Carpathians. The changes to the provision of ecosystem services due to expected forest expansion and deforestation are studied. Three ecosystem services are addressed: provision of wood, biodiversity support and regulation of landslides. A spatially explicit geographic information system (GIS) based approach results in the spatial distribution and quantitative information of potential gains and losses to ecosystem service provisioning. The paper therefore provides information on a wide variety of possible consequences of future changes to the forest cover, instead of focusing on one particular process only. Moreover, it expands the knowledge on the applicability of land change scenario modelling for decision support.

The majority of the manuscript was written by Žiga Malek. Veronica Zumpano and Haydar Hussin wrote the section on the landslide susceptibility methodology. Žiga Malek designed the research and performed the majority of the research: modifying scenarios of forest cover change, land cover and grassland mapping, and GIS assessment. Veronica Zumpano and Haydar Hussin were involved in the assessment of future changes to landslide susceptibility (methodology, modelling, and discussion).

## Peer-reviewed Conference Proceeding

### Appendix E: Scenarios of land cover change and landslide susceptibility: an example from the Buzau Subcarpathians, Romania

Malek Ž, Zumpano V, Schröter D, Glade T, Balteanu D, Micu M. 2014. Scenarios of land cover change and landslide susceptibility: an example from the Buzau Subcarpathians, Romania. In: Lollino G., Manconi A., Guzzetti F., Culshaw M., Bobrowsky P., Luino F. Engineering Geology for Society and Territory – Volume 5: Urban Geology, Sustainable Planning and Landscape Exploitation (IAEG XII Congress, Torino, Italy)

Status: Released publication

This proceeding presents another case study where the developed methodology for future land use and land cover change simulation is applied. This study focuses on future changes to the urban pattern in the Romanian Subcarpathians. As most significant driving forces, the increase in living standard (and the mean living area as a proxy) was applied, together with the changes to the population in the analysed study area. The three developed scenarios were spatially explicit, and later analysed through the prism of landslide risk. This proceeding furthermore studies the transferability of the developed methodology to other study areas, as well as to other land use and land cover processes.

The majority of the manuscript was written by Žiga Malek, supported by Veronica Zumpano. Žiga Malek developed the scenarios and modelled the future urban expansion. Žiga Malek, Dagmar Schröter and Thomas Glade designed the conceptual model of urban expansion. Veronica Zumpano, Dan Balteanu and Mihai Micu performed the susceptibility modelling and assessed the future land use and land cover changes scenarios.

## Peer-reviewed Book chapter

### Appendix F: Fuzzy-logic Cognitive Mapping: Introduction and overview of the method

Malek Ž. 2014. Fuzzy-logic Cognitive Mapping: Introduction and overview of the method. In: Gray S, Jordan R. Pallisimio M, Gray S. Including Stakeholders in Environmental Modeling: Considerations, Methods and Applications

Status: Accepted on 29.9.2014

This book chapter reviews the potential of Fuzzy-logic Cognitive Mapping to support participatory environmental modelling. It focuses on the theoretical and methodological aspects of the approach. It lists examples, where it has already been applied when dealing with environmental issues. Moreover, it includes a brief review of the importance of stakeholder participation in environmental modelling.

This chapter was written by Žiga Malek, who also performed the literature review on Fuzzy-logic Cognitive Mapping and participatory environmental modelling.

The layout of all Appendices (structure, section titles, and figure and table captions, reference style) is maintained as requested by the journal or book publisher.

# Appendix A: Understanding Land Cover Changes in the Italian Alps and Romanian Carpathians Combining Remote Sensing and Stakeholder Interviews

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*Article*

# Understanding Land Cover Changes in the Italian Alps and Romanian Carpathians Combining Remote Sensing and Stakeholder Interviews

**Žiga Malek [1,2,]*, Anna Scolobig [3] and Dagmar Schröter [4]**

[1] International Institute for Applied Systems Analysis, Risk, Policy and Vulnerability, Schlossplatz 1, 2361 Laxenburg, Austria

[2] Department of Geography and Regional Research, University of Vienna, Universitätsstrasse 7, 1010 Vienna, Austria

[3] Human Environment Systems Group, Department of Environmental Systems Science, ETH Zürich, Universitätstrasse 22, 8092 Zürich, Switzerland; E-Mail: anna.scolobig@usys.ethz.ch

[4] Transdisciplinary Lab, Department of Environmental Systems Science, ETH Zürich, Sonneggstrasse 33 SOL F4, 8092 Zürich, Switzerland; E-Mail: dagmar.schroeter@usys.ethz.ch

* Author to whom correspondence should be addressed; E-Mail: ziga.malek@gmail.com; Tel.: +43-2236-807-575; Fax: +43-2236-807-466.

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**Abstract:** In the last two decades, socio-economic changes in Europe have had a significant effect on land cover changes, but it is unclear how this has affected mountain areas. We focus on two mountain areas: the eastern Italian Alps and the Romanian Curvature Carpathians. We classified land cover from Earth observation data after 1989 by using applied remote sensing techniques. We also analyzed socio-economic data and conducted semi-structured interviews with local stakeholders. In Italy, most of the land conversion processes followed long-term trends. In Romania, they took off with the sudden political changes after 1989. In both areas, forest expansion was the biggest, but potentially not the most consequential change. More consequential changes were urbanization in Italy and small-scale deforestation in Romania, since both increased the risk of hydro-meteorological hazards. Stakeholders' views were an added value to the spatial analysis and *vice versa*. For example, stakeholders' explanations resolved the seeming contradiction of decreased economic activity and increased urbanization (Italian site), as a consequence of secondary home building. Furthermore, spatial analysis revealed that urbanization in Romania was less significant with regard to consequences for the wider human-environment system than many stakeholders thought.

**Keywords:** land cover changes; Alps; Carpathians; remote sensing; socio-economic change; interviews; perceptions; hydro-meteorological risk

## 1. Introduction

Throughout the centuries, European mountain areas have been shaped gradually by human activities, resulting in diverse landscapes. Then, the 20th century brought rapid socio-economic transformation. Thus, land use and land cover change are now intense in spatial and temporal terms, presenting a break to the long steadiness of landscape evolution [1]. Examples of sudden changes range from land abandonment after the collapse of the Soviet Union [2], substantial expansion of urban areas after the introduction of a market-based economy [3], to illegal logging due to warfare and corruption [4]. In mountains, we see a tremendous decline in agriculture, improved accessibility through new infrastructure and the increased development of recreational areas [5–7].

These land cover changes can have strong impacts on human well-being on a broader scale, since mountains provide many services, e.g., water provision, agricultural production, hazard prevention and others [6,8,9]. One main concern is that land cover changes can lead to increased hazard risks, e.g., through local changes of the runoff dynamics [8,9]. Another important trend is that of land abandonment and natural reforestation in hilly and mountain areas, combined with the removal of riparian vegetation and urbanization in the valleys, contributing to habitat loss, lower biodiversity and a more homogenous mountain landscape [1,10,11].

The strong link of mountain land cover change to human well-being has recently led to an increased interest of policy makers and planners in the causes and consequences of these changes [12]. Researchers call for increased efforts to monitor and analyze land cover changes, especially in areas affected by high rates of socio-economic changes [13].

The main goal of this study was to investigate land cover changes in two major European mountain areas: the mountain community of Gemonese, Canal del Ferro and Val Canale in the Italian Alps, and the Carpathians of Buzau County in Romania. The areas were selected due to their particular socio-economic trajectories since 1989 and their representativeness in terms of physical and biogeographic characteristics for the Alps and Carpathians, respectively. The Alps and the Carpathians are two major mountain areas in Europe. Here, the main European rivers originate, providing water and energy to a large portion of the European population. Both are acknowledged as major European biodiversity hotspots [14,15]. The Alps are considered to be one of the first tourist destinations, and here, tourism is a major economic factor [16]. In the Romanian Carpathians, tourism is still underdeveloped, however, with major potential [17].

In general, there is more research on land use and cover changes in the Alps than in the Carpathians. Focusing on the Italian Alps, the research undertaken so far ranges from identifying changes to the forest cover [18], land abandonment [19], the main drivers of land cover change [11], the role of socio-economic and natural characteristics [7] and the consequences of land cover changes on biodiversity [10]. However, there is a lack of research investigating the consequences for land cover of the significant socio-economic changes linked to the industrialization of Europe: migrations to the lowlands and the expansion of traffic routes due to mechanization [16,20]. Our Alpine study area lies in the Eastern Italian Alps, which have been experiencing the highest depopulation rates and decreases in economic activities in the last three decades [21].

In the Carpathian region, research focuses on the abandonment of grasslands and cropland and the expansion of forests as the most widespread land cover changes [22–26]. Though more rapid in nature, these changes are in line with the long-term trends for all European mountain areas, including the Alps [27]. However, there is another interesting process that is particular to the Carpathian region: the increase in the quantity of (illegal) logging, as well as changes in the spatial pattern of the logging [28–32]. Processes like this are linked to the fall of Communism since 1989 and the expansion of the European Union in the years after 2000. Their effects on land cover and the related consequences are as yet understudied.

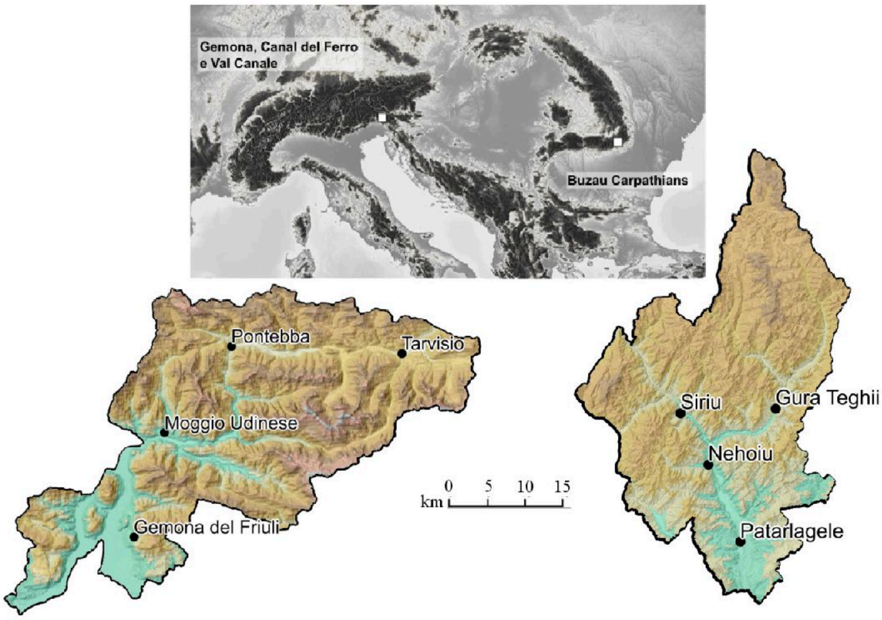
For both case study areas, our main research interests were related to land cover changes as a possible result of sudden socio-economic changes. More importantly, we were interested in which land cover changes were most significant in terms of consequences to the environment and human activities. To map and analyze land cover changes, we used applied remote sensing techniques. To study the driving forces behind land cover changes more in depth, we performed a series of interviews with stakeholders and experts.

## 2. Study Areas

### *2.1. Gemona, Canal del Ferro and Val Canale*

The mountain community of Gemona, Canal del Ferro and Val Canale study lies in the autonomous region of Friuli Venezia Giulia in northeastern Italy on the border with Austria and Slovenia (46°30′25″N, 13°26′25″E, Figure 1). It covers an area of 1,148 km$^2$ and consists of 15 municipalities. It is situated between the Carnic and Julian Alps, which rise up to 2,754 m, in the discharge area of the river Fella, a major left-hand tributary of the Tagliamento River. The relative relief in the upland area is more than 1,500 m. The area is characterized by steep slopes and high precipitation levels; the Fella river catchment has a mean altitude of 1,140 m a.s.l. and an average mean precipitation of 1,920 mm [33]. The area consists mostly of limestone [34]. The area is seismically active and exposed to many natural hazards, among which are landslides, flash floods and debris flows [34]. In the past, the main river valley was defined by a mosaic of grasslands, settlements and forests. Today, it is intensely urbanized due to numerous pieces of infrastructure. Animal husbandry in the uplands is dominated by cattle. On the southern edge of the case study area begins the lowland Friulian plain, strongly altered due to urbanization and intensified large-scale agriculture in the decades after the Second World War. The total population of the area is 33,286 inhabitants, with only two settlements over 4,000 inhabitants (Tarvisio and Gemona del Friuli, the latter situated in the lowlands). The area is of high importance for Italy, serving as a communication and energy corridor to neighboring Austria and Slovenia. It is subject to numerous efforts of the regional and national government to develop infrastructure and to mitigate risks. Interest for preserving the population and the landscape is high, also due to the growing touristic development.

**Figure 1.** Locations of the study areas. The overview map adapted from [35].




*2.2. Buzau Carpathians*

The Romanian site lies in Buzau County in the south-east of the country, bordering the counties of Brasov, Covasna, Prahova and Vrancea (45°25′18″N, 26°17′46″E, Figure 1). It is situated between the lower Subcarpathians and the higher Carpathians along the Buzau river valley and covers an area of 1,127 $km^2$. The Carpathians rise from 1,300 to 1,772 m, with a relative relief of 500 to 800 m. The mean altitude of the area is 896 m a.s.l., with the geology being represented mainly by deposits of Paleogene flysch. The yearly amount of precipitation in the area is between 630 and 700 mm. Landslides cover large areas in the case study site; in some parts, more than two-thirds of the total area [36]. The urbanization pattern is characterized by long settlements along the main Buzau river valley, also extending to side catchments. The total population of the area is 34,421 inhabitants; Nehoiu (11,355 inhabitants) and Patarlagele (7,831 inhabitants) are the biggest settlements. With a share of up to 40%, agriculture is an important part of the local economy; however, its share of the local and national economy is declining [37]. Subsistence farming evolved at the end of the 19th and the beginning of 20th century and is still important in the area [36]. It has gained importance after the collapse of socialism and the subsequent emergence of small plots following decollectivization [38]. Wood harvesting is another significant activity. The wood is mostly being exported and some used for fuel. Other notable activities in the area are mineral extraction (diatomite) and energy production (a water reservoir in Siriu).

## 3. Data and Methods

### *3.1. Data*

For the Italian study area, more data were available than for the Romanian one. For the Italian area, we acquired land use maps for the years 1980 and 2000 [39]. To perform our analysis and to update the land use map for the most recent situation (2010), we used the following data: numeric regional technical maps, orthophoto images (latest for 2011), a 25-m resolution digital elevation model (DEM), erosion and landslide maps, building cadasters, local spatial plans and forest type maps [39]. We obtained municipal and regional socio-economic, agricultural and forestry statistics from the Italian statistics portal [40], from the atlas of mountain communities [21], the agricultural census [41] and the Friuli Venezia Giulia statistical yearbooks [42].

For the Romanian case study area, we acquired Landsat 5 images (path/row 183/28) for 1989 (18 August), 2000 (5 June) and 2010 (12 August) from the United States Geological Survey [43]. We also obtained higher-resolution satellite images for the year 2010 [44]. For some localities (e.g., Nehoiu), we acquired local spatial plans and a detailed topographic map (1:5,000); otherwise, we used the 1:10,000 topographic map, produced in the 1970s. These maps were used to digitize settlements, rivers, water bodies and specific agricultural land (such as orchards). We used a 25-m resolution DEM for Buzau County [45]. Municipal and regional statistics on socio-economic, land use and agricultural and forestry variables were obtained from the Romanian National Institute of Statistics and Buzau county statistics office [46].

The DEMs were resampled to the resolution of the land cover datasets (30 m). From the DEM, we derived the slope and aspect. The ground truth for training and accuracy assessment was primarily mapped from ancillary data: high-resolution orthophoto and satellite images. For the same purpose, we also performed fieldwork in both areas: in March, August and September of 2012 in Italy and July and September 2012, in Romania.

In both areas, there were limitations to the accessibility of the data. The Italian area is affected by the economies in neighboring Slovenia and Carinthia in Austria, as well as Carnia and lowland Friuli in Italy. This is manifested in numerous landowners or farmers managing the area from neighboring regions and, therefore, not covered by accessible data. In the Romanian area, some of the data is incomplete or data from the local level is conflicting with data from the higher (national) level, which we assume is a consequence of the insecure and possibly chaotic institutional conditions in Romania after the year 1990. Furthermore, detailed data on land ownership is not accessible.

### *3.2. Land Cover Mapping and Classification*

The discrepancy in data availability between the case study areas resulted in two different land cover mapping methods. The year 1989 was chosen as a baseline year for both areas in accordance with the stakeholders and to represent the situation before the intense socio-economic changes. For the Italian case study area, we updated existent 1980 and 2000 land use maps to improve the level of detail and to generate the 2010 map, using the above-mentioned ancillary data. All maps were updated by manual digitization and the integration of different datasets (e.g., land use and forest type map) in a GIS [47]. The land use maps were stratified into land cover maps, with a smaller number of classes

(7 instead of 15), to enable comparison with the Romanian case study area. For example, different forest types (deciduous, coniferous) were joined to a single forest class, with the same procedure being used for different agricultural, grassland, built up and water classes.

For the Romanian area, we used a semi-automatic land cover classification procedure. First, we generated the most recent land cover map, using the 2010 Landsat image and ancillary data. We started with generating a forest/non-forest map by unsupervised clustering using Iterative Self-Organizing Data Analysis (ISODATA), resulting in 40 clusters. We classified the remaining areas as cultivated, grasslands, bare areas and other vegetation using supervised maximum likelihood classification, where training areas were digitized using visual assessment of satellite images, existing high-resolution data and field data. Urban (built-up) areas, roads and water were digitized manually, with cultivated areas being edited manually, as well, using the information from the census and topographic maps. Subsequently, we merged the individual classification maps (for particular classes). The 2010 map had a small number of clouds, which we masked, and then, later, digitized manually. We applied the same procedure for producing the 1989 land cover. Images were processed, co-registered (automatic tie points) and classified using the ENVI image analysis software [48]. Due to the spatial resolution of Landsat images and the nature of the possible expansion of settlements in this rural area (individual new objects), it was not possible to observe the changes of the settlements. Therefore, settlements, together with water bodies, were masked, as they were assumed to not have changed much in this area, an assumption, backed by municipal land use statistics. Areas where settlement expansion has been observed in the field or identified by stakeholders were digitized manually. The 2000 Landsat image was used to check the validity of the changes between 1989 and 2010 in the case of reforestation. For example, if an area covered by forest in 2010, had not been covered by forest in 2000, we manually edited it and classified it as “other vegetation”, as a forest cannot fully develop in this time. We applied a majority filter of 9 pixels to reduce the noise in the images.

### *3.3. Land Cover Change Detection and Accuracy Assessment*

To analyze the land cover changes, we applied a post-classification comparison of land cover maps between the years 1989 and 2010. By generating difference maps, we were able to identify the major land cover change processes and the level of persistence through a cross-tabulation matrix [49]. After identifying the major land cover change processes in the area, we analyzed them in the context of topographic (slope classes and elevation) and spatial variables (distance to settlements).

We assessed the accuracy and estimated the areas of change, using the procedures for post-classification change analysis accuracy assessment [50]. Assessments in both areas were based on an independent stratified random sample of 9 pixel sample units, visually interpreted using the previously mentioned satellite or orthophoto images. For both areas, we assessed the accuracy of the main observed land cover change categories that are described in the later chapters. We used 325 reference units, with 100 and 75 units for the persistent forest and other areas and 50 units for each remaining change category. In the procedure, we calculated the error-adjusted area of each land cover change category, its 95% confidence interval and the user’s, producer’s and overall accuracy of the change map.

### *3.4. Identifying Driving Forces of Change*

To better understand the reasons and dynamics of land cover changes, as well as the related qualitative socio-economic aspects, we conducted 24 interviews with local and regional experts, stakeholders and researchers from both areas (Table 1). The objective of the interviews was to collect information on demographic, agricultural, forestry, economic, cultural and institutional, proximate and distant driving forces and consequences of land cover change. Interviews were performed in October and November 2012, in Italy, and July and September 2012, in Romania. The interviews were grounded on a review of local, regional and national policy documents on mountains, agriculture, forestry and the environment, as well as relevant scientific literature. The interview protocol included questions on the observed land cover changes, their possible consequences and importance, possible changes to the demography, agriculture, economy and tourism of the areas, the role of decision making on different levels (local, regional, national, *etc.*) and, also, the possible effects of external driving forces, such as global political changes.

**Table 1.** List of interviewees.

| Level | Interviewee | Aspect of Change |
|---|---|---|
| Municipal | Mayor, Vice Mayor (2, I, R) | a, b, d |
| | Local historian (2, I, R) | a, b |
| | Forestry technician (3, I, R) | c, e |
| | Spatial planner (2, I, R) | c, d, e |
| | Officer for environmental protection (1, R) | c, e |
| | Technical officer, local emergency or fire department (2, I, R) | e |
| | Farmers (10, R) | b, e |
| Regional | Researchers on human and physical geography (2, I, R) | a, d, e |
| | Forestry officials (3, I, R) | b, c |
| | Geologist (1, I) | c, d |
| | Officials at regional civil protection agency (2, I, R) | e |
| | Officials at regional environmental agency (1, R) | c, e |
| | Researchers on rural economy and land cover change (2, I, R) | a, b, d, e |
| National | Statistical officials (1, R) | a, b, d |

Notes: I, Italian area; R, Romanian area; a, demographic changes; b, changes to agriculture, forestry; c, environmental (agriculture, forestry, risk) policy; d, economic development; e, consequences of land cover change.

The results of the interviews were used in different ways to describe land cover changes in the analyzed areas. First, they were used to complement accessible socio-economic data and to describe possible interactions between land cover changes and socio-economic changes. Secondly, they were used to explain intangible driving forces or the ones not covered by accessible data, such as changes to policy. Moreover, the results were used to receive information about stakeholders' perception on land cover changes. This is particularly important when trying to describe the significance of land cover changes. Furthermore, in this way, we were able to identify potential mismatches between our spatial analysis and stakeholders' knowledge, resulting in improved knowledge on land cover changes in the analyzed areas, as opposed to only analyzing accessible socio-economic data.

**4. Results**

In the following chapters, we first present the results of our remote sensing analysis: land cover maps and land cover changes since 1989. The results of the interviews follow where observed land cover changes are discussed in relation with socio-economic changes since 1989. Based on both remote sensing analysis and stakeholders' interviews, we identified seven land cover classes (Table 2) and five conversions (Table 3).

**Table 2.** Land cover class definitions.

| Land Cover Class | |
|---|---|
| Urban | Built-up areas (structures, transport network) |
| Cultivated | Arable land and land covered by permanent crops (e.g., orchards) |
| Forest | Densely vegetated areas >1 ha (otherwise, "other vegetation", as discussed with stakeholders) |
| Grasslands | Natural grasslands, pastures |
| Other vegetation | Riverine vegetation, vegetated area smaller than 1 ha, transitional shrubland |
| Water | Water courses and bodies |
| Bare | Open spaces with no vegetation, rocks, large river beds |

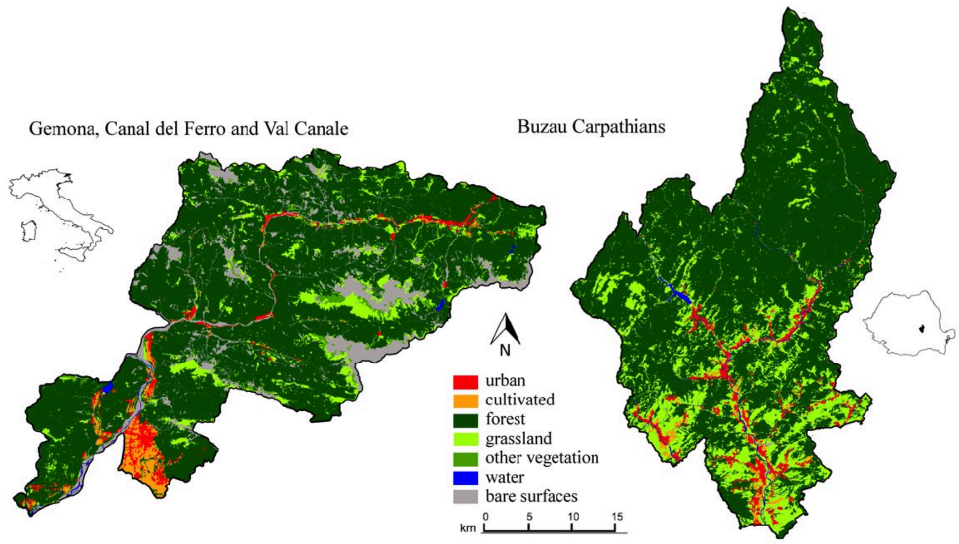
**Table 3.** Definitions and assumptions on land cover conversions.

| Conversions | |
|---|---|
| Urban expansion | to built up |
| Reforestation | to forest |
| Deforestation | removal of forest |
| Abandonment | from cultivated to grasslands or "other vegetation" |
| Remaining conversions | All remaining conversions, mostly defined by geomorphologic processes and a consequent increase in bare areas (landslides, scree areas) |

*4.1. Land Cover and Land Cover Changes*

In the Italian area, the plain is characterized by intensively cultivated and urban land. The foothills and slopes are mostly covered by forests, whereas grasslands dominate wider side valleys and areas above the tree line. Urban areas in the narrow Fella valley are present on alluvium fans and confluences of the main and side valleys (Figure 2). In 2010, most of the area was covered by forests (74.7%), bare surfaces (10.3%) and grasslands (8%) (Table 4). In terms of the change in area relative to the initial area of a particular land cover class, the most striking changes between 1989 and 2010 were urban expansion, loss of grassland and loss of "other vegetation" (Table 4). Overall, 3.9% of the area changed since 1989. Neglecting the persistent bare and water areas, 4.4% of the remaining area changed. In terms of the area of a particular conversion relative to the total changed area, by far the biggest change can be attributed to reforestation, followed by urban expansion and deforestation (Table 5, Figure 3). The loss of grasslands on account of forest expansion is comparable with similar areas in the Italian Alps [11]. The expansion of urban areas, however, was rather exceptional, especially when taking into account depopulation and the abandonment of the area, as discussed later. Remaining land cover conversions are 45% defined by geomorphologic processes and a consequence of the increase in bare areas (landslides, scree areas). In terms of the number of patches converted, urban expansion was the major land cover change, whereas the process of reforestation is characterized by the largest mean patch size. The processes of re- and de-forestation show variations in the distribution among the classes of slope, elevation and distance to settlements (Figure 4). There are also variations in the spatial distribution of other land cover changes; e.g., urban expansion occurred mainly in the main valley and in the lowlands (Figure 3). The overall accuracy for the change map is 91.7%, with high estimated accuracies for each land cover change category (Table 6). Nevertheless, the categories of urban expansion and deforestation might have been overestimated, as they are not within the margin of error (at a 95% confidence interval). Furthermore, the area covered by the process of forest expansion is characterized by a large uncertainty, as presented by the wide confidence interval of almost 45% of the adjusted area of forest expansion (Table 6).

**Figure 2.** Classified land cover maps of the case study areas for 2010.




In the Romanian case study area, the higher Carpathians are covered by forests with fragments of grasslands. In the lower Subcarpathians, the forest cover is much more fragmented and grasslands prevail in the landscape. The main Buzau river valley is characterized by urban areas and grassland; also, the majority of cultivated land is present in the flood plain (Figure 2). In 2010, forests cover most of the area (75.7%), followed by grasslands (19.4%) and urban areas (3.3%) (Table 4). In terms of the change in area relative to the initial area of a particular land cover class, most changes occurred to cultivated land, followed by “other vegetation” and grasslands. The high rate of abandonment of cultivated land after 1989 (−37.4%, Table 4) is not unusual; similar mountainous areas in Romania witnessed even higher abandonment rates [23]. In relative terms, 4.8% of the whole area has changed (Table 5). Most of the changes can be attributed to reforestation, followed by deforestation and the abandonment of agricultural areas (Figure 3). Re- and de-forestation show some similarities in the distribution among slope classes, however, varying in terms of elevation and distance to settlements

(Figure 4). Here, the majority of forest expansions occurred in higher altitudes, a consequence of grassland abandonment in these areas after 1989. Most of the deforestation occurred near the main Buzau valley (Figure 3). The overall accuracy of the change map is 89.2%. Despite being characterized by a high level of accuracy, the adjusted areas of forest expansion, deforestation and abandonment are associated with high uncertainties, as reflected by the wide margins of error. Taking into account these uncertainties, forest expansion could be between 2,714.8 and 5,247.8 ha, deforestation between 610.8 and 1,329 ha and abandonment between 516.7 and 928.7 ha (Table 6). Moreover, due to the lack of high-detail multi-temporal data and the nature of the data used (the spatial and temporal resolution of Landsat), our results might not take into account all land cover processes in the area. We suspect that some possibly substantial small-scale deforestation went unaccounted for. Furthermore, estimations of land abandonment could be problematic, as it is difficult to differentiate among particular land cover classes, e.g., between cultivated areas and grassland or bare areas.

**Table 4.** Comparison of land cover changes in both case study areas. Changes are expressed as overall increases or decreases in the percent of areas covered by the particular land cover type (net changes). Swaps are defined as the total percent of pixels that have changed from or to the particular land cover type, ignoring the persistent areas of the land cover type (100% of persistent areas). The concept of swapping is being used to show the dynamics of each particular land cover class, more precisely, the amount of both gains and losses it has experienced. Therefore, it is not only focusing on net changes, but also describing the extent of possible change trends opposing the main trend of a net increase or decrease.

| Class | Gemona, Canal del Ferro and Val Canale | | | | Buzau Carpathians | | | |
|---|---|---|---|---|---|---|---|---|
| | Land Cover (km$^2$) | | Land Cover Change (%) | | Land Cover (km$^2$) | | Land Cover Change (%) | |
| | 1989 | 2010 | Change | Swaps | 1989 | 2010 | Change | Swaps |
| Urban | 23.9 | 27.4 | 14.9 | 0 | 36.7 | 37.5 | 2.1 | 0 |
| Cultivated | 27.7 | 26.9 | −2.9 | 6.1 | 17.2 | 10.8 | −37.4 | 37.4 |
| Forest | 829.8 | 857.8 | 3.4 | 0.3 | 818.4 | 840.9 | 2.8 | 1.4 |
| Grassland | 119.5 | 92.5 | −22.6 | 25.8 | 234.7 | 218.9 | −6.7 | 13.9 |
| Other vegetation | 24.7 | 20.4 | −17.4 | 23.1 | 8.7 | 7.8 | −9.9 | 22 |
| Water | 3.9 | 3.9 | ~0 | 0 | 11.1 | 11.1 | ~0 | 0 |
| Bare surfaces | 118.9 | 119.6 | 0.7 | 1.8 | 0.5 | 0.5 | ~0 | ~0 |

**Table 5.** Major land cover conversions (%).

| Conversion | Gemona, Canal del Ferro and Val Canale | | | Buzau Carpathians | | |
|---|---|---|---|---|---|---|
| | Proportion (%) | No. of Patches | Mean Patch Size (ha) | Proportion (%) | No. of Patches | Mean Patch Size (ha) |
| Total conversion | 3.9/4.4 a (44.6 km$^2$) | 907 | 4.9 | 4.8 (52.8 km$^2$) | 1527 | 3.5 |
| Urban expansion | 8.1 | 258 | 1.4 | 0.1 | b | b |
| Reforestation | 72.5 | 227 | 14.3 | 64.3 | 838 | 4.1 |
| Deforestation | 5.8 | 75 | 1.5 | 21.9 | 332 | 2.8 |
| Abandonment | 0.8 | b | b | 13.5 | 142 | 5.0 |
| Remaining | 12.8 | 347 | 3.2 | 0.2 | 215 | 1.0 |

Notes: a, neglecting the persistent water and bare surfaces; b, few conversions were observed, either due to the spatial resolution of the data or the spatial scale of the process, and are counted in the "remaining" conversions.

**Figure 3.** Spatial distribution of land cover conversions between 1989 and 2010. See Table 4 for the conversion definition and Table 6 for the estimations of the accuracy and areas. Remaining persistence and conversion present land cover persistence or conversion other than described by abandonment, deforestation, forest and urban expansion and forest persistence.

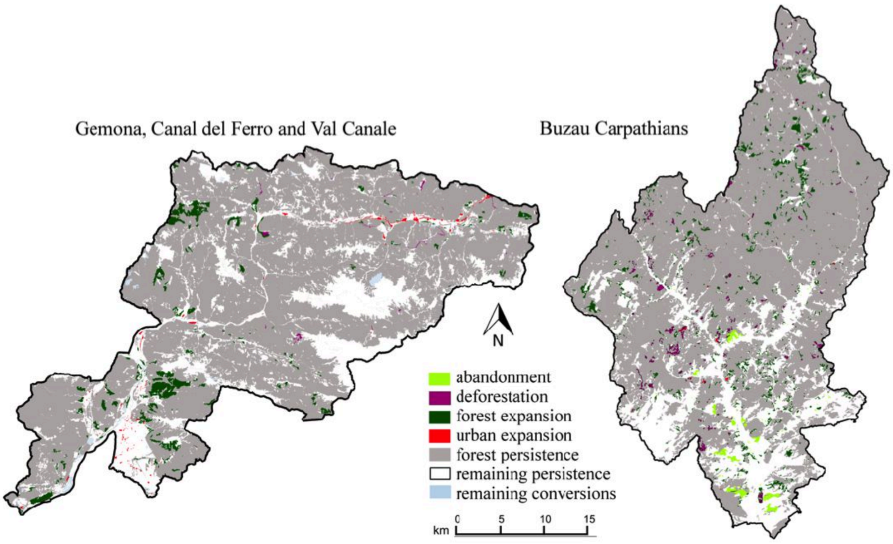
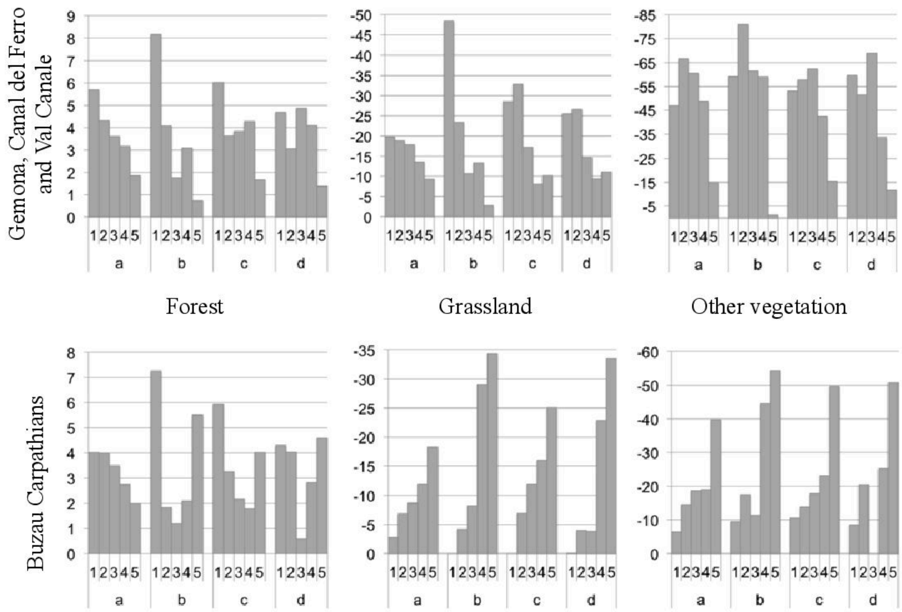



**Table 6.** Accuracy assessment and estimation of areas with a margin of error at a 95% confidence interval for both land cover change maps (Figure 3). CI, confidence interval.

| Change category | Classified Area (ha) | Adjusted Area (ha) | 95% CI (ha) | 95% CI (%) | User's Accuracy (%) | Producer's Accuracy (%) |
|---|---|---|---|---|---|---|
| **Gemona, Canal del Ferro and Val Canale** | | | | | | |
| Rem. persistence | 27,784.9 | 29,930.8 | 3,570.0 | 11.9 | 96.0 | 81.8 |
| Forest persistence | 81,442.1 | 79,977.6 | 4,020.9 | 5.0 | 95.0 | 91.3 |
| Forest expansion | 3,234.3 | 3,736.8 | 1,674.2 | 44.8 | 88.0 | 97.8 |
| Deforestation | 112.5 | 99.0 | 10.5 | 10.6 | 88.0 | 95.7 |
| Urban expansion | 350.2 | 309.8 | 21.2 | 6.8 | 86.0 | 100.0 |
| **Buzau Carpathians** | | | | | | |
| Rem. persistence | 26,657.6 | 27,712.7 | 3,664.2 | 13.2 | 90.7 | 84.0 |
| Forest persistence | 80,678.9 | 78,884.0 | 3,413.5 | 4.3 | 96.0 | 92.3 |
| Forest expansion | 3,435.8 | 3,981.3 | 1,266.5 | 31.8 | 84.0 | 85.7 |
| Deforestation | 1,085.0 | 970.0 | 359.2 | 37.0 | 86.0 | 93.5 |
| Abandonment | 715.0 | 722.7 | 206.0 | 28.5 | 82.0 | 95.3 |

**Figure 4.** Summary of major land cover changes in quintile classes of slope (**a**), elevation (**b**) and distance to settlements (**c**) and roads (**d**). The charts present the percentage of forest, grassland and other vegetation classes that changed (increased or decreased).




*4.2. Socio-Economic Changes*

Both areas experienced significant socio-economic changes in the last 20 years (Table 7). The demographic changes in both areas are characterized by a substantial decrease in population and an increase in the population-aging index. Furthermore, both witnessed a substantial decrease in agricultural activities, portrayed both by a decrease in employment in the sector, as well as in the number of livestock, especially sheep and goats. The decrease in sheep and goat populations in the analyzed areas since 1990 is around 40% above the average 23% decrease in the European Union [51].

The Italian area used to be more commercially and strategically important due to its border location and had numerous customs, commercial and military zones. A significant part of its trade and transport activities diminished after the collapse of Yugoslavia in the year 1991 and even more after the entry of Austria and, later, Slovenia to the European Union, with the introduction of the Schengen regime. The majority of the army was withdrawn from the area, and commercial and customs zones were abandoned, accompanied by a breakdown of the local industry and mining activities. The area lost its role as an important trade and employment center in the wider region, even though it became better connected with the European highway and railroad network. Tourism activities, on the other side, witnessed an increase, as tourism became a more important part of the local economy. Even though wood processing witnessed an increase of activity in the area, forest harvesting declined by a third and is well below the allowed amount of forest harvesting.

**Table 7.** Socio-economic changes in the areas since 1989.

| Change | Gemona, Canal del Ferro and Val Canale [a] | Buzau Carpathians [b] |
| --- | --- | --- |
| Population | Depopulation: −9.6% of whole area, −31% Pontebba, −21% Tarvisio, −17% Resia. | Depopulation: −12.4% of whole area, −18% Gura Teghii, −17% Panatau. |
| Aging index [c] | 151.2 in 1990; 216.3 in 2010. | 79.9 in 1990; 143.7 in 2010. |
| Agricultural activities | −36.6% of cattle, −39.2 of sheep and goats, −69.8% of farming associations, −26.5 of employees in agriculture [d]. | −4.3% of cattle, −39.7% of sheep and goats, −12% of orchards, −32% of employees in agriculture and forestry. The collapse of agricultural associations and the emergence of subsistence farming (small fields and gardens). |
| Forestry activities | Wood harvest: −33% (currently 15%–20% of the annual increment) [e]. Employment in wood processing industry: +8.2%. Forest managed by state owned forestry associations. | Wood harvest: +23% (currently around 45% of the annual increment and rising). Employment in wood processing industry: −66%. The emergence of private forestry associations. The end of the governmental reforestation program: annually 400–600 ha reforested before 1989 [e]. |
| Industry and commerce | Employment: −12% in trade, −21% in transport, storage and communications, −73% in mineral extraction. | Employment: −39% in industry, −53% in mineral extraction. |
| Tourism | 0.5% increase in employees. Substantial expansion of tourism and recreation areas and an increase of overnights. Organization of the Winter Universiade in 2003. | −33% of employees. Individual tourist accommodations and a decrease in overnights. |
| Infrastructure | After 1989, completion of the infrastructural corridor: highway, high-speed railroad, high-voltage power line and gas pipeline. | After 1989, neglected by governmental infrastructural plans. Regular reconstruction of national road and railroad due to landslides. |
| Other | Withdrawal of army from the area after 1991. | Land restitution reforms: before 1989, nearly 100% of forests state owned. After the reforms, land returned to its former owners, resulting in 34.7% of forests in private ownership in 2011 [f] |

Notes: a, all statistics, collected on a municipal level from [40], if not stated otherwise; b, all statistics, collected on a municipal level from [46], if not stated otherwise; c, (population over 64/population under 15) × 100; d, [41]; e, forestry officials, regional data; f, agricultural officials.

The Romanian area witnessed socio-economic changes similar to the whole Carpathian region after the fall of communism: the fall of large-scale collective agricultural associations, the emergence of new land use policies and land ownership reforms, resulting in numerous new land owners [52,53]. Until the end of the 1980s, the area was subject to several governmental development and infrastructural plans. Examples of these are the water reservoir near Siriu in the northwest of the area, built for flood regulation, water storage for irrigation and energy production, and the reforestation plans, with the aim of reforesting the slopes in this landslide prone area and ensuring steady economic benefits from the forests. Since the 1990s, Romania has been expanding its traffic (motorways) and energy infrastructure; however, this area has been neglected by these plans. Furthermore, since 1989, the area has witnessed a collapse of industry, mineral extraction and wood processing activities, on one side, and a rapid increase in wood harvesting, on the other.

### *4.3. Stakeholders' Perception of Land Cover Changes*

In the Italian area, the results of the stakeholders' interviews were consistent with the findings of land cover mapping and classification (Table 8). Due to the multiple direct and indirect effects on the local economy, demography and land cover, the majority of stakeholders recognized as the most important change the completion of the infrastructural corridor through the valley, *i.e.*, the highway, high-speed railroad, high-voltage power line and gas pipeline. For stakeholders at the regional level, the second most significant change was the expansion of forests. Stakeholders from the municipal level described a wide variety of significant changes, *i.e.*, the expansion of settlements and recreational and sports facilities. The municipal authorities emphasized that before the legislation on risk zoning (law 267/1998, which clearly identified building constraints depending on risk levels), settlement expansion occurred also in areas at high risk of landslides, debris flows and flash floods. In fact, high risk areas, where houses were built before the law enforcement, experienced catastrophic consequences in terms of human casualties and financial damages in 2003 when several municipalities of the area were affected by numerous flash floods [34]. Besides the aspect of increased risk, settlement and infrastructural expansion changed the alpine landscape, as mentioned by researcher in the rural economy:

**Table 8.** Summary of stakeholders' perception of land cover changes in both areas.

| | **Gemona, Canal del Ferro and Val Canale** | **Buzau Carpathians** |
|---|---|---|
| | **Stakeholders' Observations** | |
| Major changes observed | Forest and urban expansion | Urban expansion |
| Possible causes identified | Forest expansion follows a long-term trend of agricultural abandonment, whereas urban expansion was caused by promoting economic activities, real estate investment and demand for secondary housing | Rapid economic development of Romania in the last 20 years, the increase in the well-being of the population and the demand for more housing and enterprise areas; chaotic dispersal as a result of legislative difficulties in the transition era |
| Perception of land cover changes | Associated with negative consequences due to landscape degradation and increased hydro-meteorological risk | Mostly positive, as the changes went hand-in-hand with economic development; recognized the increase in the hydro-meteorological risk |
| | **Researchers' Observations** | |
| Major changes observed | Forest and urban expansion | Forest expansion and deforestation |
| Comment on perceived changes | Stakeholders' observations in line with data | Stakeholders mostly think that land cover changes observed by the researchers are not that significant, as they compare the region to other Romanian regions, where similar changes happened on a larger scale |
| Perception of the consequences of land cover changes | Stakeholders' mostly aware of possible consequences of land cover changes | Stakeholders' minimize the possible negative consequences of deforestation, such as increased erosion and changes to landslide occurrence. They are aware of a possible higher risk, due to the increase in the value and number of the elements of risk |

> *"New infrastructure, together with the abandonment of the old one (mostly still present) caused severe degradation of the alpine landscape of the area. Some parts of the valley, like near Pontebba, are almost devastated due to the dense network of infrastructure."*

In the Romanian area, a few of the involved stakeholders identified deforestation among the most important land cover processes, as was revealed by our spatial data analysis (see Section 4.1 and Table 5). A usual explanation of the perceived irrelevance of this process was that the neighboring regions were more affected by it. As the rates and spatial pattern of deforestation after land ownership reforms in Romania vary in different regions [23,30,31], the process in Buzau County might be considered moderate by comparison. As reported by a representative of a privately owned forestry association: "Most illegal wood harvesting activities do not occur in the form of clear cuttings, with the majority of the clear cuts occurring in privately owned forests. Compared to other Romanian regions, large scale clear cuts have not reached alarming levels and mostly occur in the form of smaller patches."

Instead, the majority of stakeholders in Romania identified the increase of urban areas as most important, even though, in quantitative terms, our analysis observed it as relatively minor. This might be explained by their own focus on the process of obtaining building permits and dealing with the increasing demands of residents and investors, after Romania's entry into the European Union. As reported by one of the interviewees:

> *"Most of our time in the last 10 years has been spent on enabling the increase of economic activities and the well-being of the population. Expansion of urban areas was a consequence of this. I consider these changes as positive and most important, even though they might have some negative consequences. These changes have led to more funds for the local authorities, enabling the development of new activities."* (Spatial planner)

Table 9 summarizes the results emerging from these discussions with local stakeholders in a qualitative way. The aim of the table is to capture, in relatively simple and immediate terms, the variability of land cover processes resulting from long- *versus* short-term trends. We identified the perceived position intuitively without quantitative evaluation. As "short-term", we define conversions that were influenced mostly by recent socio-economic changes, while "long-term" refers to conversions following a trajectory specific for the case study for a longer time period than was analyzed.

At first glance, conversions in Romania are predominately due to recent events, or classified as "short-term" (Table 9), with the exception of "reforestation", which has a longer history than the other conversions, which were mostly spiked by the end of the communist regime in 1989. Most conversion trends in Italy have a longer history, with the exception of urbanization. Further stakeholder views together with why urbanization may be occurring despite factors otherwise indicating economic decline (see Table 7) will be discussed below.

**Table 9.** Land cover changes as defined as short- or long-term processes. This qualitative evaluation is based on the results of stakeholders' interviews. Short-term changes were influenced mostly by recent socio-economic changes, whereas long-term ones describe changes specific for the case study for a longer time period than was analyzed.

| Land Cover Conversion | Gemona, Canal del Ferro and Val Canale | Buzau Carpathians |
|---|---|---|
| Urban expansion | Short-term | Medium to long-term |
| Reforestation | Long-term | Medium-term |
| Deforestation | Medium to long-term | Short-term |
| Land abandonment | Long-term | Short-term |

## 5. Discussion

Drastic socio-economic changes since 1989 have had a significant effect on land cover changes in both areas. Even though the processes differ in spatial and relative terms between both case study areas, we could observe some surprising land cover processes, when relating them to socio-economic trends, especially depopulation in both areas. Examples of that are the significant increases of human influences in the form of urban expansion in Italy and deforestation in Romania. Further reasons behind these processes are discussed in this section.

Despite the decline in population and economic activities, a notable expansion of the urban land cover occurred in the Italian case study area. This can be associated with an increase in infrastructural and real estate development since the end of the 1980s. Three factors worked together to result in urban expansion: policy-makers encouraging real estate building to promote economic activity and wellbeing in the area, people building real estate as a form of investment and people building secondary homes due to the region's recreational and aesthetic value. In our area, all three factors were at work, while the last one, encouragement by policy-makers and real estate as investment, seem to have been dominant. As one interviewee stated:

> "*Policy-makers in the last few decades promoted construction, due to its influence on other economic activities, and saw it as a way to increase the living standard. Construction firms were engaging in housing and infrastructure projects, resulting in a large number of empty objects and possibly over-dimensioned infrastructure. Moreover, the emergence of secondary homes did not occur solely due to the attractive landscape in the area, but also as it was endorsed as a good way to save money through real estate.*" (Researcher in human geography)

Two other changes in the Italian site are more intuitively consistent with the decline of population and economic activity: land abandonment and reforestation. Both started after the Second World War, starting at the higher elevation areas: until 1989 most of the grassland areas at higher elevations had already been reforested, resulting in the doubling of the forest cover since 1950, as explained by the forestry officials.

At the same time, we identified deforestation as a minor land cover change process in the Italian area. According to our spatial analysis, 63.2% of this deforestation was due to the expansion of recreational areas (ski resorts) or energy infrastructure (gas pipelines, high voltage power lines), which occurred after 1989. Therefore, we attributed deforestation partly to the changes in the last 20 years.

In the Romanian area, the majority of land cover changes can be attributed to the sudden political changes and the consequent socio-economic and legislative difficulties. For example, after 1989, Romania introduced three land ownership reforms, where previously seized land is returned, with the 247/2005 restitution law being the latest [37]. Whereas most of the agricultural land is now under private ownership, the majority of the forest is still owned by the government (Table 7). As the following quote implies, ownership changes are among the most significant causes of deforestation:

> "*The Romanian forest code itself promotes sustainable forestry. The difficulties in its implementation and insufficient monitoring, together with the interplay between unemployment, poverty and chaotic land ownership legislation (three different reforms), lead to illegal logging.*" (Private forestry official)

Remaining land cover processes, such as land abandonment and consequential reforestation, are associated with the collapse of former agricultural associations, the evident decline of agricultural activities and the fragmented new land ownership pattern (Table 7). This made the management of the existent agricultural land nearly impossible, resulting in land abandonment and reforestation. On the other hand, the emergence of subsistence farms increased the pressure on slopes. This phenomenon, basically unknown to most European mountain areas, has been identified in the field, as the scale of the process (individual gardens and fields) prevents it from being identified by accessible data. Nevertheless, it is significant, as the potential side effects of steep slope farming are known to be severe (soil erosion, increased hazard occurrence) [54].

In both areas, the most extensive land cover change process was reforestation. It is well recognized in societies that experience economic development with urbanization and industrialization [55,56] and typical for European mountain areas. As summarized in Table 9, land cover change processes in Italy (except for urban expansion) were mostly following long-term trends, as opposed to Romania, where most of the processes can be attributed to socio-economic changes in the last 20 years, *i.e.*, what we consider short term. Interviewees in both areas agreed that it is difficult to cope with and manage external influences. What is more, they argued that external influences are the prevailing cause behind the negative consequences of land cover change (e.g., landscape degradation, increased risk).

Furthermore, for both study areas, the proportion of the area that changed (below 5%) might seem unimportant. Pontius *et al.* [49], however, noted that scientists should resist indicating the importance of land use/cover change processes solely due to their statistical importance. Therefore, we argue that the observed land cover changes are significant, when putting them into the context of changes to ecosystem services provisioning and the short analyzed time frame of a little over 20 years. Both case study areas are defined by complex physical-geographic characteristics, where deforestation and settlement expansion could have led to soil erosion and the increased occurrence or consequences of hydro-meteorological hazards, Moreover, land abandonment and forest expansion can have a significant effect on the landscape image and biodiversity of the areas.

This study has shown how a brief analysis of land cover change might lead to ignoring processes of land cover change, which occur on a smaller spatial extent, that, however, have significant consequences. Furthermore, while some processes (e.g., forest expansion) might be following a long-term trend typical for European mountain areas, others might be experiencing a rapid change that can be attributed solely to the context of the case study area. We demonstrated how necessary it is to recognize these particular processes of land cover change and to try to identify the possible driving forces behind them. Overall driving forces, such as depopulation and general economic development, are not enough to describe land cover changes, as they might result in contrasting and unanticipated results. Other driving forces, such as external investors (in real estate), political decisions on the national level (infrastructural projects), changes to policy (land ownership, forest management) and the uncertainty connected with all these driving forces might prevail, especially in a time of transition. What is more, these external driving forces are beyond the abilities of local decision makers to cope with the pressures to the land cover. This is especially important in mountain areas, as they have to deal with the possible negative consequences of these changes, for example, in the form of increased risk or degradation of the landscape.

## 6. Conclusions

Socio-economic changes in Europe after the end of the 1980s resulted in a variety of land cover changes in the Alps and the Carpathians. In relative terms, the most widespread land cover process in both of the analyzed mountain areas was the expansion of forest cover. The spatial and temporal rate of this long-term process is similar to most European mountain areas. This process goes along with the loss of important habitats for biodiversity, such as grasslands, and changes in traditional forms of agriculture, such as sheep and goat pastures.

Other observed land cover changes show how local processes differ from general trends. The Eastern Italian Alps area witnessed a substantial expansion of urban areas, among others, due to secondary housing, tourism and traffic infrastructure. In the Romanian Carpathians, deforestation was identified as one of the most significant land cover change processes. Results in both areas pose new questions on the possible increase of risk to hydro-meteorological hazards due to the observed land cover changes. Another important potential consequence to the land cover changes includes soil degradation due to erosion.

The complex relationship between socio-economic changes as driving forces, and land cover changes as a consequence, is difficult to describe and analyze. Therefore, different types of data and methods, *i.e.*, quantitative remote sensing analysis and qualitative interviews, have been used and integrated. In this way, we were able to portray a broader picture of land cover changes in a time of intense socio-economic changes. The revealed mismatches between stakeholders' perceptions and the results of spatial data analysis represent an added value to the spatial research results, particularly in answering the possible causes behind land cover changes and in understanding the importance of particular changes that seem relatively small, as, for example, in the Romanian site.

It is a continuing challenge in studies of local land cover changes and socio-economic transitions to integrate all observations, in order to understand the driving forces of land cover changes in a more comprehensive and systematic way. From our experiences in both study areas, we suspect that a continuous, long-term and inclusive transdisciplinary process may best help define scientific questions and support politicians and decision makers in understanding and managing the expected land cover changes in European mountain areas.

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**Author Contributions**

Žiga Malek was involved in all stages of the research: data gathering and interpretation, field visits, land cover classification, GIS and statistical analysis, performing the majority of interviews. Anna Scolobig was involved in data gathering, design of the interview protocol, performing interviews, stakeholder perception analysis and socio-economic data interpretation. Dagmar Schröter was involved in the design of interview protocol, stakeholder perception analysis and socio-economic data interpretation. All authors were involved in the design of the research and writing of the report.

**Conflicts of Interest**

The authors declare no conflict of interest.

**References**

1. Olsson, E.G.A.; Austrheim, G.; Grenne, S.N. Landscape change patterns in mountains, land use and environmental diversity, Mid-Norway 1960–1993. *Landsc. Ecol.* **2000**, *15*, 155–170.
2. Ioffe, G.; Nefedova, T.; Zaslavsky, I. From spatial continuity to fragmentation: The case of russian farming. *Ann. Assoc. Am. Geogr.* **2004**, *94*, 913–943.
3. Bičík, I.; Jeleček, L.; Štěpánek, V. Land-use changes and their social driving forces in Czechia in the 19th and 20th centuries. *Land Use Policy* **2001**, *18*, 65–73.
4. Irland, L.C. State failure, corruption, and warfare: Challenges for forest policy. *J. Sustain. For.* **2008**, *27*, 189–223.
5. MacDonald, D.; Crabtree, J.; Wiesinger, G.; Dax, T.; Stamou, N.; Fleury, P.; Gutierrez Lazpita, J.; Gibon, A. Agricultural abandonment in mountain areas of Europe: Environmental consequences and policy response. *J. Environ. Manag.* **2000**, *59*, 47–69.
6. Körner, C.; Spehn, E.; Baron, J.; Ohsawa, M. Mountain Systems. In *Ecosystems and Human Well-Being: Current State and Trends: Findings of the Condition and Trends Working Group of the Millennium Ecosystem Assessment*; Island Press: Washington, DC, USA, 2005; pp. 681–716.
7. Tasser, E.; Walde, J.; Tappeiner, U.; Teutsch, A.; Noggler, W. Land-use changes and natural reforestation in the Eastern Central Alps. *Agric. Ecosyst. Environ.* **2007**, *118*, 115–129.
8. Tasser, E.; Mader, M.; Tappeiner, U. Effects of land use in alpine grasslands on the probability of landslides. *Basic Appl. Ecol.* **2003**, *4*, 271–280.
9. Glade, T. Landslide occurrence as a response to land use change: A review of evidence from New Zealand. *Catena* **2003**, *51*, 297–314.
10. Chemini, C.; Rizzoli, A. Land use change and biodiversity conservation in the Alps. *J. Mt. Ecol.* **2003**, *7*, 1–7.

11. Giupponi, C.; Ramanzin, M.; Sturaro, E.; Fuser, S. Climate and land use changes, biodiversity and agri-environmental measures in the Belluno province, Italy. *Environ. Sci. Policy* **2006**, *9*, 163–173.
12. Schneeberger, N.; Bürgi, M.; Hersperger, A.M.; Ewald, K.C. Driving forces and rates of landscape change as a promising combination for landscape change research—An application on the northern fringe of the Swiss Alps. *Land Use Policy* **2007**, *24*, 349–361.
13. Lambin, E.F.; Geist, H. *Land-Use and Land-Cover Change: Local Processes and Global Impacts*; Springer: Berlin/Heidelberg, Germany, 2006.
14. Kräuchi, N.; Brang, P.; Schönenberger, W. Forests of mountainous regions: Gaps in knowledge and research needs. *For. Ecol. Manag.* **2000**, *132*, 73–82.
15. Cremene, C.; Groza, G.; Rakosy, L.; Schileyko, A.A.; Baur, A.; Erhardt, A.; Baur, B. Alterations of steppe-like grasslands in Eastern Europe: A threat to regional biodiversity hotspots. *Conserv. Biol.* **2005**, *19*, 1606–1618.
16. Bätzing, W. *Die Alpen: Geschichte und Zukunft Einer Europäischen Kulturlandschaft*; C.H.Beck: München, Germany, 2005.
17. Erdeli, G.; Dinca, A.I. Tourism—A vulnerable strength in the protected areas of the Romanian Carpathians. *Procedia-Soc. Behav. Sci.* **2011**, *19*, 190–197.
18. Dalla Valle, E.; Lamedica, S.; Pilli, R.; Anfodillo, T. Land use change and forest carbon sink assessment in an alpine mountain area of the Veneto region (Northeast Italy). *Mt. Res. Dev.* **2009**, *29*, 161–168.
19. Cocca, G.; Sturaro, E.; Gallo, L.; Ramanzin, M. Is the abandonment of traditional livestock farming systems the main driver of mountain landscape change in Alpine areas? *Land Use Policy* **2012**, *29*, 878–886.
20. Bender, O.; Borsdorf, A.; Fischer, A.; Stotter, J. Mountains Under Climate and Global Change Conditions—Research Results in the Alps. In *Climate Change—Geophysical Foundations and Ecological Effects*; Blanco, J.A., Ed.; InTech: Rijeka, Croatia, 2011.
21. Instituto Nazionale della Montagna. *Atlante Statistico Della Montagna Italiana. Statistical Atlas of Italian Mountains*; Bononia University Press: Bologna, Italy, 2007.
22. Turnock, D. Ecoregion-based conservation in the Carpathians and the land-use implications. *Land Use Policy* **2002**, *19*, 47–63.
23. Kuemmerle, T.; Müller, D.; Griffiths, P.; Rusu, M. Land use change in Southern Romania after the collapse of socialism. *Reg. Environ. Chang.* **2008**, *9*, 1–12.
24. Müller, D.; Kuemmerle, T.; Rusu, M.; Griffiths, P. Lost in transition: Determinants of post-socialist cropland abandonment in Romania. *J. Land Use Sci.* **2009**, *4*, 109–129.
25. Taff, G.N.; Müller, D.; Kuemmerle, T.; Ozdeneral, E.; Walsh, S.J. Reforestation in Central and Eastern Europe After the Breakdown of Socialism. In *Reforesting Landscapes*; Nagendra, H.; Southworth, J., Eds.; Springer-Netherlands: Dordrecht, The Netherlands, 2009; Volume 10, pp. 121–147.
26. Baumann, M.; Kuemmerle, T.; Elbakidze, M.; Ozdogan, M.; Radeloff, V.C.; Keuler, N.S.; Prishchepov, A.V.; Kruhlov, I.; Hostert, P. Patterns and drivers of post-socialist farmland abandonment in Western Ukraine. *Land Use Policy* **2011**, *28*, 552–562.
27. Kozak, J.; Estreguil, C.; Vogt, P. Forest cover and pattern changes in the Carpathians over the last decades. *Eur. J. For. Res.* **2007**, *126*, 77–90.

28. Kuemmerle, T.; Hostert, P.; Radeloff, V.C.; Perzanowski, K.; Kruhlov, I. Post-socialist forest disturbance in the Carpathian border region of Poland, Slovakia, and Ukraine. *Ecol. Appl.* **2007**, *17*, 1279–1295.
29. Kuemmerle, T.; Chaskovskyy, O.; Knorn, J.; Radeloff, V.C.; Kruhlov, I.; Keeton, W.S.; Hostert, P. Forest cover change and illegal logging in the Ukrainian Carpathians in the transition period from 1988 to 2007. *Remote Sens. Environ.* **2009**, *113*, 1194–1207.
30. Griffiths, P.; Kuemmerle, T.; Kennedy, R.E.; Abrudan, I.V.; Knorn, J.; Hostert, P. Using annual time-series of Landsat images to assess the effects of forest restitution in post-socialist Romania. *Remote Sens. Environ.* **2012**, *118*, 199–214.
31. Knorn, J.; Kuemmerle, T.; Radeloff, V.C.; Keeton, W.S.; Gancz, V.; Biriş, I.A.; Svoboda, M.; Griffiths, P.; Hagatis, A.; Hostert, P. Continued loss of temperate old-growth forests in the Romanian Carpathians despite an increasing protected area network. *Environ. Conserv.* 2012, *40*, 1–12.
32. Knorn, J.; Kuemmerle, T.; Radeloff, V.C.; Szabo, A.; Mindrescu, M.; Keeton, W.S.; Abrudan, I.; Griffiths, P.; Gancz, V.; Hostert, P. Forest restitution and protected area effectiveness in post-socialist *Romania. Biol. Conserv.* **2012**, *146*, 204–212.
33. Sangati, M. Flash Flood Analysis and Modelling in Mountain Regions. Ph.D. Thesis, University of Padova, Padova, Italy, 2009.
34. Borga, M.; Boscolo, P.; Zanon, F.; Sangati, M. Hydrometeorological analysis of the 29 August 2003 flash flood in the eastern Italian Alps. *J. Hydrometeorol.* **2007**, *8*, 1049–1067.
35. Jarvis, A.; Reuter, H.I.; Nelson, A.; Guevara, E. Hole-Filled Seamless SRTM Data V4. International Centre for Tropical Agriculture (CIAT). Available online: http://srtm.csi.cgiar.org (accessed on 11 November 2013).
36. Muică, N.; Turnock, D. A toponomical approach to the agrarian history of the pătârlagele depression (Buzău Subcarpathians, România). *Hum. Geogr.* **2008**, *2*, 928–949.
37. Ministry of Agriculture and Rural Development of Romania. *Programul Naţional de Dezvoltare Rurală 2007–2013*; Government of Romania: Bucharest, Romania, 2012.
38. Bălteanu, D.; Popovici, E.A. Land use changes and land degradation in post-socialist Romania. *Romanian J. Geogr.* **2010**, *54*, 95–105.
39. Regione, F.V.G. Catalog of Territorial and Environmental Data of the Autonomous Region Friuli Venezia Giulia. Available online: http://irdat.regione.fvg.it/WebGIS/ (accessed on 20 January 2012).
40. Instituto Nazionale di Statistica (ISTAT). Italian National Institute for Statistics Data Warehouse. Available online: http://dati.istat.it/ (accessed on 19 April 2012).
41. Instituto Nazionale di Statistica (ISTAT). Censimento Generale dell'Agricoltura. Italian Agricultural Census. Available online: http://dati-censimentoagricoltura.istat.it (accessed on 19 April 2012).
42. Autonomous Region of Friuli Venezia Giulia. Statistics of the Autonomous Region of Friuli Venezia Giulia. Available online: http://www.regione.fvg.it/rafvg/cms/RAFVG/ (accessed on 20 April 2012).
43. US Geological Survey (USGS). Earth Explorer. Available online: http://earthexplorer.usgs.gov/ (accessed on 18 January 2013).
44. Google Earth 7.0 Nehoiu, Romania. 45°25′18″N, 26°17′46″E. Digital Globe 2012. Available online: http://earth.google.com/ (accessed on15 September 2012).

45. Romanian Academy, Institute for Geography (IGAR). *Digital Elevation Model for Buzau County*; IGAR: Bucharest, Romania, 2012.
46. Institutul National de Statistica (INSSE). Romanian National Institute of Statistics Data Portal. Available online: http://www.insse.ro/ (accessed on 11 May 2012).
47. Quantum GIS Geographic Information System. Open Source Geospatial Foundation Project 2012. Available online: http://www.qgis.org (accessed on 10 January 2013)
48. *Exelis ENVI*; Exelis Visual Information Solutions: Boulder, CO, USA, 2012.
49. Pontius, R.G., Jr.; Shusas, E.; McEachern, M. Detecting important categorical land changes while accounting for persistence. *Agric. Ecosyst. Environ.* **2004**, *101*, 251–268.
50. Olofsson, P.; Foody, G.M.; Stehman, S.V.; Woodcock, C.E. Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation. *Remote Sens. Environ.* **2013**, *129*, 122–131.
51. Ataide Dias, R.; Mahon, G.; Dore, G. *EU Sheep and Goat Population in December 2007 and Production Forecasts for 2008*; Eurostat Publication No. 67; European Comission, Eurostat: Luxemburg, 2008.
52. Mathijs, E.; Swinnen, J.F.M. The economics of agricultural decollectivization in East Central Europe and the former Soviet Union. *Econ. Dev. Cult. Chang.* **1998**, *47*, 1–26.
53. Lerman, Z.; Csaki, C.; Feder, G. Evolving farm structures and land use patterns in former socialist countries. *Quart. J. Int. Agric.* **2004**, *43*, 309–336.
54. Lal, R. Soil degradation by erosion. *Land Degrad. Dev.* **2001**, *12*, 519–539.
55. Mather, A. The Transition from Deforestation to Reforestation in Europe. In *Agricultural Technologies and Tropical Deforestation*; Angelsen, A., Kaimowitz, D., Eds.; CABI Publishing: Wallingford, UK, 2001; pp. 35–54.
56. Rudel, T.K.; Coomes, O.T.; Moran, E.; Achard, F.; Angelsen, A.; Xu, J.; Lambin, E. Forest transitions: Towards a global understanding of land use change. *Glob. Environ. Chang.* **2005**, *15*, 23–31.

# Appendix B: The impact of future land use change under tourism development scenarios: an example from the Italian Alps

Malek Ž, Boerboom L.

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**Abstract**

Changes to the land use, such as the removal of natural vegetation or expansion of urban areas can result in an increase to hydro-meteorological risk. This has led to higher interest of decision makers and scientists in their future consequences of these driving forces. Due to high uncertainties regarding modeling future changes to hydro-meteorological risk, a suitable tool is scenario development. Scenarios are not exact forecasts, but images of plausible futures. When studying future land dynamics, emphasis should especially be given to areas experiencing high rates of socio-economic change. We have focused on the eastern Italian Alps, facing increasing pressure due to tourism development. Identified driving forces of local land use changes are mostly external and difficult to quantify. Moreover, this area is subject to numerous natural hazards, among them flash floods, debris flows and rockfall, making it necessary to study potential future land use changes. We present a scenario generation methodology, based on existing decisions and assumptions of future socio-economic development. We aimed to develop a framework leading to plausible scenarios that can overcome data inaccessibility, and can address external driving forces. We combined a set of different methods: qualitative methods such as stakeholder interviews and cognitive mapping, together with geospatial methods such as GIS, geostatistics and environmental modeling. We involved stakeholders from the beginning to support the steps of data generation, understanding the system of land change, and developing a land dynamic model for scenario development. This way we generated spatio-temporal scenarios that can assist future spatial planning or improve the preparedness for possible undesirable development.

## Introduction

Land use changes can have significant consequences in mountainous environments, characterized by high occurrence of hydro-meteorological hazards, vulnerable mountain societies and slower recovery rates of ecosystems (Körner et al. 2005). They can affect hydro-meteorological risk, defined as potential loss to a system exposed to hydro-meteorological hazards such as floods and landslides (Fuchs et al. 2013). They can increase the risk by affecting the occurrence of hazards due to increased surface runoff after deforestation or expansion of impervious surfaces (Glade and Crozier 2005). Moreover, land use changes such as urban expansion can result in an increase and changes to the spatial distribution of elements at risk (Bronstert et al. 2002; Glade 2003). This acknowledged relationship between land use change and their impact on mountain communities has recently led to increased attention of decision makers in driving forces and consequences of such changes (Schneeberger et al. 2007). Research of future land use change has so been proposed as significant when dealing with changes to hydro-meteorological risk (Tollan 2002; Barredo and Engelen 2010).

A suitable method to address potential future land use changes is scenario development; it offers exploring possible futures and their environmental consequences, and aids decision-making as it enables to analyze possible options (Kriegler et al. 2012). Scenarios are not exact forecasts, but images of plausible futures (Abildtrup et al. 2006). This way, they are a creative, visionary tool, assisting us to plan for a desired future, or preparing for possible undesirable events (Deshler 1987; Wollenberg et al. 2000). Instead of being developed by researchers only, it is more suitable to develop scenarios through stakeholder participation. Interactive "two way" participatory approaches offer a chance for discussion, negotiation and reaching agreement (Patel et al. 2007). Participatory scenario development can thus be considered as more reliable and relevant (Von Korff et al. 2010).

Participatory scenario development has been applied in a variety of issues: community forest management (Wollenberg et al. 2000), rural funding policy in mountainous landscapes (Bayfield et al. 2008), deforestation in Brazil (Kok 2009), forest management impacts on livelihoods (Kassa et al. 2009), future environmental changes (Odada et al. 2009), management of natural parks (Daconto and Sherpa 2010), and changes to freshwater resources (van Vliet, Kok, and Veldkamp 2010). These attempts however rarely generate spatially explicit results.

Spatially explicit modeling is needed to identify critical areas that are likely subject to change (Verburg et al. 1999). This is of high importance in mountain areas, with specific biophysical (terrain, hydrology, soil, geology) and socio-economic characteristics (accessibility, population and employment density). Still, there are few attempts where participatory scenario development has resulted in spatially explicit results (Castella and

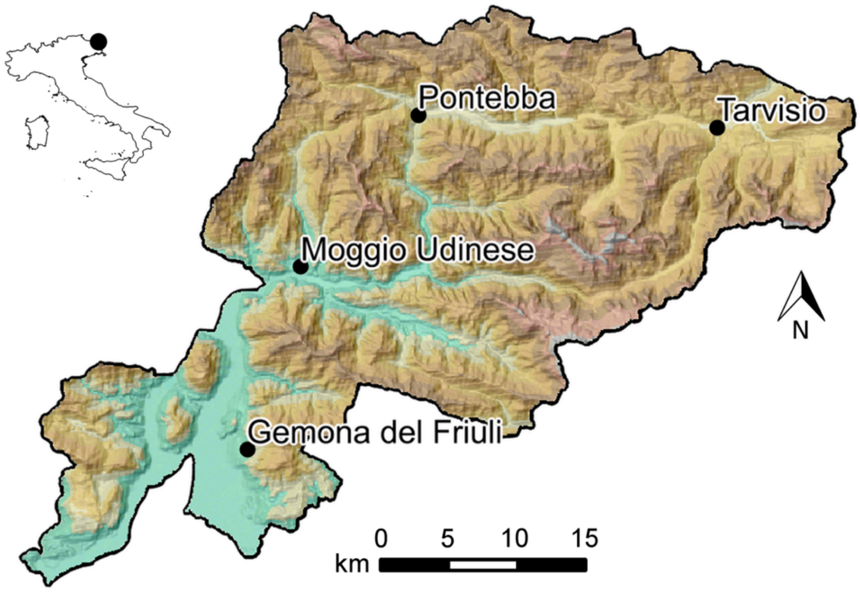
Verburg 2007; Potvin et al. 2007; Swetnam et al. 2011; Hoyer and Chang 2014). To further investigate the possibility to integrate participatory approaches with spatial simulation, we propose a multi-step scenario generation framework. The framework was developed and applied in a regional scale case study in the Italian Alps, where the uncertainties regarding future driving forces of land use change are high. We aimed to develop a framework with following characteristics: (1) it is able to develop scenarios that are plausible, (2) it can overcome data inaccessibility, and (3) can address external driving forces that are difficult to quantify. Moreover, our aim was to identify potential hot spots of change and changes to the land pattern.

## Study area

The Mountain community of Gemona, Canal del Ferro and Val Canale (Figure 1) lies in northeastern Italy in the Autonomous Region of Friuli Venezia Giulia, bordering Austria and Slovenia (46°30′25″N, 13°26′25″E). The size of the area is 1150 $km^2$. It lies in the Carnian and Julian Alps, rising up to 2754 m. The area is defined by steep slopes, high relative relief (up to 1500 m) and the mean precipitation of 2000 mm (Cucchi et al. 2000). The area is subject to various natural hazards, among them flash floods and debris flows (Borga et al. 2007). Around 33000 people inhabit the area, however only two settlements are larger than 4000 inhabitants (Tarvisio and Gemona del Friuli). Since 1990 the area witnessed a 10 % decrease in population (ISTAT 2014). Despite depopulation and a dramatic decrease in economic activities since the 1980s, the area witnessed a 12 % increase in built up areas due to tourism development, real estate development and infrastructural projects (Malek et al. 2014). The area receives a lot of efforts from the regional and national government to maintain the population and landscape in the area, mainly due to the growing touristic development and strategic importance of the area as an international energy and communication corridor. Interest for further development and consequently sustainable land development and risk management is therefore high.

**FIGURE 1**

Map and location of the study area. Data provided by Regione FVG (2013)




**Methods**

**Elicitation of stakeholders' knowledge**

We began our analysis by investigating local system knowledge. First, we performed interviews and group discussions with 10 stakeholders, representing all levels of decision-making and research in the study area, from local to regional level (Table 1). The interviews were performed in October and November 2012. We developed cognitive maps by collecting concepts on demographic, institutional, economic, cultural and environmental aspects of past, present and future land use change. Cognitive mapping is a qualitative methodology, where numerous concepts are connected to each other in a form of a graph, representing an expert based mental model (Axelrod 1976). Through involvement of experts, significant knowledge about the system can be encoded and visualized, thus improving inaccessible data or intangible driving forces (Eden 1992). The participants' answers were used to identify most relevant elements in the area, relating to causes and consequences of land use change. The concepts covered the observed changes, their perceived importance, and consequences; a special emphasis was given to identify possible external and other intangible driving forces. Later, the concepts were connected depending on the recognized relationships between them. This was done, by generating an entity-relation matrix, to represent binary relationships between the concepts. Then, the matrix was visualized in the form of a cognitive map (Figure 2). This was done using Gephi, software for visualizing and analyzing networks (Bastian et al. 2009).

**TABLE 1**

Involved stakeholders and their focus on land use changes; a) demographic changes; b) changes to agriculture, forestry; c) environmental (agriculture, forestry, risk) policy; d) economic development; e) consequences of land use changes.

| | | **Aspect of land use change** | | | | |
|---|---|---|---|---|---|---|
| **Level** | Stakeholder | a | b | c | d | e |
| **Local (Municipalities)** | Mayor | x | x | | x | |
| | Local | x | x | | | |
| | Forestry technician | | x | x | | x |
| | Spatial planner | | | x | x | x |
| | Civil protection officer | | x | | | x |
| | Researcher on human geography | x | | | x | x |
| **Regional (Autonomous region)** | Forestry official | | x | x | | x |
| | Geologist | | | x | | x |
| | Officials at regional civil | | | x | | x |
| | Researcher on rural economy | x | x | | x | |

**Structuring stakeholders' knowledge into a conceptual model**

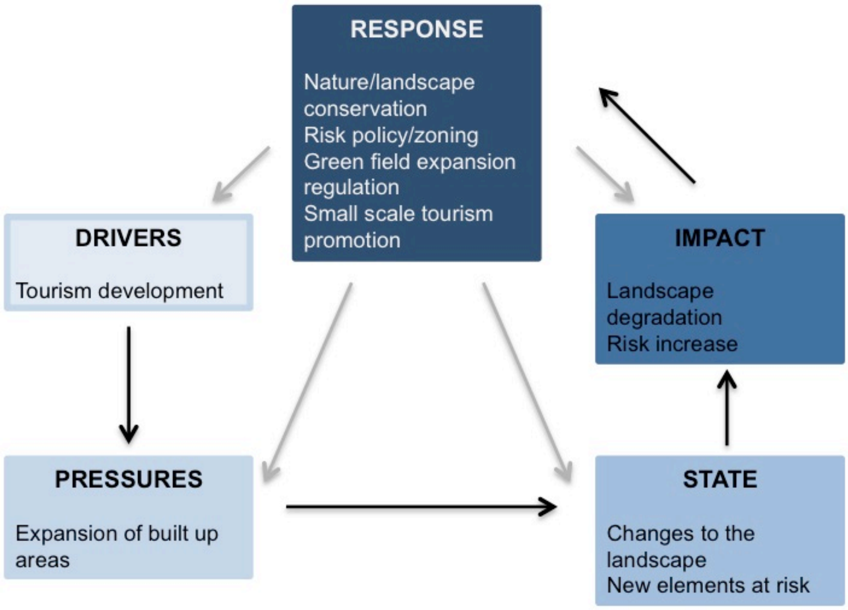
To structure the relationships between the concepts in the observed human-environment system depicting land change processes in the study area, we adopted the Driving Forces – Pressure – State – Impact – Response (DPSIR) framework (EEA 1999). Here, we selected the most significant concepts on future land use change and organized and reframed them in a cause-response framework (Figure 3). This enabled us to derive indicators, identify management objectives and preferences, and served as a framework for scenario development. There are many applications of the DPSIR framework in land systems science, especially to bridge the gap between the biophysical and socio-economic variables of the human-environment system (Bürgi et al. 2004; Verburg 2006). Concepts, categorized as Driving forces (D) have been defined as key scenario concepts, as they were recognized as most significant to influence future land changes. With the P, S and I concepts we defined the concepts that would subsequently need to be generated by external statistical, GIS, and spatial allocation models by the researchers. The Response (R) concepts represent the options for land use management identified by the experts. Choice of indicators for these concepts followed. Indicators have been chosen according to next criteria: (1) significance and understanding by the stakeholders, (2) relevance for land change processes, (3) data accessibility, and (4) possibility of expressing them in quantitative, spatial terms.

**FIGURE 2**

Example of an unstructured Cognitive Map on land use changes in the area

**FIGURE 3**

Drivers-Pressures-State-Impact-Response framework of land use changes in the study area




## Developing scenarios

After establishing a conceptual land use change model, it was more straightforward to develop future scenarios. These are a consequence of possible future states of concepts categorized as Driving forces (D). Preferable, these should not only be distinguished as low, normal and high based on different increase or decrease rates, but grounded on different logic and assumptions (Ogilvy and Schwartz 1998). Having identified tourism development as a main driver of land use change in the area, the stakeholders did not consider possible future scenarios abstract anymore, as they could associate it with a tangible indicator of tourism accommodation.

The stakeholders had concrete development plans in terms of future tourism development, defined in form of a desirable 30 % increase in accommodation facilities until 2035 (Table 3). This goal is relatively high, due to the competition of the study area with other, more successful Italian Alpine tourist areas, such as the neighbouring Carnia, South Tyrol and also Carinthia in Austria. Compared to these areas, the study area is falling behind in terms of accommodation facilities and tourism infrastructure (ISTAT 2014). In order to achieve the desired higher tourism revenue it is therefore necessary to increase the accommodation facilities, as only intensifying the current lodging objects or increasing the prices would not suffice (according to the development plans). However, the stakeholders recognized two options how to achieve this goal: to continue with the business as usual development pattern, where tourism accommodation was mostly based on individual incentives and small scale tourism objects; or whether to focus on an alternative pathway where tourism development is driven by larger objects such as hotel or chalet resorts (Table 3). These two options however have different consequences in terms of demands for space and the spatial pattern of land change.

**TABLE 2**

Indicators of DPSIR components

| DPSIR component | Indicator | Quantification |
|---|---|---|
| **Drivers** | | |
| Tourism development | Tourist accommodation | Nr. of beds |
| **Pressures** | | |
| Expansion of built up areas | Demand for built up land | Bed density per ha |
| **State** | | |
| Changed landscape, New elements at risk | New built up areas | Ha of new built up areas |
| **Impact** | | |
| Landscape degradation | Lost “green” areas | Forest, grassland and agricultural loss in ha |
| Risk increase | Built up areas in risk zones | Ha of built up areas in high risk zones |
| **Response** | | |
| Nature/landscape conservation | Protected areas | Restriction zones |
| Risk policy | Excluded areas (zoning, slopes) | Restriction zones |
| Green field expansion regulation | Promotion of intensive hotel resorts | Allocation of built up demand in form of fewer larger built up patches (scenario related) |
| Small scale tourism promotion | Promotion of individual small tourism facilities | Allocation of built up demand in form of numerous smaller built up patches (scenario related) |

**TABLE 3**

Description of the baseline and scenarios. Current data on beds obtained from ISTAT (2014).

| Scenario | Description |
|---|---|
| Baseline (2013) | total beds = 5731<br><br>hotel beds = 2334<br><br>beds in other individual tourism facilities = 3397 |
| Business as usual | 30 % increase of accommodation facilities until 2035<br><br>Promoting small scale tourism facilities (individual objects) |
| Alternative development | 30 % increase of accommodation facilities until 2035<br><br>Promoting high density tourism facilities (hotels, chalet resorts) |

**Spatial allocation and impact evaluation**

Following the conceptual DPSIR model (Figure 3) and the quantitative indicators (Table 2), we developed a spatial allocation model in Dinamica EGO (Soares-Filho, Cerqueira, and Pennachin 2002). This environmental modeling platform has already been applied in modeling urban dynamics, agricultural expansion, or forest cover change (de Almeida et al. 2003; Maeda et al. 2011; Kamusoko et al. 2013). The two scenarios described before define the demand for urban expansion between 2013 and 2035 calculated over 5 year time steps. These projected 5 year demands were allocated, according to spatial transition rules, explained below. We have modeled the transitions from all agricultural, forest and grassland land cover types, to new urban areas, either hotel areas or individual tourism facilities.

The transitions were calibrated in Dinamica EGO using land cover data from 1990, 2000 and 2013, and a variety of spatial factors: elevation, slope, aspect, distance to roads, distance to recreational and ski areas, distance to service areas (towns) and distance to water bodies. This was done by applying the weights of evidence technique, a Bayesian probability method to identify the influence of spatial factors on land change transitions using historic observations of that transition (Bonham-Carter 1994; Hosseinali and

Alesheikh 2008). The result was a probability map showing the areas, where urban expansion is more likely.

The transitions were then allocated on a 30 m resolution using a cellular automata (CA) module. CA models are bottom-up models, consisting of a grid based landscape, where every cell is associated with a state, in this case land cover types (Engelen et al. 1995). Cells change their states, according to transition rules and cell neighborhood (Mitsova, Shuster, and Wang 2011). All areas where it is legally forbidden to develop built up areas, were excluded from a possible transition in our model. These were nature-protection areas, and areas of legally defined highest and high hydro-meteorological risk as defined by the regional government (Regione FVG 2013). We also included other limitations, such as areas on steep slopes, erosion areas and land adjacent to water bodies. These exclusions were defined as Response options in the local DPSIR concept of land changes (Figure 2).

The change allocation followed different rules for hotels and for individual tourism facilities, described by the mean urban patch size of the simulated urban expansion. Both the demand per tourist bed, as well as its spatial pattern of allocation (the mean size of a new built up patch) were calibrated by relating statistical data on tourism between 1990 and 2013 with observed tourism related urban expansion in the same period. Moreover, spatial allocation in the Business as usual development allowed the expansion of existing urban areas, as well as forming new individual smaller urban patches (such as individual houses). In the Alternative development scenario, the spatial allocation promoted the formation of new hotel areas near existing settlements.

The impact of both scenarios was assessed in a GIS (Quantum GIS Development Team 2013). To identify the extent of built up areas on risk zones, we measured all new built up areas on zones with possible geological restrictions, and zones with moderate flood risk. These areas defined by the regional government, and new buildings on these areas are allowed if they comply with the general regulations of the spatial plan (Regione FVG 2013). Land use changes can also have other consequences than changes to hydro-meteorological risk, such as habitat loss, degraded biodiversity levels, and a lower quality of the landscape image (Chemini and Rizzoli 2003; Giupponi et al. 2006). Therefore, we identified the areal extent of lost natural and semi-natural areas, by measuring the loss of forests, grasslands and agricultural areas.

## Results

The urban expansion probability shows the most attractive areas for urban expansion (Supplement data, Appendix S1). Preference is given to flatter areas, on the valley floor near the existing settlements, water bodies and road network. Whilst we did not exclude areas high in the Alps on purpose, the weights of evidence model calculated a very low probability of expansion on these areas, based on an analysis of land use changes between the 1990 and 2013.

The scenarios differ both in terms of the total urban expansion due to the increase in accommodation (Table 4), as well as in the spatial pattern and distribution of these changes (Figure 4). The Business as Usual (BAU) scenario results in a higher increase of urban areas compared to the Alternative scenario, following the fact that the observed accommodation density (beds per ha) is lower than in the Alternative scenario (Table 4). The results become more obvious when focusing more in detail on particular areas, like on the surroundings of Tarvisio, where the projected urban expansion is 3.7 times for the BAU and 3.3 times higher in the Alternative scenario, compared to the regional average increase.

It is difficult to quantify the impact on the landscape and risk solely by looking at the increase of urban areas. Therefore, the impact is assessed by presenting the loss of particular natural and semi-natural land cover types due to urban expansion (Figure 5a), or by identifying the extent of new areas on areas with possible risk (Figure 5b). The BAU scenario results in a higher loss of forests, grasslands and agricultural areas. Also, in this scenario more areas are projected to occur on areas with possible geological risk. The Alternative scenario however results in more urban expansion on areas with moderate flood risk. This is mostly due to the fact, that the simulated urban expansion in this scenario is defined by larger homogeneous areas. If situated in areas with moderate flood hazard, these larger urban patches cover more hazard prone areas, than smaller urban patches of the BAU scenario, that are more evenly scattered across the landscape.

**TABLE 4**

Results of both scenarios in form of the DPSIR framework

| | **BAU** | **Alternative** |
|---|---|---|
| **Drivers** | | |
| Increase of accommodation facilities (nr. of beds) | 1769 | 1769 |
| **Pressures** | | |
| Demand for built up areas (and spatial pattern) | 180 beds per ha<br><br>0.10 mean urban patch size | 281 beds per ha<br><br>0.66 mean urban patch size |
| **State** | | |
| New built up areas (ha) and relative increase | 73.4 (2.7 %) | 53.5 (2.0 %) |
| Local relative increase in the most touristic area (Tarvisio) | 9.9 % | 6.6 % |
| **Impact** | | |
| Landscape degradation (ha) | | |
| Forest loss | 28.9 | 22.4 |
| Grassland loss | 29.3 | 18.2 |
| Agricultural loss | 13.9 | 11.5 |
| Risk increase (ha) | | |
| Expansion on areas with high geological risk | 18.0 | 13.9 |
| Expansion on areas with moderate flood risk | 4.4 | 5.9 |

**FIGURE 4**

Simulated 2035 scenarios, zoomed in to the tourism attraction area near Tarvisio. The maps show the difference in the spatial distribution between the BAU (a) and Alternative (b) scenario. The red patches show the simulated urban expansion for each scenario.

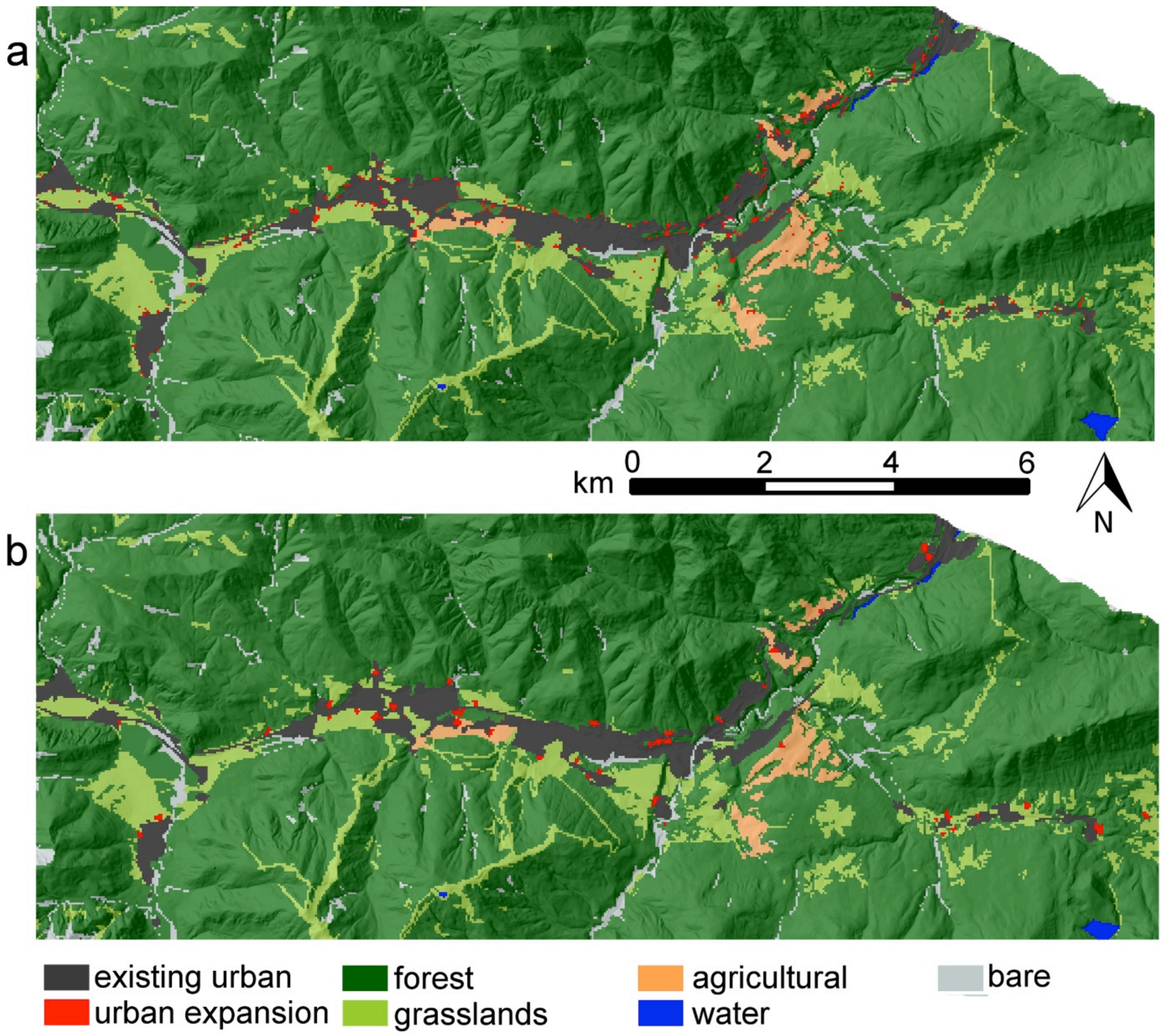
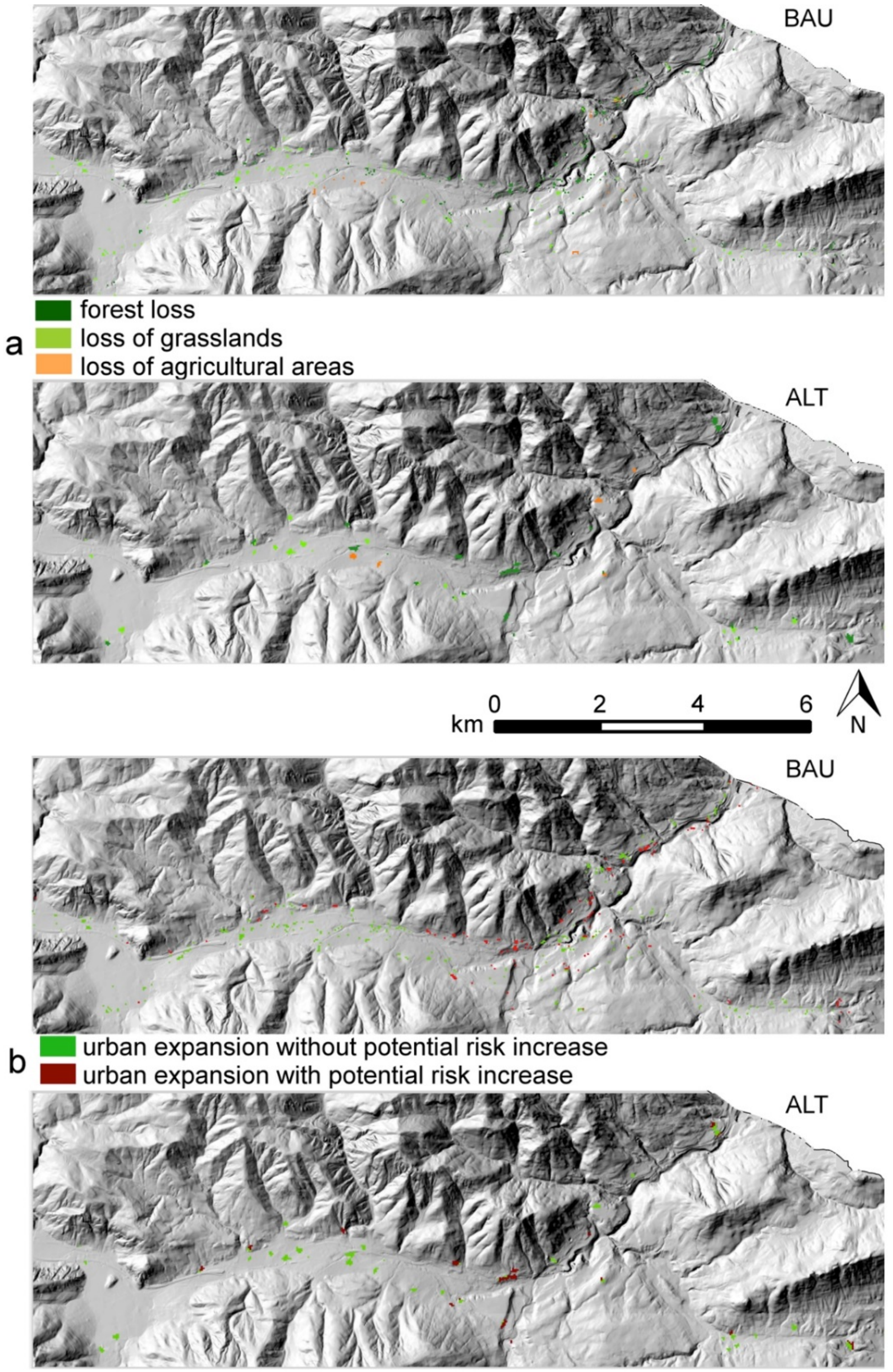


**FIGURE 5**

Impact of simulated scenarios on the landscape and hydro-meteorological risk, zoomed in to the tourism attraction area near Tarvisio. The maps show the (a) projected losses of particular land cover types, and (b) the potential risk increase in the BAU and Alternative scenario



## Discussion

In this study we developed a methodology to generate future scenarios of land change in mountainous regions, with an example of an Alpine region in Italy. Based on participatory modeling and analysis of past trends, we simulated two urban expansion scenarios due to tourism development. Moreover, we tried to identify possible consequences of both scenarios in terms of changes to the landscape and hydro-meteorological risk.

The aim of the first, qualitative part of this study was to address the uncertain future, lack of data, intangible driving forces of change and the abstractness of future land use change. This is why stakeholders from the area have been involved from the beginning on. The developed conceptual DPSIR model is not only serving as an explanation of the experts' belief and knowledge system, but also as a starting point in the later development of a spatial simulation model. This participatory approach therefore differs from other studies, where there is a lower level of expert participation. This is usually manifested by the experts providing only their vision on future trends to individual land use classes, not being involved in the development of the model (Giupponi et al. 2006; Schirpke et al. 2012; Promper et al. 2014). Other studies involving cognitive mapping in environmental modeling have shown, that the number of involved stakeholders can improve the results and introduce a higher number of concepts (Özesmi and Özesmi 2004). Whereas the number of involved stakeholders in our study area might seem low, we still managed to involve experts and decision makers from all levels. Nevertheless, performing the same procedure focusing only on one particular locality in the study area, or on the regional level only could result in different identified future driving forces and consequent scenarios.

Our scenarios focused solely on future tourism development, due to three main reasons. First, it was recognized by the stakeholders as the most significant driving force. Secondly, the local and regional development plans emphasize tourism as a prevailing economic activity in the study area. Lastly, the concept of future land change was abstract and sometimes difficult to understand by the stakeholders. Also, when we already defined the role of tourism in the future of the area, it was difficult for the stakeholders to relate future urban expansion as a consequence of tourism development to any other land change conversion (e.g. pasture abandonment, forest expansion). Other mountain-oriented studies involving stakeholders did achieve to model multiple land use transitions or took into account market mechanisms, however did not generate spatially explicit results suitable for analyzing changes to risk (Bayfield et al. 2008; Balbi et al. 2012). Moreover, studies have shown how difficult it is to assess only past land use changes in mountain areas, due to the complexity of numerous driving forces of land use change (Rutherford et al. 2008). Taking into account numerous land use transitions and also urban expansion due to other economic activities would mean incorporating a different set of transition rules. These would also need to be differentiated across the different parts of the study area, as the spatial pattern of economic activities differs significantly between the lowland and upland part of the area.

The spatial demand for accommodation (beds) and the allocation of future scenarios based on these demands was calculated by relating tourism accommodation data between 1990 and 2013 to the spatial extent of tourism facilities (e.g. hotels with accompanying parking spaces and green areas). The same goes for the spatial pattern (e.g. mean patch size). This way we aimed at capturing a more realistic spatial pattern of tourism facilities, instead of coming up with a spatial pattern independent from study area specific characteristics. Introducing extreme values for spatial demand and pattern from other regions could be considered as another future scenario, however we did not identify potential dramatic changes to the tourism type, when discussing future scenarios with stakeholders. Our aim was to study possible spatial consequences of plausible, likely scenarios; therefore this served our objectives completely.

Despite the high preference for urban expansion in the southwestern part of the study area where the valley opens (Supplement data, Appendix S1) most of the urban expansion due to the accommodation increase is projected in the northeastern part around Tarvisio, which we also portrayed on the maps (Figure 4 and 5). This is due to the fact that this area already serves as a touristic center of the region. As discussed with the stakeholders further tourism development will based on winter and alpine tourism and will be promoted in areas with already existing tourism facilities (Tarvisio and surroundings), and not around the lowland Gemona del Friuli, which serves as a residential, commercial and industrial center of the wider area.

Developing more land in order to increase tourism facilities could result in the increased well-being of the local population in terms of new jobs and increased revenue. On the other hand, these changes could result in a degraded landscape or increased risk. We tried to analyse these consequences, and compare both scenarios. The indicators we used to quantify the impact of both scenarios were merely in terms of areal extent of possible future changes.

We find the indicators describing the loss of forests, grasslands and agricultural areas as sufficient. Still, in order to fully study changes to the landscape image and aesthetics, additional research taking into account the architectural type and height of new buildings should be performed. The BAU scenario namely resulted in more urban expansion, however it might be having a lower influence on the landscape image, as the urban expansion there occurred solely due to new smaller individual objects. New larger hotels and chalet resorts however could affect the landscape more.

The indicators for risk increase however, might not be enough, as we only used proxy spatial data. The geological risk is defining areas, where additional surveys should be performed before a plot is developed. Also, the flood risk proxy data only describes the extent of urban expansion on areas with moderate risk. In order to determine the whole specter of changes to the risk, additional studies should therefore be performed. These should study the possible changes to hydro-meteorological hazards (including expected climate changes) and changes to value of elements at risk (and not only their new spatial extent). Still, future land use scenarios have been recognized as a vital contribution to studying potential changes to hydro-meteorological risk (Promper et al. 2014).

Studies have shown that spatially explicit models of land use change in mountain areas can achieve a high rate of accuracy (Schirpke et al. 2012). Assessing the performance of such spatial simulation approaches is difficult, especially as the interest is in the location of these changes and not only their quantity (Veldkamp and Lambin 2001). Also, the uncertainty of the data used should be taken into account as well. The simulated future urban expansion should therefore be discussed with care. Instead of considering the projected scenarios as exact locations of future change, we suggest they should be considered as potential hotspots for future development. Nevertheless, we consider the approach particularly useful for evaluating possible decision options through the use of scenarios.

## Conclusion

The aim of this paper was to identify the driving forces of future land changes, develop future scenarios of land change and study their potential consequences, based on an example in an Alpine study area. First we needed to identify driving forces of future change, which is why we involved stakeholders. Through participatory modeling, we developed expert based cognitive maps, presenting the knowledge and belief domain from the involved stakeholders. Then, under a set of assumption regarding tourism development, together with actual development plans, we developed two urban expansion scenarios. We allocated the two scenarios using a spatially explicit land change model. Finally, we analyzed possible consequences of these changes in terms of changes to the landscape and hydro-meteorological risk.

The two identified scenarios both followed a 30 % increase of accommodation facilities, however resulted in a different spatial demand and spatial pattern of future urban expansion. The Business as Usual (BAU) scenario, defined as tourism expansion in form of small scale individual objects, resulted in a 2.7 % increase of urban areas. The Alternative scenario on the other resulted in a 2 % increase. This scenario is described by new hotels and other larger objects with a higher accommodation density per hectare.

When analyzing potential consequences of both scenarios, we observed that the BAU had as expected, a larger effect on the loss of grasslands, forests and agricultural areas, as well as possible geological risk. The Alternative scenario however resulted in a higher potential increase of flood risk due to more concentrated urban expansion. In order to fully study the effect on hydro-meteorological risk we however propose additional research taking into account expected climate changes and changes to hazard pattern and occurrence.

This research presents a new methodology, combining participatory modeling with spatial simulation in order to address unavailable data and intangible driving forces. Scenarios generated in a participatory way have a higher degree of likelihood, as they encompass local expert knowledge otherwise not possible to understand with available statistical data. Moreover, the spatial explicitness of the proposed approach enables the identification of possible critical areas and spatial patterns of future changes. Therefore, this study contributes to the understanding to future environmental changes in Alpine areas, driven by external, global driving forces.

## REFERENCES

Abildtrup J, Audsley E, Fekete-Farkas M, Giupponi C, Gylling M, Rosato P, Rounsevell M. 2006. Socio-economic scenario development for the assessment of climate change impacts on agricultural land use: a pairwise comparison approach. Environmental Science & Policy 9(2):101–115.

De Almeida CM, Batty M, Vieira Monteiro AM, Câmara G, Soares-Filho BS, Cerqueira GC, Pennachin CL. 2003. Stochastic cellular automata modeling of urban land use dynamics: empirical development and estimation. Computers, Environment and Urban Systems 27(5):481–509.

Axelrod RM. 1976. Structure of Decision: The Cognitive Maps of Political Elites. Princeton, NJ: Princeton University Press.

Balbi S, Giupponi C, Perez P, Alberti M. A spatial agent-based model for assessing strategies of adaptation to climate and tourism demand changes in an alpine tourism destination. Environmental Modelling & Software 45:29-51

Barredo JI, Engelen G. 2010. Land Use Scenario Modeling for Flood Risk Mitigation. Sustainability 2(5):1327–1344.

Bastian M, Heymann S, Jacomy M. 2009. Gephi: an open source software for exploring and manipulating networks. ICWSM [International AAAI Conference on Weblogs and Social Media] Proceedings. San Jose, CA: Association for the Advancement of Artificial Intelligence.

Bayfield N, Barancok P, Furger M, Sebastià MT, Domínguez G, Lapka M, Cudlinova E, Vescovo L, Ganielle D, Cernusca A, et al. 2008. Stakeholder Perceptions of the Impacts of Rural Funding Scenarios on Mountain Landscapes Across Europe. Ecosystems 11(8):1368–1382.

Bonham-Carter G. 1994. Geographic information systems for geoscientists: modelling with GIS. Oxford, UK: Pergamon.

Borga M, Boscolo P, Zanon F, Sangati M. 2007. Hydrometeorological Analysis of the 29 August 2003 Flash Flood in the Eastern Italian Alps. Journal of Hydrometeorology 8(5):1049–1067.

Bronstert A, Niehoff D, Bürger G. 2002. Effects of climate and land-use change on storm runoff generation: present knowledge and modelling capabilities. Hydrological Processes 16(2):509–529.

Bürgi M, Hersperger AM, Schneeberger N. 2004. Driving forces of landscape change – current and new directions. Landscape Ecology 19(8):857–868.

Castella J-C, Verburg PH. 2007. Combination of process-oriented and pattern-oriented models of land-use change in a mountain area of Vietnam. Ecological Modelling 202(3-4):410–420.

Chemini C, Rizzoli A. 2003. Land use change and biodiversity conservation in the Alps. Journal of Mountain Ecology 7:1–7.

Cucchi F, Piano C, Marinetti E, Massari G, Oberti S, Zini L. 2000. Studies For The Realization Of The Hydrogeological Map Of Friuli-Venezia Giulia. Ipogea 3:57 – 71.

Daconto G, Sherpa LN. 2010. Applying Scenario Planning to Park and Tourism Management in Sagarmatha National Park, Khumbu, Nepal. Mountain research and development 30(2):103–112.

Deshler D. 1987. Techniques for generating futures perspectives. New Directions for Adult and Continuing Education 1987(36):79–92.

Eden C. 1992. On the Nature of Cognitive Maps. Journal of Management Studies 29(3):261–265.

EEA. 1999. Environmental indicators: Typology and overview. Copenhagen: European Environment Agency.

Engelen G, White R, Uljee I, Drazan P. 1995. Using cellular automata for integrated modelling of socio-environmental systems. Environmental Monitoring and Assessment 34:203–214.

Fuchs S, Keiler M, Sokratov S, Shnyparkov A. 2013. Spatiotemporal dynamics: the need for an innovative approach in mountain hazard risk management. Natural Hazards 68:1217–41

Giupponi C, Ramanzin M, Sturaro E, Fuser S. 2006. Climate and land use changes, biodiversity and agri-environmental measures in the Belluno province, Italy. Environmental Science & Policy 9(2):163–173.

Glade T. 2003. Landslide occurrence as a response to land use change: a review of evidence from New Zealand. Catena 51(3-4):297–314.

Glade, T, Crozier MJ. 2005. The Nature of Landslide Hazard Impact. In Glade T, Anderson M, Crozier MJ, editors. Landslide Hazard and Risk. Chichester, United Kingdom: John Wiley & Sons, Ltd, pp. 41–74.

Hosseinali F, Alesheikh AA. 2008. Weighting Spatial Information in GIS for Copper Mining Exploration. American Journal of Applied Sciences 5(9):1187–1198.

Hoyer RW, Chang H. 2014. Development of Future Land Cover Change Scenarios in the Metropolitan Fringe, Oregon, U.S., with Stakeholder Involvement. Land 3(1):322–341.

ISTAT. 2014. Instituto Nazionale di Statistica. Italian National Institute for Statistics Data Warehouse. [accessed 2014 Jan 20]. http://dati.istat.it/

Kamusoko C, Wada Y, Furuya T, Tomimura S, Nasu M, Homsysavath K. 2013. Simulating Future Forest Cover Changes in Pakxeng District, Lao People's Democratic Republic (PDR): Implications for Sustainable Forest Management. Land 2(1):1–19.

Kassa H, Campbell B, Sandewall M, Kebede M, Tesfaye Y, Dessie G, Seifu A, Tadesse M, Garedew E, Sandewall K. 2009. Building future scenarios and uncovering persisting challenges of participatory forest management in Chilimo Forest, Central Ethiopia. Journal of Environmental Management 90(2):1004–1013.

Kok K. 2009. The potential of Fuzzy Cognitive Maps for semi-quantitative scenario development, with an example from Brazil. Global Environmental Change

19(1):122–133.

Von Korff Y, D'Aquino P, Daniell KA, Bijlsma R. 2010. Designing Participation Processes for Water Management and Beyond. Ecology and Society 15(1):29.

Körner C, Ohsawa M, Spehn E, Berge E, Bugmann H, Groombridge B, Hamilton L, Hofer T, Ives J, Jodha N. 2005. Mountain Systems. In: Ecosystems and human well-being: current state and trends: findings of the Condition and Trends Working Group of the Millennium Ecosystem Assessment. p. 681–716.

Kriegler E, O'Neill BC, Hallegatte S, Kram T, Lempert RJ, Moss RH, Wilbanks T. 2012. The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. Global Environmental Change 22(4):807–822.

Maeda EE, de Almeida CM, de Carvalho Ximenes A, Formaggio AR, Shimabukuro YE, Pellikka P. 2011. Dynamic modeling of forest conversion: Simulation of past and future scenarios of rural activities expansion in the fringes of the Xingu National Park, Brazilian Amazon. International Journal of Applied Earth Observation and Geoinformation 13(3):435–446.

Malek Ž, Scolobig A, Schröter D. 2014. Understanding Land Cover Changes in the Italian Alps and Romanian Carpathians Combining Remote Sensing and Stakeholder Interviews. Land 3(1):52–73.

Mitsova D, Shuster W, Wang X. 2011. A cellular automata model of land cover change to integrate urban growth with open space conservation. Landscape and Urban Planning 99(2):141–153.

Odada EO, Ochola WO, Olago DO. 2009. Understanding future ecosystem changes in Lake Victoria basin using participatory local scenarios. African Journal of Ecology 47:147–153.

Ogilvy JA, Schwartz P. 1998. Plotting your scenarios. In: Learning from the Future: Competitive Foresight Scenarios. New York, NY: Wiley. p. 464.

Özesmi U, Özesmi SL. 2004. Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. Ecological Modelling 176(1-2):43–64.

Patel M, Kok K, Rothman DS. 2007. Participatory scenario construction in land use analysis: An insight into the experiences created by stakeholder involvement in the Northern Mediterranean. Land Use Policy 24(3):546–561.

Potvin C, Tschakert P, Lebel F, Kirby K, Barrios H, Bocariza J, Caisamo J, Caisamo L, Cansari C, Casama J, et al. 2007. A participatory approach to the establishment of a baseline scenario for a reforestation Clean Development Mechanism project. Mitigation and Adaptation Strategies for Global Change 12(8).

Promper C, Puissant A, Malet JP, Glade T. 2014. Analysis of land cover changes in the past and the future as contribution to landslide risk scenarios. Applied Geography 53:11–19

Quantum GIS Development Team. 2013. Quantum GIS Geographic Information System. Open Source Geospatial Foundation Project.

Regione FVG. 2013. Catalogue of Enviromental and Territorial Data. [accessed 2013 Jan 17]. http://irdat.regione.fvg.it/consultatore-dati-ambientali-territoriali/

Rounsevell M, Reginster I, Araújo MB, Carter T, Dendoncker N, Ewert F, House J, Kankaanpaa S, Leemans R, Metzger M, et al. 2006. A coherent set of future land use change scenarios for Europe. Agriculture, Ecosystems & Environment 114(1):57–68.

Rutherford GN, Bebi P, Edwards PJ, Zimmermann NE. 2008. Assessing land-use statistics to model land cover change in a mountainous landscape in the European Alps. Ecological Modelling 212(3–4):460–471.

Schirpke U, Leitinger G, Tappeiner U, Tasser E. 2012. SPA-LUCC: Developing land-use/cover scenarios in mountain landscapes. Ecological Informatics 12:68–76.

Schneeberger N, Bürgi M, Hersperger AM, Ewald KC. 2007. Driving forces and rates of landscape change as a promising combination for landscape change research—An application on the northern fringe of the Swiss Alps. Land Use Policy 24(2):349–361.

Soares-Filho BS, Cerqueira GC, Pennachin CL. 2002. Dinamica—a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. Ecological Modelling 154(3):217–235.

Swetnam RD, Fisher B, Mbilinyi BP, Munishi PKT, Willcock S, Ricketts T, Mwakalila S, Balmford A, Burgess ND, Marshall AR, et al. 2011. Mapping socio-economic scenarios of land cover change: A GIS method to enable ecosystem service modelling. Journal of Environmental Management 92(3):563–574.

Tasser E, Tappeiner U, Cernusca A. 2005. Ecological Effects of Land-use Changes in the European Alps. In: Huber UM, Bugmann HKM, Reasoner MA, editors. Global Change and Mountain Regions. Advances in Global Change Research. Springer Netherlands. p. 409–420.

Tollan A. 2002. Land-use change and floods: what do we need most, research or management? Water Science and Technology: A Journal of the International Association on Water Pollution Research 45(8):183–190.

Veldkamp A, Lambin E. 2001. Predicting land-use change. Agriculture, Ecosystems & Environment 85(1-3):1–6.

Verburg PH. 2006. Simulating feedbacks in land use and land cover change models. Landscape Ecology 21(8):1171–1183.

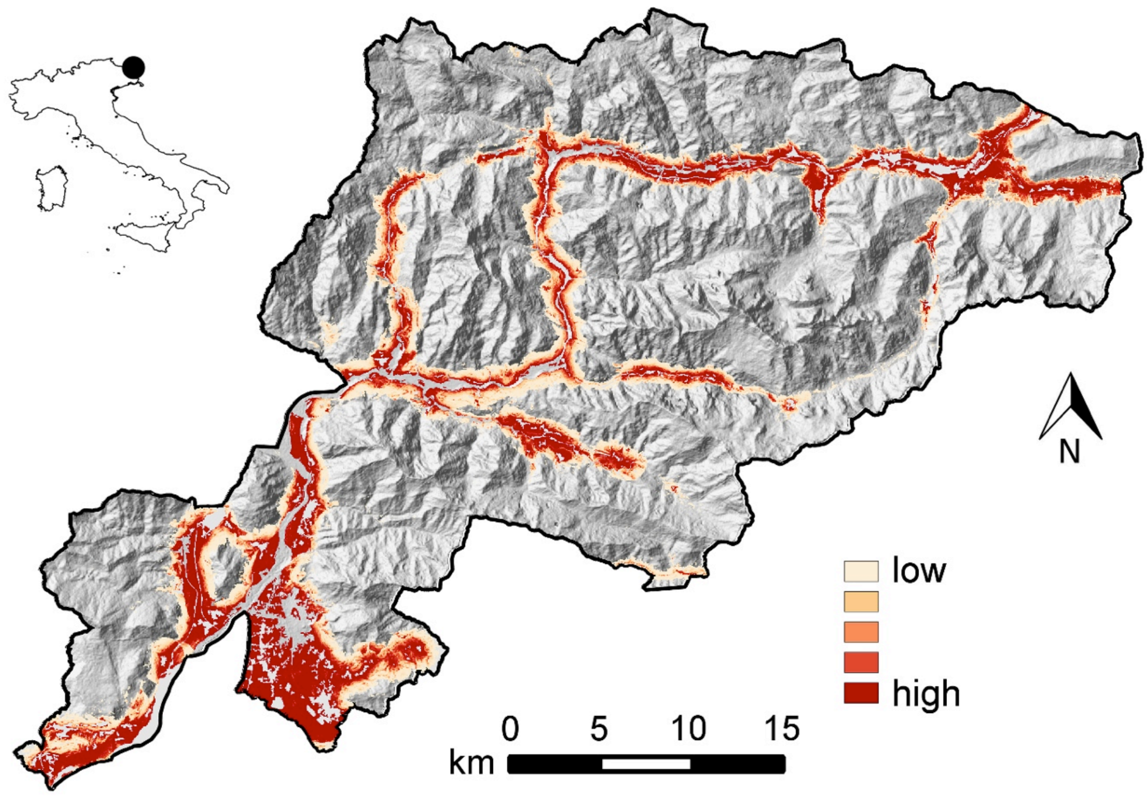
Verburg PH, de Koning GHJ, Kok K, Veldkamp A, Bouma J. 1999. A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. Ecological Modelling 116(1):45–61.

Van Vliet M, Kok K, Veldkamp T. 2010. Linking stakeholders and modellers in scenario studies: The use of Fuzzy Cognitive Maps as a communication and learning tool. Futures 42(1):1–14.

Wollenberg E, Edmunds D, Buck L. 2000. Using scenarios to make decisions about the future: anticipatory learning for the adaptive co-management of community forests. Landscape and Urban Planning 47(1-2):65–77.

## ANNEX map

S1 Urban expansion probability map



# Appendix C: Future forest cover change under a set of forest policy scenarios: An example from Buzau Subcarpathians, Romania

Malek Ž, Glade T, Boerboom L.

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**Abstract**

To prepare for possible negative future consequences of forest cover change it is necessary to study where they are most likely to occur. This paper focuses on Buzau Subcarpathians, a landslide prone region in Romania. Past and current trends suggest that the area might expect a future increase in deforestation. We developed spatially explicit scenarios until 2040 to investigate potential impacts of forest cover changes on landslide risk. Expert interviews were integrated with raster-based simulation (Dinamica EGO) and a landslide susceptibility map. The Alternative scenario (ALT) defined by increased clear-cutting limits resulted in 67 % more deforestation than the Business as Usual scenario (BAU). In both scenarios, most of deforestation was projected in areas where landslides are less likely to occur. Still, 483 (ALT) and 276 (BAU) ha of deforestation were projected on areas with a higher likelihood of landslide occurrence. Thus, deforestation could lead to a local scale increase in landslide risk, in particular near or adjacent to forestry roads. The parallel 10 % forest expansion until 2040 was identified as a prevailing process in the area, occurring mostly on areas with high landslide susceptibility. On a regional scale, forest expansion could so result in improved slope stability. We modeled two additional scenarios with an implemented landslide risk policy, excluding high-risk zones. The reduction of deforestation on high-risk areas was achieved without a drastic decrease in the accessibility of the areas subject to clear-cutting. Together with forest expansion, it could therefore be used as a risk reduction strategy.

**Keywords**

Forest change – Land cover change – Scenarios – Spatial simulation – Carpathians – Landslide risk

## Introduction

Changes to the forest cover can result in a variety of negative environmental consequences. Deforestation for example can affect the vegetation composition and water balance, and can increase erosion rates (Glade 2003; Ghimire et al. 2013). This leads to increased environmental risks, such as landslide occurrence, and can have strong impacts on the human well-being on a larger scale (Tasser et al. 2003; Körner et al. 2005; Papathoma-Köhle and Glade 2013). On the other side, reforestation due to grassland abandonment can contribute to habitat loss, lower biodiversity levels and a more homogenous landscape (Olsson et al. 2000; Chemini and Rizzoli 2003). Studying how human-environment interactions can change the forest cover is therefore essential (Rounsevell et al. 2006).

An important tool for exploring future consequences of environmental changes are scenarios. Scenarios are images of possible, likely futures (Abildtrup et al. 2006). They encourage creativity and help to generate visions, and help us to plan for a desirable future (Deshler 1987). Moreover, by breaking the established pattern of planning, scenarios can help us to prepare for possible undesirable future developments (Wollenberg et al. 2000). They offer a possibility to analyze available response options, hence aiding decision makers (Shearer 2005; Kriegler et al. 2012). Incorporating land change scenarios in environmental research is well acknowledged and has already been addressed in various disciplines (Verburg et al. 2004). Among others, these methods have been applied in studying flood risk (Barredo and Engelen 2010), soil erosion (Hessel et al. 2003), habitat availability (Falcucci et al. 2008), influence of protected areas (Soares-Filho et al. 2006), and effects on biodiversity levels (Giupponi et al. 2006).

In this study we generated future scenarios of changes to the forest cover in the Subcarpathians of Buzau County in Romania. Recent deforestation trends and a dense network of landslides in the area suggest a need for analyzing potential consequences of future forest management (Malek et al. 2014). Thus, we focused on possible future deforestation patterns, as a result of changes to the amount and pattern of forest harvesting. The area was selected due to its complex socio-economic trajectory since 1989, as well as growing pressures to increase forest harvesting.

The Carpathians are a major European mountain range and biodiversity hotspot, which host one of the largest continuous forest ecosystems in Europe. Forest expansion and deforestation are considered among the major environmental issues in the Carpathian region (Björnsen Gurung et al. 2009). Long-term forest expansion due to land abandonment in the Carpathian region is in line with the trends of other European mountain areas (Kozak et al. 2007b). The fall of communist regimes in Europe after 1989, however, lead to radical political and socio-economic changes in the region. The post 1989 era was characterized by the fall of large scale collective agricultural associations, new land use policies and land ownership reforms resulting in numerous new land owners (Mathijs and Swinnen 1998; Lerman et al. 2004). Numerous authors identify land abandonment and reforestation as some of the most important land cover changes in the region (Kuemmerle et al. 2008; Müller et al. 2009; Taff et al. 2009; Baumann et al. 2011; Griffiths et al. 2013). One particularly remarkable process, differing from other European mountain areas, is the increase in quantity and changes in the spatial pattern of deforestation as a consequence of both legal and illegal logging (Knorn et al. 2012; Griffiths et al. 2012; Griffiths et al. 2014). It is among the most significant land cover change processes in Buzau Subcarpathians in terms of possible negative consequences (Malek et al. 2014).

The first objective of the study is to understand possible future changes to forest management in a transitional European mountainous region. More precisely, the objective is to generate future spatially explicit scenarios taking into account future changes to forest harvesting, instead of only extrapolating past trends. Secondly, forest management in a mountainous and landslide prone area is closely linked to landslide risk management. Thus the second objective was to investigate the relationship between future forest management and landslide risk. Finally, our third objective was to analyse the effect of implementing a landslide risk reduction strategy for forest management.

## Study area

The study area (Fig. 1) lies in South East Romania in Buzau County (centroid 45°27’3’’ N, 26°30’23’’ E). It covers 2421 km2 of the Subcarpathian hills between the higher Carpathian mountains and the Buzau plain. The Subcarpathians rise up to 1370 m, with the mean elevation of the area being 429 m. Geologically, the area consists mainly of Neogene molasse deposits. The geology of the area together with the mean slope of 11.5 degrees, is a significant predisposing factor for landslide occurrence (Micu and Bălteanu 2013). The yearly precipitation in the area is between 630-700 mm, with heavy spring and summer rainfall. In some parts of the Subcarpathians, landslides (Fig. 1a) cover more than two-thirds of the total area (Muică and Turnock 2008). Forests dominate the landscape (Fig. 1b) covering 40.5 % of the area (981 km2), followed by grasslands (27.4 %).

With a 40 % share of the regional economy, agriculture is significant, however it is declining (MADR 2012). Forest harvesting is a major economic activity, with wood mostly being exported (INSSE 2013). The area's population is around 160,000. Since the economic and political change of 1989, the area witnessed a striking economic decrease, high depopulation rates (11% since 1990), and agricultural abandonment (INSSE 2013). Nevertheless, like in similar areas in the Romanian Carpathians, forest disturbances increased (Fig. 1c). This could be attributed to a number of reasons: (1) poor socio-economic conditions in the area following 1989; (2) Romanian land ownership reforms, where government owned land was allocated to private owners; and (3) difficulties in implementing forest policy (Malek et al. 2014). Before 1989, nearly 100 % of the forests were government property, whereas in 2010 34.7 % of the forests were privately owned (INSSE 2013). Besides the increase in the number of owners, the ownership spatial pattern is characterized by numerous smaller plots, which increases the difficulty of forest management (Bălteanu and Popovici 2010). Increasing the amount of forest harvesting in the area could be a significant part of regional economic growth. It is however important to analyze the consequences of these activities in the area, as the increase in forest exploitation could result in a higher demand for new road and landslide risk mitigation infrastructure, as well as reforestation measures.

## Materials and Methods

### Scenario development

We conducted 13 semi-structured interviews and group meetings with forestry, environmental and risk experts on the local level (forest association), as well as on the regional level (county) in July and September 2012. Interviews contained questions on observed and expected future forest cover changes, their consequences and importance; influence of socioeconomic development; the role of different levels of decision-making (local, regional, national); and also possible effects of external driving forces, such as political changes. We adopted the Drivers – Pressures – State – Impact – Response (DPSIR) framework (EEA 1999) to translate the expert knowledge to a conceptual deforestation model (Fig. 2). Together with the experts we identified each part of the DPSIR, simulating the cause-response framework of planning and management of forest harvesting in the region. This enabled us to structure the relationship between the driving forces of deforestation with their consequences. We later used the DPSIR model to develop forest cover change scenarios and the allocation model. Together with the experts we defined the Drivers, Pressures and Response parameters of the conceptual model (Fig. 2) in advance (Table 1). The State and Impact parts were a result of subsequent modeling, and presented the resulting deforestation and the potential landslide risk.

**Fig. 1**

Location of study area. Typical examples of (a) landslide activity, (b) forest-dominated landscape and (c) deforestation

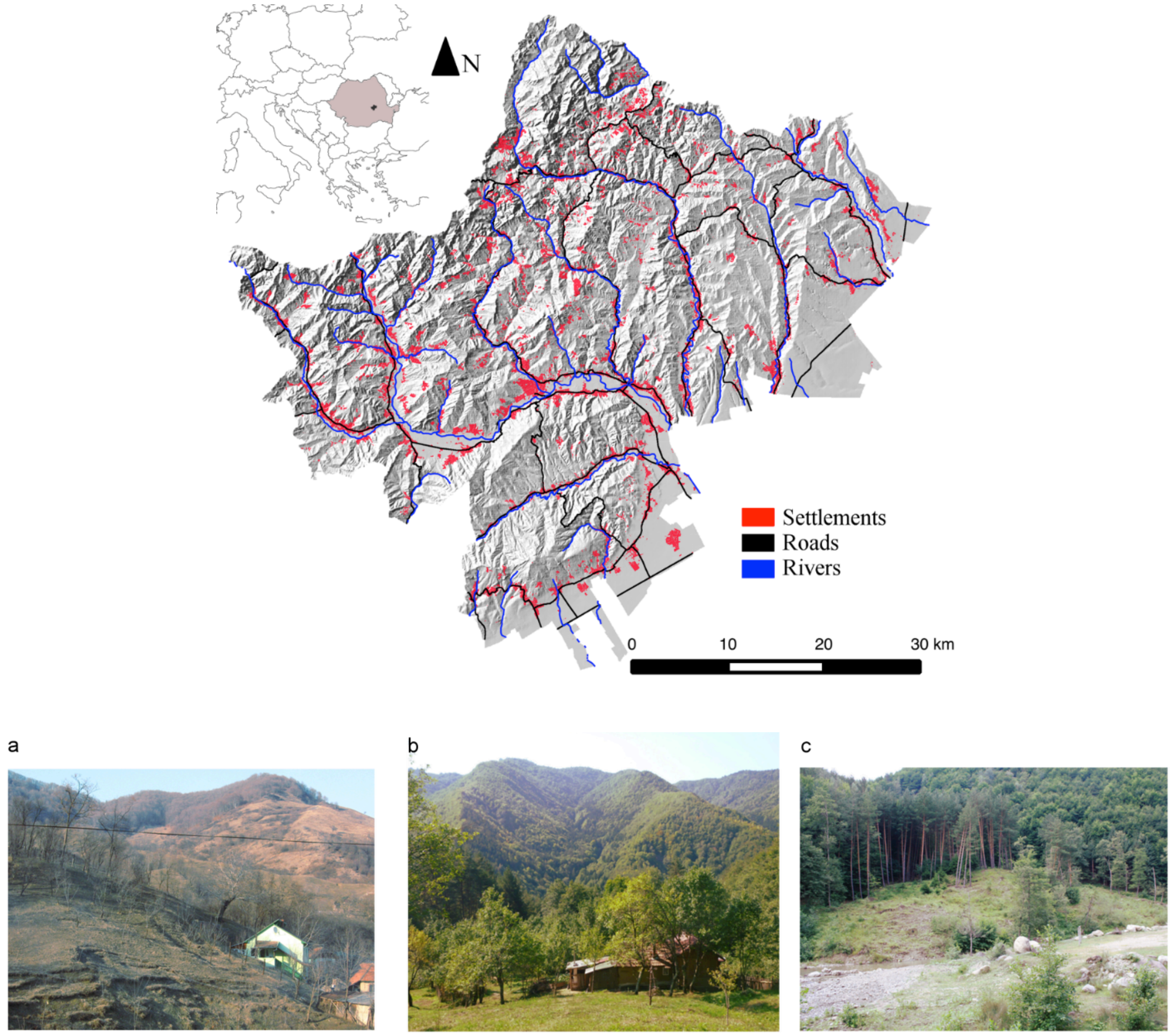
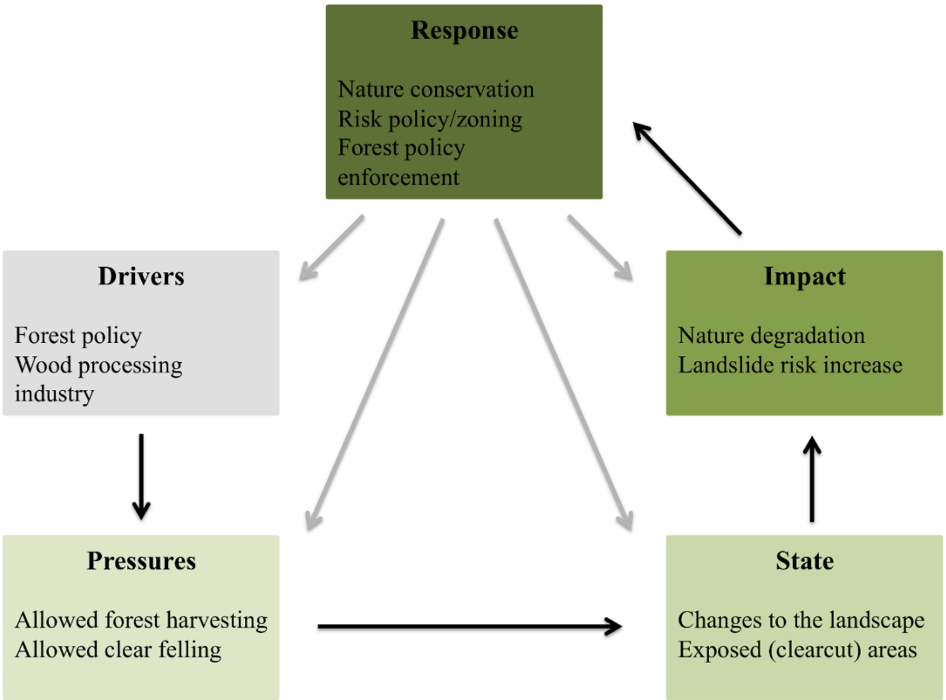


**Fig. 2**

Drivers – Pressures – State – Impact – Response conceptual model of the forest harvesting system




Based on the conceptual deforestation model (Fig. 2), we developed two forest cover change scenarios: Business as Usual (BAU) and Alternative scenario. In both scenarios we modeled two processes of forest cover change: deforestation and forest expansion. Deforestation was defined as a land cover transition from forest to non-forest, as a result of clear-cutting. In the study area, clear-cutting is characterized as the removal of all trees in a pre-defined and limited area, usually smaller than 3 ha. Although it is not a prevailing forest management practice in Romania, it is the main focus of the developed scenarios. Deforestation can increase the occurrence of landslides, acknowledged both by the involved experts and literature (Schmidt et al. 2001; Glade 2003). Following expert interviews, we developed a simplified model that calculates scenario based deforestation transition rates, resulting in the demand for forest areas in spatial terms. We used a simplified annual deforestation estimation model:

$$d_t = \frac{f_t \times n_t \times a_t \times c_t}{g_t}$$

where for the year *t*:

$d_t$ is the estimated annual deforestation in ha,

$f_t$ the allowed forest harvesting defined as percentage of the net annual increment,

$n_t$ the net annual increment in $m^3$/ha,

$a_t$ are forest areas in ha,

$c_t$ the clear felling potential in % of total forest harvesting,

$g_t$ the forest growing stock in $m^3$/ha.

In our conceptual model, the forest policy and wood processing industry influence the allowed forest harvesting (Fig. 2, Table 1). They are based on the proposed outlook for the development of Romanian forest resources (Schelhaas et al. 2006). The allowed forest harvesting Pressure has the same biophysical assumptions in both scenarios: an increase of the growing stock (total standing tree volume) and the decrease of the net annual increment (average annual volume increase) per hectare (Table 1). Forest data for Buzau County for the year 2010 served as a starting point: the mean growing stock was 217 m3 per hectare, and the mean net annual increment was 6 m3 per hectare. The maximum annual clear-cutting potential was estimated to be 3 % of the total amount of allowed forest harvesting (Bohateret 2012), even though the potential can vary among different forest types. This potential defines the limit of allowed forest harvesting through clear-cutting and is set as a threshold for protection and sustainable management of Romanian forests (Giurgiu 2004). Differences in growing stock, net annual increment and clear-cutting potential across the landscape were not taken into account, as the data on spatial variation of forest types, quality and age was not available. Therefore, we used mean values for the whole Buzau Subcarpathians. The two scenarios differ in the amount and spatial pattern of clear-cutting. The BAU scenario follows existing policy, thus maintaining the potential of clear-cutting at 3 % of the total forest harvesting. The involved experts identified the existing policy as sustainable. Its problems are related to its implementation: field control of allowed clear-cuts is currently difficult due to lack of personnel, funds and institutional issues, resulting in excessive clear-cutting in sizes above the legal 3 ha. Therefore, we applied a time lag of 10 years in this scenario, where the values for the size of clear-cuts remain the same until 2020. This way we simulated the successful implementation of the current policy after 10 years from 2010 on one side, and compensation in form of smaller clear-cut areas due to excessive clear-cuts until 2020. Thus, the mean size of clear-cut patches after 2020 was 2 ha, instead of 2.5 ha as observed between 1989 and 2010 (Table 1). The Alternative scenario was oriented towards the desired goals of investors in the wood harvesting and processing industry. Involved experts revealed that investors in the forestry sector support the increase of the allowed clear-cutting. This would enable easier, faster, and less costly exploitation of forest resources, especially with the existent forest road network. Thus, in the Alternative scenario the percentage of clear-cutting in the total forest harvesting rose up to 5 %, with the remaining larger mean size of clear-cut patches (2.5 ha). Finally, we modeled two additional scenarios: an implemented simplified risk policy for the BAU and ALT scenario. Here, we excluded all areas highly susceptible to landslides in the 90 m vicinity of roads and settlements as explained later in the Landslide risk section.

Additionally, we modeled future forest expansion. We defined it as a change from non-forest to forest; from grasslands or other vegetation to forest. This process was taken into account in both scenarios, as we wanted to study the potential positive impact of forest expansion on landslide risk and compare it to the impact of deforestation. The transition rate for forest expansion was the same for both scenarios. It followed the observed trends between 1989 and 2010, simulating more long-term forest expansion trends instead of the more recent ones. We modeled forest expansion only on the basis of past remote sensing observations and the influence of the spatial factors of forest expansion as described later. Therefore, forest expansion was not subject to any forest harvesting scenarios. Non-forest areas that were transformed into forest areas during the run of the model were not considered for deforestation. According to Romanian legislation, these areas will not have reached the appropriate age for exploitation in the modeled time span (Parlamentul României 1996). They can be considered in calculating the allowed forest harvesting after 10 years (FAO 1997).

## Preparation of spatial factors of forest cover change

Land cover maps for the years 1989, 2000 and 2010 were obtained through hybrid classification of LANDSAT images previously presented by Malek et al. (Malek et al. 2014). We prepared the following spatial factors of forest cover change: slope and elevation derived from the digital elevation model, distance to settlements and roads generated from the road network and land cover map. We also defined exclusion areas, where forest harvesting is legally forbidden: Natura 2000 protected areas, protected forests (ecologically significant forests), and all slopes above 25 degrees (FAO 1997). We processed all spatial factors with the obtained data on forest associations (districts) in a GIS, and resampled them to the 30 m resolution of the land cover maps (Quantum GIS Development Team 2013).

**Table 1**

Scenario characteristics

| | Alternative | BAU |
|---|---|---|
| **DRIVERS** | | |
| Forest policy | Immediate changes to the forest policy, oriented towards desires of the wood processing industry. | The current forest policy, complete implementation after 2020. |
| Wood processing industry | Increase of the allowed harvested forests, 66 % increase of clear-cutting, increase of size of areas that can be subject to clear-cutting | Increase of the allowed harvested forests |
| **PRESSURES** | | |
| **Amount of deforestation** | | |
| Net Annual Increment (NAI) | -13.2 % until 2040 | -13.2 % until 2040 |
| Forest growing stock | +24.2 % until 2040 | +24.2 % until 2040 |
| Allowed forest harvesting per NAI | 42 % (2010) to 85 % (2040) | 42 % (2010) to 85 % (2040) |
| **Spatial pattern of forest cover change** | | |
| Mean patch size (MPS) | Deforestation: 2.5<br>Forest expansion: 2.0 | Deforestation: 2.5, 2.0 after 2020<br>Forest expansion: 2.0 |
| MPS Variance | Deforestation: 5.5<br>Forest expansion: 4.0 | Deforestation: 5.5, 5 after 2020<br>Forest expansion: 4.0 |
| Isometry | Deforestation: 0.9<br>Forest expansion: 0.8 | Deforestation: 0.9<br>Forest expansion: 0.8 |
| Transition rate | Deforestation: estimated annual deforestation, 5 % clear felling potential<br>Forest expansion: 0.32 % annual transition rate (1989 – 2010 observation) | Deforestation: Estimated annual deforestation, 3 % clear felling potential<br>Forest expansion: 0.32 % annual transition rate (1989 – 2010 observation) |
| **RESPONSE** | | |
| Current exclusion zones | Deforestation: slopes > 25 degrees,<br>protected areas and forests<br>Forest expansion: grasslands in protected areas | Deforestation: slopes > 25 degrees,<br>protected areas and forests<br>Forest expansion: grasslands in protected areas |
| **Landslide risk reduction scenarios: High risk exclusion zones** | Areas with >50 % landslide susceptibility in the 90 m distance from roads and settlements | Areas with >50 % landslide susceptibility in the 90 m distance from roads and settlements |

## Spatial allocation model

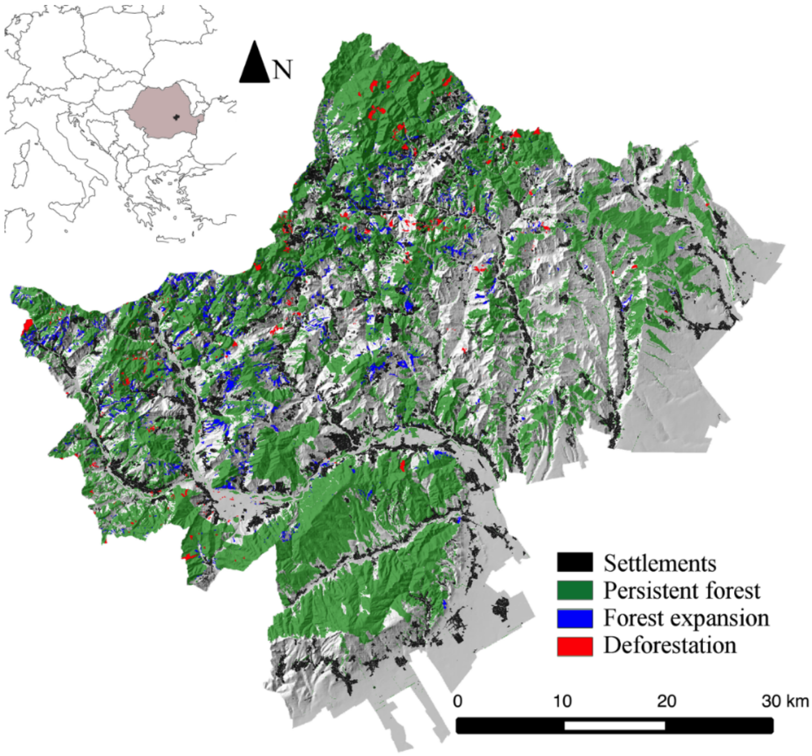
We developed a spatially explicit forest cover change model in Dinamica EGO. The software is suitable for raster-based simulation of numerous land cover changes on a high spatial resolution (Soares-Filho et al. 2002). It has already been applied to urban modeling, agricultural expansion and forest dynamics (de Almeida et al. 2003; Maeda et al. 2011; Kamusoko et al. 2013). Two different techniques were combined to spatially allocate forest cover changes: weights of evidence (WoE) and cellular automata (CA). While we applied the WoE method to generate a forest cover change transition probability map, we used the CA model to spatially allocate the changes to the forest cover on a 30 m resolution.

WoE is a Bayesian probability method, where individual influences of the spatial factors affecting a transition from one land cover to another are calculated from the historic frequency of that transition (Bonham-Carter 1994). We applied WoE as it is robust in handling missing data, and minimizing bias and subjectivity when evaluating different criteria (Hosseinali and Alesheikh 2008; Thapa et al. 2013). WoE values present the probability that a land cover transition will occur for a particular spatial factor of change. In this case, the WoE values describe the relationship between a specific spatial factor and a forest cover change process. High values promote a particular transition, whereas lower values discourage them. Dinamica EGO enables the generation of a spatially explicit probability map, where each cell is described by the transition probability, based on WoE values. We calculated the probability map using the changes to the forest cover between 1989 and 2010 (Fig. 3) for both deforestation and forest expansion. To ensure the independence of selected spatial factors, we calculated the Cramer's Coefficient.

CA allocation models are effective at simulating spatial patterns of land change, and are very adaptable thus they are able to simulate a wide variety of dynamic spatial processes (Wijesekara et al. 2014). CA models are bottom-up models, where the landscape is defined as a grid of cells associated with a state, in this case land cover types (Engelen et al. 1995). The cells change their states with each time step, according to the neighborhood defined by adjacent cells influencing the central cell, and transition rates that are the same for the whole landscape (Mitsova et al. 2011). The CA allocation model in Dinamica EGO consists of two stochastic allocation algorithms, the expander and the patcher. Both algorithms sort out the cells with highest transition probability in the initial land cover map, and then randomly select the calculated amount of cells using an internal stochastic selection procedure (Soares-Filho et al. 2002). The expander algorithm models the expansion of existing patches of a particular land cover (e.g. forest expansion on the account of adjacent abandoned grasslands). The patcher algorithm on the other hand, generates new patches within a patch defined by a different land cover. This way, forest dynamics were modeled more realistically. Observed clear-cutting in the study area did not occur in the form of clearing the forest edge, but mostly as new non-forest patches within a larger patch of forest (Fig. 3). The expander function was attributed to forest expansion, whereas deforestation was assigned mostly (95 % of the transition) to the patcher function.

**Fig. 3**

Forest cover map and with observed changes between 1989 and 2010




By analyzing landscape metrics of changes between 1989 and 2010 we obtained the parameters of the spatial pattern of forest cover change: mean patch size and patch size variance (Gustafson 1998). We used them together with isometry to generate a more plausible pattern of spatial allocation of forest cover change (Table 1). The mean patch size and the variance define the size and its diversity of the new patches, and isometry describes how equal in shape and compact the new patches are. Isometry lower than 1 results in less equal, and between 1 and 2 in more equal patches (Soares-Filho et al. 2002).

We used the 2010 map as the initial time step when allocating future scenarios. The model performed the allocation individually in each forest district, dividing forest harvesting among forest associations. Each forestry association manages forest harvesting in their own district, meaning that the estimated deforestation is distributed among districts and not only throughout the whole region. To validate the model, we used a multi-resolution windows approach (Hagen 2003). We compared the difference map of the initial and the reference map to the difference map of the initial and simulated map. We applied windows with different spatial resolutions, evaluating the cell change agreement on one cell resolution to the agreement in a defined neighborhood of the observed cell. This approach is suitable when testing the similarity of the observed and simulated spatial pattern of changes when the maps usually do not match on a single cell resolution. The result was the fuzzy similarity index, based on the agreement of change cells in both difference maps in expanding windows sizes (in this case from 1 to 15 cells). Therefore, we defined the performance of the model as the success rate of modeling the spatial occurrence of change in a range of vicinity (Hagen 2003).

### Landslide risk

We overlaid the model outputs with a landslide susceptibility map for Buzau County (Hussin et al. 2013) in a GIS (Fig. 4a). Landslide susceptibility is the probability of spatial occurrence of known landslides under a set of environmental characteristics (Glade and Crozier 2005; Guzzetti et al. 2006). Susceptibility maps can therefore be used to predict the locations of future landslides, based on an assumption they will occur on the same conditions as they did in the past (Guzzetti et al. 2005; Petschko et al. 2014). This way, they are useful when a landslide hazard map is either missing or incomplete, as is in this case. We assessed each scenario in terms of occurrence of deforestation in landslide susceptibility classes. Finally, we modeled two additional scenarios where we simulated both scenarios again with high landslide risk areas excluded. As a proxy for high-landslide risk in this data poor area, we defined areas with above 50 % landslide susceptibility in the distance of 90 m of significant elements at risk (settlements, roads, Fig. 4b). We compared the results with the two scenarios without landslide information, to identify the possible costs of this simplified risk policy. We achieved this by observing the occurrence of deforestation for both scenarios in slope classes and distance to roads, as proxies for accessibility.

## Results

### Weight of evidence and forest cover change probability

The WoE varied substantially between deforestation and forest expansion (Fig. 5). The probability for deforestation decreased with the distance from roads, whereas it slightly increased for forest expansion (Fig. 5a). The probability for deforestation decreased with increasing slopes, and substantially increased for forest expansion (Fig. 5b). The probability map for forest expansion showed, that remote areas on higher altitudes and steeper slopes had a higher probability for forest expansion (Fig. 6a). More accessible grasslands and pastures on gradual slopes and lower altitude were therefore less susceptible to abandonment and forest expansion. The probability map for deforestation showed that the role of altitude is less significant, and factors like distance to roads and slopes are more important (Fig. 6b).

**Fig. 4**

(a) Landslide susceptibility map (modified from Hussin et al. 2013) and (b) areas excluded for the additional model run: areas over 50 % susceptibility within a 90 m distance from settlements and roads

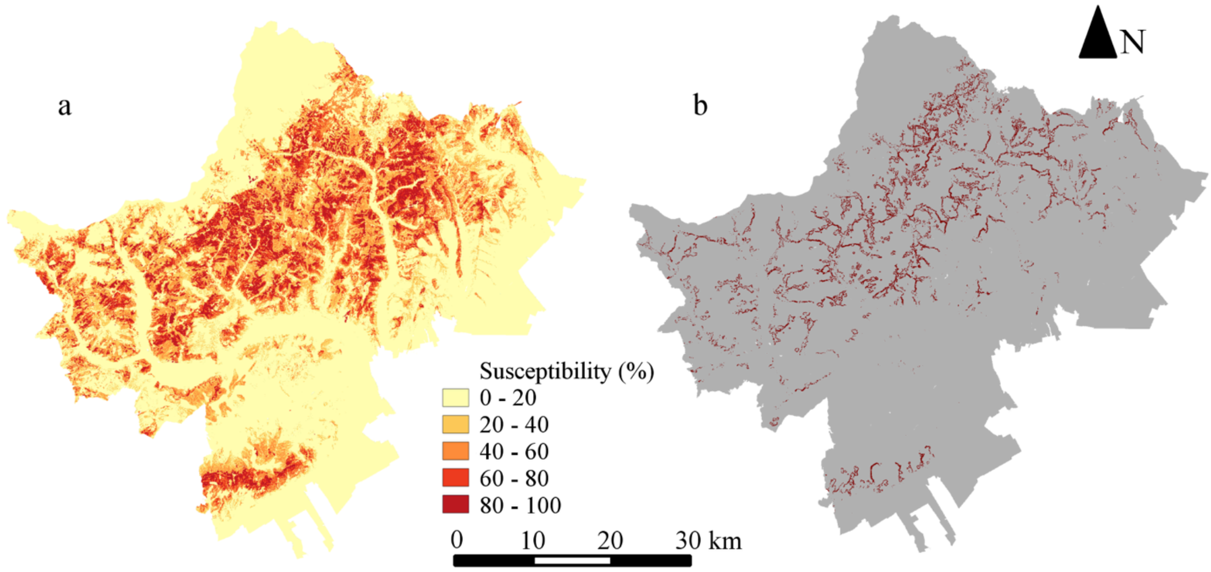



**Fig. 5**

Weights of Evidence values for distance to roads (a) and slopes (b)

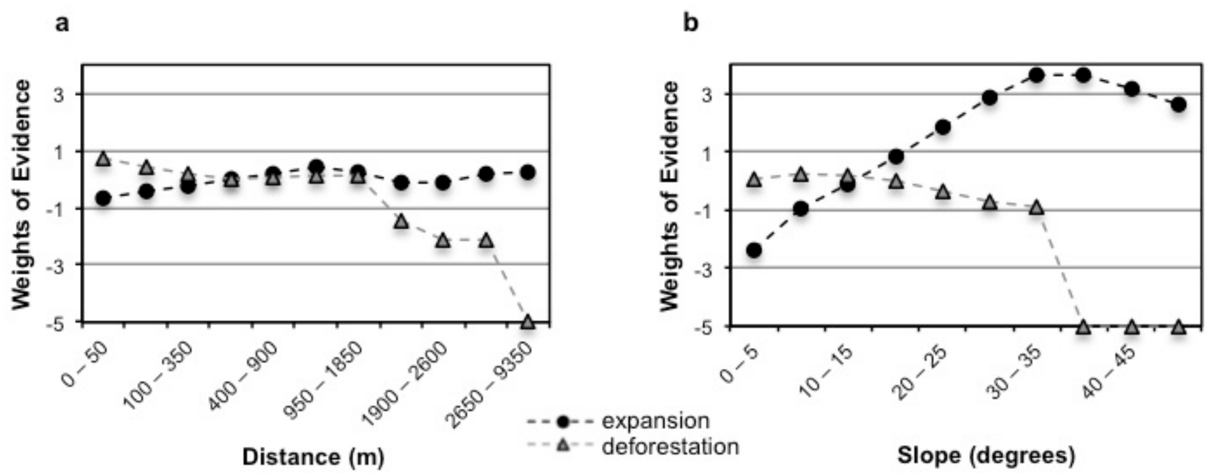
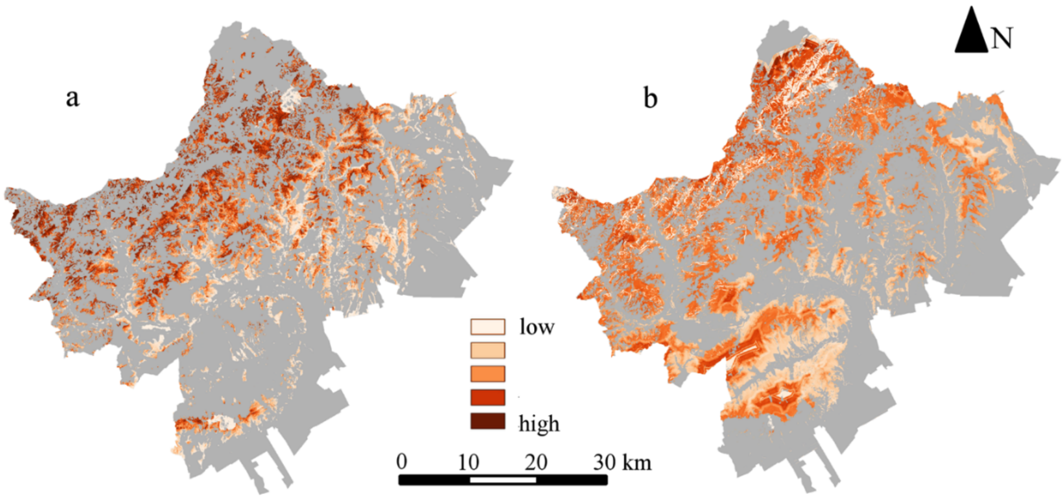


**Fig. 6**

Transition probability maps for (a) forest expansion and (b) deforestation for the year 2010, ranging from 0 (low) to 1 (high)




### Simulated scenarios

The 2040 scenarios show all locations where deforestation was projected to occur during the 30-year model run. For example, if an area had experienced deforestation in the earlier years of the run, this area was still portrayed as deforested in 2040. This way, we demonstrated the full spatial distribution of the landscape affected by deforestation. There were no considerable differences in the spatial distribution of forest cover changes between the two scenarios (Fig. 8). This is because they were both based on identical spatial factors and transition probability maps (Fig. 6). The two scenarios did however differ in the total 2010 forest areas subject to deforestation until 2040: 2.2 % in the Alternative and 1.3 % in the BAU scenario (Table 2). The amount of forest expansion was 99.93 km2, resulting in an 8 % increase of forest cover in the Alternative, and an 8.8 % increase in the BAU scenario. For both scenarios this meant a 14.3 % decrease in grasslands.

### Model performance

The spatial agreement of change cells between the actual and modeled difference maps was described by the fuzzy similarity index (Fig. 7). This agreement ranged from 51.5 % at the windows size of 30 m (single cell) to 83.9 % at the windows size of 450 m (15 cells neighborhood). All spatial factors had a Cramer coefficient below 0.25, with 0.5

being a threshold under which the spatial factors are independent (de Almeida et al. 2003).

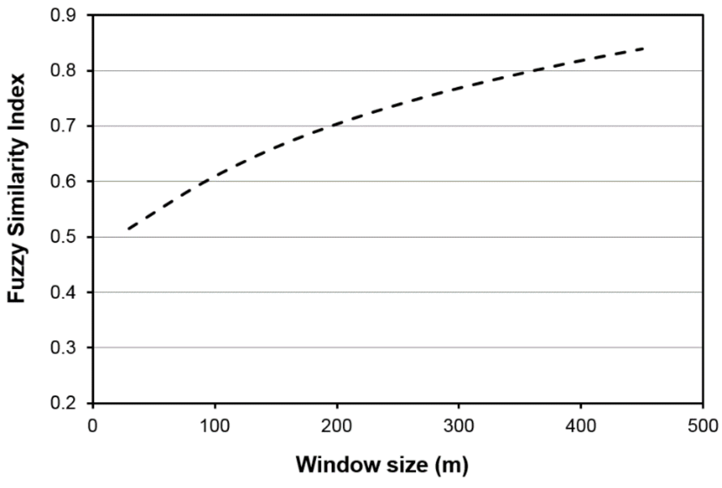
**Table 2**

Distribution of forest cover change scenarios and baseline among landslide susceptibility classes. The values for the scenarios are in ha and % of the total forest cover change process, the values for the baseline are in km2 and %

| | Scenarios – ha (%) | | | Baseline 2010 – $km^2$ (%) | | |
|---|---|---|---|---|---|---|
| **Susceptibility (%)** | **Deforestation Alternative** | **Deforestation BAU** | **Forest expansion** | **Total area** | **Forest** | **Non-forest areas** |
| 0 – 20 | 980.7 (45.9) | 607.7 (47.4) | 1844.7 (18.5) | 1172.7 (48.4) | 364.3 (37.1) | 808.2 (56.2) |
| 20 – 40 | 673.8 (31.5) | 399.5 (31.1) | 1407.0 (14.1) | 534.2 (22.1) | 350.6 (35.7) | 183.1 (12.7) |
| 40 – 60 | 374.7 (17.5) | 219.8 (17.1) | 1839.7 (18.4) | 328.7 (13.6) | 203.4 (20.7) | 125.3 (8.7) |
| 60 – 80 | 105.7 (4.9) | 53.8 (4.2) | 2344.4 (23.4) | 216.9 (9.0) | 59.5 (6.1) | 158.0 (10.9) |
| 80 – 100 | 2.9 (0.1) | 1.9 (0.1) | 2558.2 (25.6) | 168.5 (7.0) | 3.2 (0.3) | 165.3 (11.5) |
| Total | 2138 | 1283 | 9993 | 2421 | 981 | 1440 |

**Fig. 7**

Fuzzy similarity index, describing the agreement of change cells between the actual and modeled difference map using multiple resolution windows



## Landslide risk

The vast majority of deforestation was modeled in areas with low landslide susceptibility, as opposed to forest expansion (Table 2). In total, 483 ha in the Alternative run, and 276 ha in the BAU scenario were projected to occur in areas with a landslide susceptibility over 40 %. The amount of deforestation remained the same in model runs with excluded highly susceptible areas, with a slightly different spatial distribution (Fig. 8c and 8d). There are two main reasons behind the majority of deforestation being projected in areas with low susceptibility. First, the weights of evidence and consequent deforestation probability maps promoted deforestation on areas with lower slopes (Fig. 5b and Fig. 6). Secondly, non-forest areas had a higher likelihood of being characterized with higher landslide susceptibility than forest areas. In our example more than 80 % of forests were defined with a susceptibility value below 50 % (Table 2). This means, that a landslide would be less likely to occur on a forested area, as opposed to a non-forested area with similar environmental characteristics (slope, lithology). This is not surprising, as evidence shows the positive influence of roots mechanically reinforcing soils in forested landscapes (Schmidt et al. 2001).

We demonstrated the impact of implementing a risk policy by observing the changes in the distribution in distance and slope classes in the two additional scenarios (Fig. 9). We did not observe any evidence on increasing the distance of clear-cuts from roads. There were gains and losses in both the near and more distant 10-quantile classes (Fig. 9a). The impact of the risk policy is more significant when looking at differences to distribution in slope classes. In the Alternative scenario, more deforestation was projected on steeper areas (above 15 degrees), whereas in the BAU scenario, substantially more changes occurred in the slope class between 5 and 10 degrees (Fig. 9b). Considering both distribution differences, the accessibility of clear-cuts decreased in the Alternative and did not change in the BAU scenario. Thus, the implemented risk policy could result in additional costs to forest exploitation when raising the clear-cut limit (Alternative) and no costs in the BAU clear-cut quantities.

**Fig. 8**

2040 forest cover scenarios: (a) Alternative, (b) BAU; scenarios considering landslide risk: (c) Alternative, (d) BAU

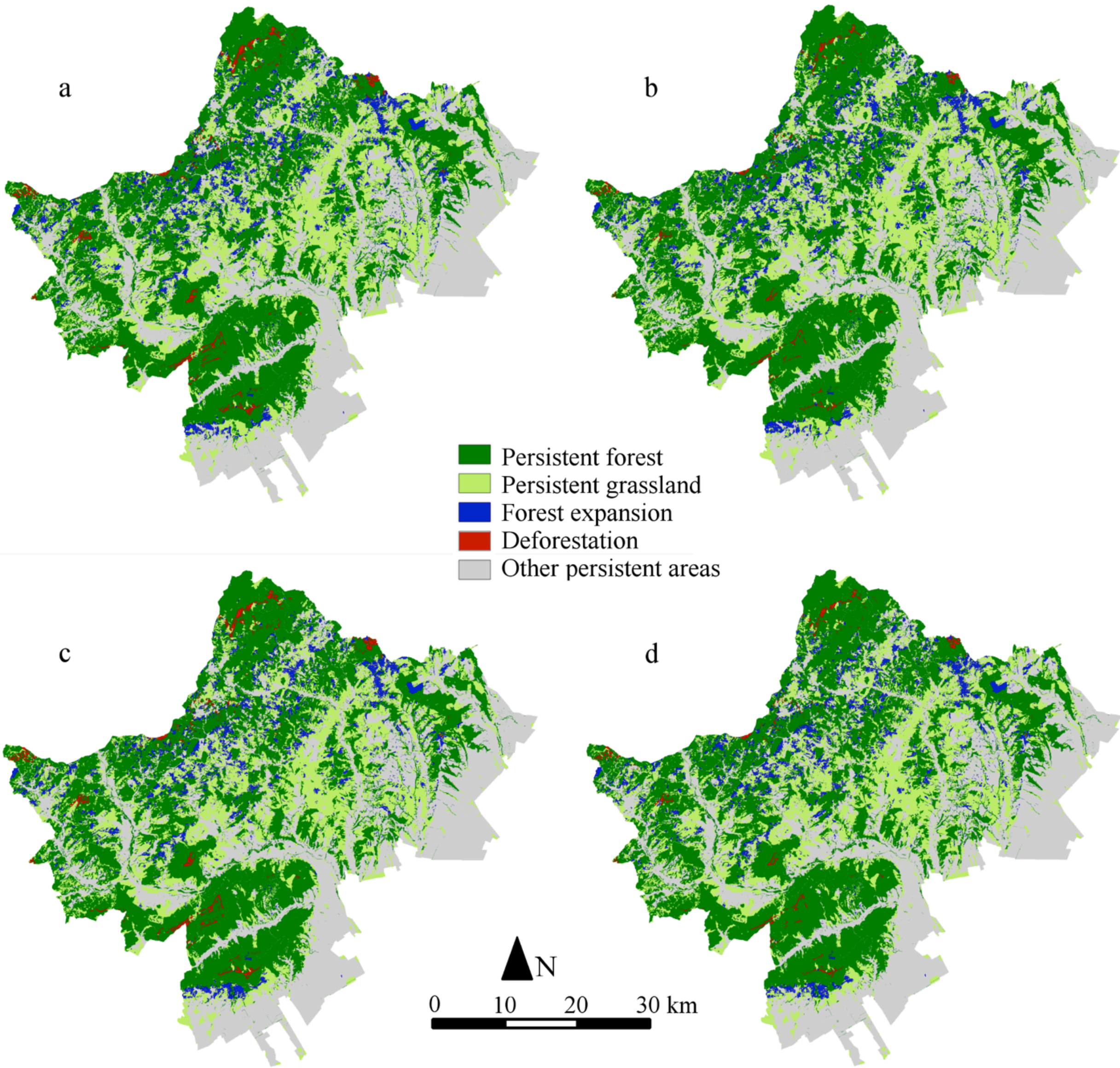
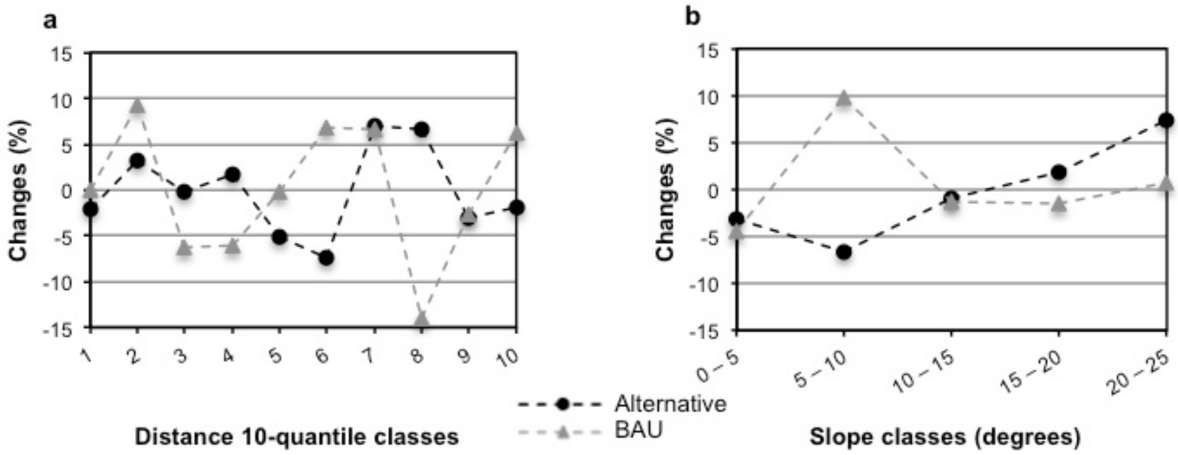


**Fig. 9**

Difference in distribution of deforestation taking into account risk information in (a) distance 10-quantile classes and (b) slope classes




## Discussion and Conclusion

Current and past forest changes in the Carpathian region are well understood. The complex causes of forest cover changes are well studied and focus among others on changes to the ownership, forest policy and emergence of private forestry and wood processing industry (Ioras and Abrudan 2006; Griffiths et al. 2012; Munteanu et al. 2014; Griffiths et al. 2014). Nevertheless, there is a lack of future projections on how continuing socio-economic and policy changes can affect the forest cover in a region in socio-economic transition, such as the Carpathians. In this study we generated future forest cover scenarios in a region in the Romanian Carpathians. These scenarios were based on identified possible changes to current forest policy. We then assessed potential future changes to landslide risk and the effect of a risk mitigation policy.

The deforestation estimation part of the model differs substantially from other similar scale forest cover change studies. It is based on the identified changes in regards to the allowed forest harvesting and clear-cutting. This is not the case in several other studies, where estimates are based on observed historic forest cover transition rates: examples range among others from Brazil (Yanai et al. 2012), Indonesia (Fuller et al. 2011) to Laos (Kamusoko et al. 2013). These examples, however offer insight into the spatial allocation procedure, and the identification of spatial factors (elevation, slope, distance to settlements, roads). The process of forest expansion was based on remote sensing observations between 1989 and 2010. Forest expansion in the Carpathians is a long-term process similar to other European mountain areas (Mather 2001; Kozak et al.

2007a; Munteanu et al. 2014). Therefore, we chose a longer period to simulate a long-term forest expansion trend. The possible different rates of past forest expansion were thus not considered in the scenarios. Some parts of the Romanian Carpathians did however experience different rates of forest expansion due to different land abandonment rates in the past decades (Griffiths et al. 2013).

It remains difficult to assess the performance of land cover change models, as they are calibrated with past observations, particularly when dealing with the location of changes and not just their quantity (Veldkamp and Lambin 2001). Nevertheless, we consider the performance of the model as satisfactory. The spatial agreement of our model is comparable with previous high resolution land change models developed in Dinamica EGO (Soares-Filho et al. 2002; Maeda et al. 2010; Maeda et al. 2011; Kamusoko et al. 2013; Thapa et al. 2013). The results, however should be taken with care, as the uncertainty of the spatial allocation model is aggregated with the uncertainties in the input land cover and susceptibility maps.

Several studies have addressed the influence of future land cover changes on risk, either through identifying risk hotspots (Promper et al. 2014) or overlaying the scenarios with a hazard map (Barredo and Engelen 2010). Due to lack of data on landslide hazard or risk, we used a landslide susceptibility map. Landslide susceptibility analysis has already been used to study the influence of past and current land cover (Chitu et al. 2015; Reichenbach et al. 2015). Still, landslide data used for generating the susceptibility map could ignore landslides occurring in forests. This could result in underestimation of susceptibility values in forests and overestimation of susceptibility values on non-forest areas. The projected amount of deforestation in areas with higher landslide susceptibility cannot be considered insignificant, as the Subcarpathians are a relatively densely populated area. However, as most of the forest expansion was projected on areas with higher landslide susceptibility, we expect an overall regional decrease in landslide susceptibility. Reforestation can improve slope stability and could be considered as a risk reduction measurement (Phillips and Marden 2005).

The cellular automata allocation algorithm simulates the choice of plots (cells) subject to deforestation and can explain the influence of the implemented risk policy. In the case of an excluded area (due to high susceptibility), the changes occurred in the nearest cells with a similar deforestation probability. This did not result in evident changes to the distance of deforestation from roads, however could still result in deforestation on steeper slopes. Therefore, the evidence on higher costs related to the accessibility of the clear-cuts is stronger in the case of slopes and less evident in the case of the distance.

Deforestation could also lead to other consequences besides the potential changes to landslide risk. Among others, it might affect habitat fragmentation and changes to landscape connectivity (Körner et al. 2005; Millenium Ecosystem Assessment 2005). This is important, as the Buzau Subcarpathians are characterized by a high frequency of European large carnivores such as the brown bear (Ursus arctos), and the wolf (Canis lupus) (van Maanen et al. 2006). Thus, we suggest additional research on analyzing the impact of deforestation on biodiversity. Forest expansion can also have a wide variety of other consequences: e.g. it can be beneficial for bird and large mammal habitats (Baur et al. 2006; Bowen et al. 2007; Navarro and Pereira 2012). Forest expansion can also have detrimental effects. Several studies have emphasized the influence of forest expansion and loss of grasslands on ecosystem services provisioning: loss of high-value nature grasslands, landscape diversity, and potential loss of important habitats (MacDonald et al. 2000; Fischer et al. 2008; Zimmermann et al. 2010).

In this study we focused on plausible scenarios, however we could also study less likely, extreme scenarios. First example are scenarios where forest management is following only market demands, thus promoting less costly large scale clear-cutting (Thapa et al. 2013). Secondly, possible influence of new road infrastructure could be studied (Maeda et al. 2011; Kamusoko et al. 2013). Furthermore, our scenarios did not take into account illegal logging, a significant issue in the Carpathian region (Griffiths et al. 2012; Griffiths et al. 2014). Due to lack of data and the randomness of the phenomena, we believe other approaches such as agent based modeling should address this issue. Finally, we could investigate radical political changes, similar to the events after 1989 (ownership reforms, introduction of a market economy), or possible shocks as a dramatic wood demand due to bioenergy policy changes. The level of plausibility of both developed scenarios (both are likely to happen) also lead to seemingly small differences between the two scenarios. Our results however showed, that already allowing an increase in amount and size of clear-cutting could lead to significant changes to landslide risk. Moreover, we showed that avoiding this risk could lead to higher costs to forest harvesting in case of the increase in clear-cutting. Therefore, we believe our approach is especially significant in providing information on possible changes to landslide risk and the effect of risk related policies.

Scenarios are not exact projections of future states of the environment (Abildtrup et al. 2006). Nevertheless, they can serve as a valuable tool to study policy decisions, leading to improved knowledge on forest exploitation and protection. Even though the uncertainties of data and the model have to be taken into account, the results suggest most likely areas where deforestation might occur in the future. Therefore, they could be prioritized as locations, where risk reduction measures need to be considered (reforestation, technical works). Moreover, improving the model with better data – especially in terms of landslide risk – could lead to more precise results, enabling the support and improvement of decision-making in forest management.

The use of scenarios as a methodology for studying land cover changes has been studied thoroughly on different scales and in different areas. This study however presents a new approach integrating qualitative methods such as interviews, with geospatial technologies such as GIS and spatial simulation. The developed scenarios were based on the understanding of the system of forest management, and were not based solely on extrapolating past trends. Moreover, the scenarios are spatially explicit, enabling the identification of the spatial pattern of change and possible critical areas of forest cover change. Another innovative aspect of the study is, that it analyzes possible changes to landslide risk, as a consequence of future forest cover change. Finally, this study contributes to the understanding of future environmental consequences of today's decisions in the field of forest and land use management in the Carpathian region.

## Acknowledgement

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## References

Abildtrup J, Audsley E, Fekete-Farkas M, et al. (2006) Socio-economic scenario development for the assessment of climate change impacts on agricultural land use: a pairwise comparison approach. Environ Sci Policy 9:101–115. doi: 10.1016/j.envsci.2005.11.002

Bălteanu D, Popovici EA (2010) Land use changes and land degradation in post-socialist Romania. Romanian J Geogr 54:95–105.

Barredo JI, Engelen G (2010) Land Use Scenario Modeling for Flood Risk Mitigation. Sustainability 2:1327–1344. doi: 10.3390/su2051327

Baumann M, Kuemmerle T, Elbakidze M, et al. (2011) Patterns and drivers of post-socialist farmland abandonment in Western Ukraine. Land Use Policy 28:552–562. doi: 10.1016/j.landusepol.2010.11.003

Baur B, Cremene C, Groza G, et al. (2006) Effects of abandonment of subalpine hay meadows on plant and invertebrate diversity in Transylvania, Romania. Biol Conserv 132:261–273. doi: 10.1016/j.biocon.2006.04.018

Björnsen Gurung A, Bokwa A, Chełmicki W, et al. (2009) Global Change Research in the Carpathian Mountain Region. Mt Res Dev 29:282–288. doi: 10.1659/mrd.1105

Bohateret VM (2012) Readjusting Romania's Forestry Policy with a View to the Year 2050. J Settl Spat Plan 1:27–42.

Bonham-Carter G (1994) Geographic information systems for geoscientists: modelling with GIS. Pergamon, Oxford; New York

Bowen ME, McAlpine CA, House APN, Smith GC (2007) Regrowth forests on abandoned agricultural land: A review of their habitat values for recovering forest fauna. Biol Conserv 140:273–296. doi: 10.1016/j.biocon.2007.08.012

Chemini C, Rizzoli A (2003) Land use change and biodiversity conservation in the Alps. J Mt Ecol 7:1–7.

Chitu Z, Istrate A, Adler M-J, et al. (2015) Comparative Study of the Methods for Assessing Landslide Susceptibility in Ialomiţa Subcarpathians, Romania. In: Lollino G, Giordan D, Crosta GB, et al. (eds) Eng. Geol. Soc. Territ. - Vol. 2. Springer International Publishing, pp 1205–1209

De Almeida CM, Batty M, Vieira Monteiro AM, et al. (2003) Stochastic cellular automata modeling of urban land use dynamics: empirical development and estimation. Comput Environ Urban Syst 27:481–509. doi: 10.1016/S0198-9715(02)00042-X

Deshler D (1987) Techniques for generating futures perspectives. New Dir Adult Contin Educ 1987:79–92. doi: 10.1002/ace.36719873609

EEA (1999) Environmental indicators: Typology and overview. European Environment Agency, Copenhagen

Engelen G, White R, Uljee I, Drazan P (1995) Using cellular automata for integrated modelling of socio-environmental systems. Environ Monit Assess 34:203–214. doi: 10.1007/BF00546036

Falcucci A, Maiorano L, Ciucci P, et al. (2008) Land-cover change and the future of the Apennine brown bear: a perspective from the past. J Mammal 89:1502–1511. doi: 10.1644/07-MAMM-A-229.1

FAO (1997) Issues and Opportunities in the Evolution of Private Forestry and Forestry Extension in Several Countries with Economies in Transition in Central and Eastern Europe. Food and Agriculture Organization of the United Nations, Rome

Fischer M, Rudmann-Maurer K, Weyand A, Stöcklin J (2008) Agricultural Land Use and Biodiversity in the Alps. Mt Res Dev 28:148–155. doi: 10.1659/mrd.0964

Fuller DO, Hardiono M, Meijaard E (2011) Deforestation Projections for Carbon-Rich Peat Swamp Forests of Central Kalimantan, Indonesia. Environ Manage 48:436–447. doi: 10.1007/s00267-011-9643-2

Ghimire S, Higaki D, Bhattarai T (2013) Estimation of Soil Erosion Rates and Eroded Sediment in a Degraded Catchment of the Siwalik Hills, Nepal. Land 2:370–391. doi: 10.3390/land2030370

Giupponi C, Ramanzin M, Sturaro E, Fuser S (2006) Climate and land use changes, biodiversity and agri-environmental measures in the Belluno province, Italy. Environ Sci Policy 9:163–173. doi: 10.1016/j.envsci.2005.11.007

Giurgiu V (2004) Gestionarea durabilă a pădurilor României. Silvologie, vol. III B. The Publishing House of the Romanian Academy, Bucharest

Glade T (2003) Landslide occurrence as a response to land use change: a review of evidence from New Zealand. Catena 51:297–314. doi: 10.1016/S0341-8162(02)00170-4

Glade T, Crozier MJ (2005) The Nature of Landslide Hazard Impact. In: Glade T, Anderson M, Crozier MJ (eds) Landslide Hazard Risk. John Wiley & Sons, Ltd, pp 41–74

Griffiths P, Kuemmerle T, Baumann M, et al. (2014) Forest disturbances, forest recovery, and changes in forest types across the Carpathian ecoregion from 1985 to 2010 based on Landsat image composites. Remote Sens Environ 151:72–88. doi: 10.1016/j.rse.2013.04.022

Griffiths P, Kuemmerle T, Kennedy RE, et al. (2012) Using annual time-series of Landsat images to assess the effects of forest restitution in post-socialist Romania. Remote Sens Environ 118:199–214. doi: 10.1016/j.rse.2011.11.006

Griffiths P, Müller D, Kuemmerle T, Hostert P (2013) Agricultural land change in the Carpathian ecoregion after the breakdown of socialism and expansion of the European Union. Environ Res Lett 8:045024. doi: 10.1088/1748-9326/8/4/045024

Gustafson EJ (1998) Quantifying Landscape Spatial Pattern: What Is the State of the Art? Ecosystems 1:143–156. doi: 10.1007/s100219900011

Guzzetti F, Reichenbach P, Ardizzone F, et al. (2006) Estimating the quality of landslide susceptibility models. Geomorphology 81:166–184. doi: 10.1016/j.geomorph.2006.04.007

Guzzetti F, Reichenbach P, Cardinali M, et al. (2005) Probabilistic landslide hazard assessment at the basin scale. Geomorphology 72:272–299. doi: 10.1016/j.geomorph.2005.06.002

Hagen A (2003) Fuzzy set approach to assessing similarity of categorical maps. Int J Geogr Inf Sci 17:235–249. doi: 10.1080/13658810210157822

Hessel R, Messing I, Liding C, et al. (2003) Soil erosion simulations of land use scenarios for a small Loess Plateau catchment. Catena 54:289–302. doi: 10.1016/S0341-8162(03)00070-5

Hosseinali F, Alesheikh AA (2008) Weighting Spatial Information in GIS for Copper Mining Exploration. Am J Appl Sci 5:1187–1198. doi: 10.3844/ajassp.2008.1187.1198

Hussin H, Zumpano V, Sterlacchini S, et al. (2013) Comparing the predictive capability of landslide susceptibility models in three different study areas using the Weights of Evidence technique. EGU Gen. Assem. Conf. Abstr. Vienna, p 12701

INSSE (2013) Romanian National Institute of Statistics Data Portal. http://www.insse.ro/. Accessed 11 May 2013

Ioras F, Abrudan I. (2006) The Romanian forestry sector: privatisation facts. Int For Rev 8:361–367. doi: 10.1505/ifor.8.3.361

Kamusoko C, Wada Y, Furuya T, et al. (2013) Simulating Future Forest Cover Changes in Pakxeng District, Lao People’s Democratic Republic (PDR): Implications for Sustainable Forest Management. Land 2:1–19. doi: 10.3390/land2010001

Knorn J, Kuemmerle T, Radeloff VC, et al. (2012) Forest restitution and protected area effectiveness in post-socialist Romania. Biol Conserv 146:204–212. doi: 10.1016/j.biocon.2011.12.020

Körner C, Ohsawa M, Spehn E, et al. (2005) Mountain Systems. Ecosyst. Hum. Well-Curr. State Trends Find. Cond. Trends Work. Group Millenn. Ecosyst. Assess. pp 681–716

Kozak J, Estreguil C, Troll M (2007a) Forest cover changes in the northern Carpathians in the 20th century: a slow transition. J Land Use Sci 2:127–146. doi: 10.1080/17474230701218244

Kozak J, Estreguil C, Vogt P (2007b) Forest cover and pattern changes in the Carpathians over the last decades. Eur J For Res 126:77–90. doi: 10.1007/s10342-006-0160-4

Kriegler E, O'Neill BC, Hallegatte S, et al. (2012) The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. Glob Environ Change 22:807–822. doi: 10.1016/j.gloenvcha.2012.05.005

Kuemmerle T, Müller D, Griffiths P, Rusu M (2008) Land use change in Southern Romania after the collapse of socialism. Reg Environ Change 9:1–12. doi: 10.1007/s10113-008-0050-z

Lerman Z, Csaki C, Feder G (2004) Evolving farm structures and land use patterns in former socialist countries. Q J Int Agric 43:309–336.

MacDonald D, Crabtree J., Wiesinger G, et al. (2000) Agricultural abandonment in mountain areas of Europe: Environmental consequences and policy response. J Environ Manage 59:47–69. doi: 10.1006/jema.1999.0335

MADR (2012) Programul Naţional de Dezvoltare Rurală 2007-2013. National Rural Development Program. Ministry of Agriculture and Rural Development of Romania

Maeda EE, Clark BJF, Pellikka P, Siljander M (2010) Modelling agricultural expansion in Kenya's Eastern Arc Mountains biodiversity hotspot. Agric Syst 103:609–620. doi: 10.1016/j.agsy.2010.07.004

Maeda EE, de Almeida CM, de Carvalho Ximenes A, et al. (2011) Dynamic modeling of forest conversion: Simulation of past and future scenarios of rural activities expansion in the fringes of the Xingu National Park, Brazilian Amazon. Int J Appl Earth Obs Geoinformation 13:435–446. doi: 10.1016/j.jag.2010.09.008

Malek Ž, Scolobig A, Schröter D (2014) Understanding Land Cover Changes in the Italian Alps and Romanian Carpathians Combining Remote Sensing and Stakeholder Interviews. Land 3:52–73. doi: 10.3390/land3010052

Mather A (2001) The transition from Deforestation to Reforestation in Europe. In: Angelsen A, Kaimowitz D (eds) Agric. Technol. Trop. Deforestation. CABI, Wallingford, Oxon, p 422

Mathijs E, Swinnen JFM (1998) The economics of agricultural decollectivization in East Central Europe and the former Soviet Union. Econ Dev Cult Change 47:1–26. doi: 10.1086/452384

Micu M, Bălteanu D (2013) A deep-seated landslide dam in the Siriu Reservoir (Curvature Carpathians, Romania). Landslides 10:323–329. doi: 10.1007/s10346-013-0382-8

Millenium Ecosystem Assessment (2005) Ecosystems and human Well-Being: Synthesis. Island Press, Washington, DC

Mitsova D, Shuster W, Wang X (2011) A cellular automata model of land cover change to integrate urban growth with open space conservation. Landsc Urban Plan 99:141–153. doi: 10.1016/j.landurbplan.2010.10.001

Muică N, Turnock D (2008) A Toponomical Approach to the Agrarian History of the Pătârlagele Depression (Buzău Subcarpathians, România). Hum. Geogr. - J. Stud. Res. Hum. Geogr. 2:

Müller D, Kuemmerle T, Rusu M, Griffiths P (2009) Lost in transition: determinants of post-socialist cropland abandonment in Romania. J Land Use Sci 4:109–129. doi: 10.1080/17474230802645881

Munteanu C, Kuemmerle T, Boltiziar M, et al. (2014) Forest and agricultural land change in the Carpathian region—A meta-analysis of long-term patterns and drivers of change. Land Use Policy 38:685–697. doi: 10.1016/j.landusepol.2014.01.012

Navarro LM, Pereira HM (2012) Rewilding Abandoned Landscapes in Europe. Ecosystems 15:900–912. doi: 10.1007/s10021-012-9558-7

Olsson EGA, Austrheim G, Grenne SN (2000) Landscape change patterns in mountains, land use and environmental diversity, Mid-Norway 1960–1993. Landsc Ecol 15:155–170. doi: 10.1023/A:1008173628016

Papathoma-Köhle M, Glade T (2013) Papathoma-Köhle M. and Glade T., 2013. The role of vegetation cover change for landslide hazard and risk. In: Renaud FG, Sudmeier-Rieux K, Estrella M (eds) Role Ecosyst. Disaster Risk Reduct. UNU-Press, Tokyo, pp 293–320

Parlamentul României (1996) Law No. 26/1996. The Romanian Forest Code. Monitorul Oficial. Official Journal of Romania, Bucharest

Petschko H, Brenning A, Bell R, et al. (2014) Assessing the quality of landslide susceptibility maps – case study Lower Austria. Nat Hazards Earth Syst Sci 14:95–118. doi: 10.5194/nhess-14-95-2014

Phillips C, Marden M (2005) Reforestation Schemes to Manage Regional Landslide

Risk. In: Glade T, Anderson lcolm, Crozier MJ (eds) Landslide Hazard Risk. John Wiley & Sons, Ltd, pp 517–547

Promper C, Puissant A, Malet J-P, Glade T (2014) Analysis of land cover changes in the past and the future as contribution to landslide risk scenarios. Appl Geogr 53:11–19. doi: 10.1016/j.apgeog.2014.05.020

Quantum GIS Development Team (2013) Quantum GIS Geographic Information System. Open Source Geospatial Foundation Project

Reichenbach P, Busca C, Mondini AC, Rossi M (2015) Land Use Change Scenarios and Landslide Susceptibility Zonation: The Briga Catchment Test Area (Messina, Italy). In: Lollino G, Manconi A, Clague J, et al. (eds) Eng. Geol. Soc. Territ. - Vol. 1. Springer International Publishing, pp 557–561

Rounsevell M, Reginster I, Araújo MB, et al. (2006) A coherent set of future land use change scenarios for Europe. Agric Ecosyst Environ 114:57–68. doi: 10.1016/j.agee.2005.11.027

Schelhaas MJ, van Brusselen J, Pussinen A, et al. (2006) Outlook for the Development of European Forest Resources, a study prepared by the European Forest Sector Outlook Study (EFSOS). United Nations Economic Commission for Europe (UNECE), Geneva

Schmidt KM, Roering JJ, Stock JD, et al. (2001) The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. Can Geotech J 38:995–1024. doi: 10.1139/t01-031

Shearer AW (2005) Approaching scenario-based studies: three perceptions about the future and considerations for landscape planning. Environ Plan B Plan Des 32:67–87. doi: 10.1068/b3116

Soares-Filho BS, Cerqueira GC, Pennachin CL (2002) Dinamica—a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. Ecol Model 154:217–235. doi: 10.1016/S0304-3800(02)00059-5

Soares-Filho BS, Nepstad DC, Curran LM, et al. (2006) Modelling conservation in the Amazon basin. Nature 440:520–523. doi: 10.1038/nature04389

Taff GN, Müller D, Kuemmerle T, et al. (2009) Reforestation in Central and Eastern Europe After the Breakdown of Socialism. In: Nagendra H, Southworth J (eds) Reforesting Landsc. Springer Netherlands, Dordrecht, pp 121–147

Tasser E, Mader M, Tappeiner U (2003) Effects of land use in alpine grasslands on the probability of landslides. Basic Appl Ecol 4:271–280. doi: 10.1078/1439-1791-00153

Thapa RB, Shimada M, Watanabe M, et al. (2013) The tropical forest in south east Asia: Monitoring and scenario modeling using synthetic aperture radar data. Appl Geogr 41:168–178. doi: 10.1016/j.apgeog.2013.04.009

Van Maanen E, Predoiu G, Klaver R, et al. (2006) Safeguarding the Romanian Carpathian ecological network. A vision for large carnivores and biodiversity in Eastern Europe. Icas Wildlife Unit, Brasov

Veldkamp A, Lambin E. (2001) Predicting land-use change. Agric Ecosyst Environ 85:1–6. doi: 10.1016/S0167-8809(01)00199-2

Verburg PH, Schot PP, Dijst MJ, Veldkamp A (2004) Land use change modelling: current practice and research priorities. GeoJournal 61:309–324. doi: 10.1007/s10708-004-4946-y

Wijesekara GN, Farjad B, Gupta A, et al. (2014) A Comprehensive Land-Use/Hydrological Modeling System for Scenario Simulations in the Elbow River Watershed, Alberta, Canada. Environ Manage 53:357–381. doi: 10.1007/s00267-013-0220-8

Wollenberg E, Edmunds D, Buck L (2000) Using scenarios to make decisions about the future: anticipatory learning for the adaptive co-management of community forests. Landsc Urban Plan 47:65–77. doi: 10.1016/S0169-2046(99)00071-7

Yanai AM, Fearnside PM, Graça PML de A, Nogueira EM (2012) Avoided deforestation in Brazilian Amazonia: Simulating the effect of the Juma Sustainable Development Reserve. For Ecol Manag 282:78–91. doi: 10.1016/j.foreco.2012.06.029

Zimmermann P, Tasser E, Leitinger G, Tappeiner U (2010) Effects of land-use and land-cover pattern on landscape-scale biodiversity in the European Alps. Agric Ecosyst Environ 139:13–22. doi: 10.1016/j.agee.2010.06.010

# Appendix D: Spatial assessment of future changes to the provision of ecosystem services in Buzau Subcarpathians, Romania

Malek Ž, Zumpano V, Hussin HY.

Status: In preparation for Environmental Earth Sciences


### Abstract

When planning future management of environmental resource and preparing for potential undesirable events, it is necessary to study the consequences of possible futures. This study examines the effects of future changes to the forest cover in the Romanian Carpathians. It is an area with abundant forest resources, high biodiversity levels and dense distribution of landslides. Past trend of forest harvesting suggest that the ecosystem services provided by the forests and grasslands in the study area are subject to degradation. A geographic information systems based approach was used to analyse two scenarios of forest cover change, resulting in spatial distributions of gains and losses to three ecosystem services: wood provision, biodiversity support and landslide regulation. The results show that on a regional scale there will be many more gains than losses to wood provision and landslide regulation, and an overall loss to biodiversity support provided by high value nature grasslands. Still, several areas will experience a loss in terms of a steady provision of wood, as well as a potential increase of landslide occurrence due to deforestation. The approach can be applied to similar areas, where the lack of detailed data prevents more elaborate modeling procedures. Moreover, by performing a spatial analysis of changes to the provision of ecosystem services, potential hot-spots where environmental degradation can be expected can be identified.


### Introduction

Mountain ecosystems provide vital resources and services to European societies, such as forest products, protection from natural hazards, tourism and recreation related services, and maintenance of biological diversity (Körner et al 2005; Schröter et al 2005). They are essential to the survival of the complex global ecosystem as they support about one quarter of terrestrial biodiversity, with almost half of the biodiversity on Earth concentrated in mountains and hills (Körner et al 2005). This is also the case in the Romanian Carpathians, providing valuable ecosystem services (ES) on a local, regional and wider European scale, being one of the biggest continuous forest ecosystems and shelters for large carnivores and herbivores (van Maanen et al 2006; Kozak et al 2007; Kuemmerle et al 2008). After the fall of socialism, the Carpathian region experienced the fall of large collective agricultural associations, changes to land use policy and dramatic changes to land ownership resulting in numerous new land owners (Mathijs and Swinnen 1998; Lerman et al 2004). As a consequence, the region witnessed land abandonment and reforestation, but also an increase in forest harvesting activities (Kuemmerle et al 2008; Müller et al 2009; Taff et al 2009; Baumann et al 2011). Indeed, the Romanian Carpathian ecosystems are among the most vulnerable to anthropogenic change due to severe natural conditions defined by altitude, slope, temperature, soil and precipitation that can result in slow recovery (Kozak et al 2007; Kuemmerle et al 2008).

Ecosystems may deliver more than one service, and their manipulation to maximize one particular service can lead to unsustainable management and risks reducing other services. This decreases their value for other uses, leading to conflicts between different stakeholders that perceive different benefits from ecosystems (Scheffer et al 2000; Fisher et al 2009; Castro et al 2011). Traditional multi-function landscapes are often turned into simple, single functioning land use types or into eroded or over-exploited areas (De Groot 2006). To fully understand the environmental impact of resource exploitation, we analyzed possible consequences of forest harvesting in the Romanian Carpathians. More precisely, we focused on possible negative feedback in the form of poorer resource provision, biodiversity levels, and elevated landslide risk.

The Subcarpathians of the Buzau County in Romania are a suitable case study area to apply the ecosystem services concept. This is due to its physical-geographic characteristics affected by the occurrence of hydro-meteorological hazards and the socio-economic background, as a result of recent policy and economic changes. The area is experiencing an increased human influence, mostly in the form of a steady growth in forest exploitation. In addition, the Buzau county is characterized by high levels of biodiversity, and acts as a refuge for important European habitats and species within the Romanian Carpathians (Oszlányi et al 2004).

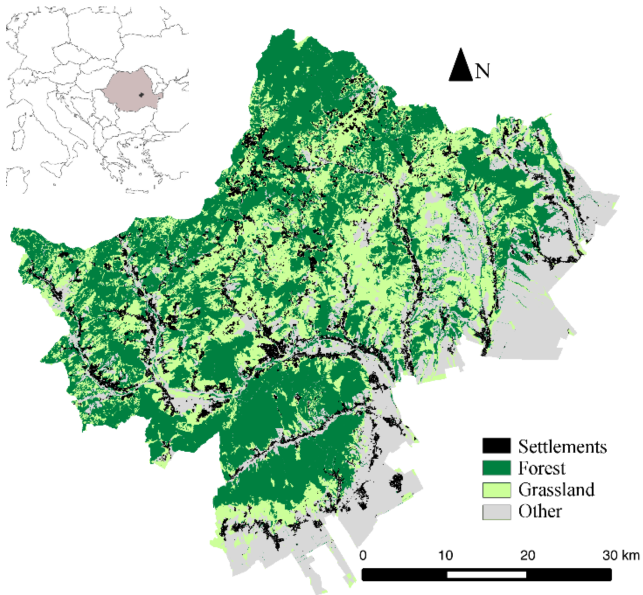
In order to identify critical areas of changes to ecosystem services provisioning and to understand the changes in their spatial pattern, a spatially explicit approach is needed (Verburg et al 1999). A spatially explicit approach considers biophysical factors, such as terrain, hydrology, soil, geology, together with other spatial factors like distance to cities or population density. The changes in landscape, in terms of geographic location and spatial pattern, are reflected by changes in ES provisioning. There are several examples of spatially explicit analysis of ecosystem services provisioning. Burkhard et al. (2010) assigned each landscape unit a value for provision of a variety of ecosystem services. Egoh et al. (2008) used different models to identify the location of hotspots for multiple ecosystem services provisioning. In terms of mapping ecosystem services, attempts have been made to map their demand and supply, as in the case of regulating river flows and floods (Nedkov and Burkhard 2012). In another example, the result was a spatially explicit valuation of ecosystem services (Grêt-Regamey et al 2008). Other studies focused on a spatial analysis of the ecosystem services value transfer (Troy and Wilson 2006). All these approaches involve a set of different models, demanding abundant data, especially when valuating ecosystem services in quantitative or monetary terms.

To study the changes to ecosystem services provisioning, we adopted a geographic information system (GIS) based approach, suitable for data poor environments. We analysed the changes to wood provision, biodiversity support and the potential for landslide regulation by comparing future forest cover change scenarios with the existing forest cover. Forest change scenarios were used for the year 2040 generated in a previous study by Malek et al. (2014b). For wood provision, we observed the potential changes to the forest growing stock. The change in biodiversity support was analyzed by identifying the loss of high nature value (HNV) grasslands due to forest expansion. Potential changes to the ecosystems service of regulating landslides was assessed using a statistical landslide susceptibility model for different land-use scenarios. Our method resulted in a quantifiable and spatially explicit approach in order to describe a wider variety of possible changes to ecosystem services provisioning in the Buzau Subcarpathians.

## Study area

The Buzau Subcarpathians (Figure 1) are situated in the Buzau County in southeastern Romania (45°27’3’’ N, 26°30’23’’ E). The area covers 2421 km$^2$ located between the higher altitude Carpathian mountains and the lower Buzau plain. The mean altitude of the Subcarpathians is 429 m, with a maximum elevation of 1370 m above sea-level. An average slope of 11.5° combined with a geological composition of deposits of Neogene molasse, has caused the area to be highly predisposed to landslide occurrences (Micu and Bălteanu 2013). The annual precipitation ranges between 630-700 mm, with heavy spring and summer rainfall. In some localities, landslides cover more than two-thirds of the total area (Muică and Turnock 2008). Forests covers 40.5 % of the area (981 km$^2$), together with grasslands (27.4 % of the area). The area has around 160000 inhabitants, with a 11% decrease in population since 1989 (INSSE 2013). Agricultural activities such as orchard growing and raising cattle and sheep still has a significant role in the local economy, but is drastically declining (MADR 2012). One of the major economic activities in the area is forest harvesting and wood processing that has a growing trend, both in employment and export. The socio-economic changes in Romania since 1989 have resulted in the area being affected by economic collapse, abandonment of agricultural land and stagnation of urban development (INSSE 2013), while witnessing an increase in forest disturbances. This could be related to numerous reasons, from poor socio-economic conditions after 1989; chaotic land ownership reforms, land retribution; to inefficient forest policy implementation (Malek et al 2014). Indeed, the ownership situation has changed drastically since 1989, while 100% of all forests were previously government property, at least 34.7% has become privately owned since 2010 (INSSE 2013).

Fig.1: Study area. The land cover map is modified from Malek et al. (2014)




## Methods

### Future forest cover scenarios

We generated two spatially explicit scenarios for the year 2040, based on the assumptions of future changes to forest harvesting policy in Romania in our previous study (Malek et al. under prep.). Participatory scenario modeling was combined with Dinamica EGO, a raster based environmental modeling software to develop a spatially explicit forest cover change model (Soares-Filho et al 2002). In the scenarios, we focused on two forest transitions: (1) forest expansion and (2) deforestation. Forest expansion was defined as a change from non-forest (e.g. grassland, agricultural areas and other types of vegetation) to forested areas. Deforestation was defined as a transition from forest to non-forested areas. The first part of the model consisted of the scenario module, which estimated the amount of deforested areas based on the assumption of the forest harvesting policy in Romania. It considered the most likely changes to the amount of allowed forest harvesting, potential clear felling (deforestation) and risk related policy. The second part was the spatial allocation module, which defined the spatial pattern and location of forest expansion and deforestation. This was done by training the model with topographic, forest and remote sensing data between 1989 and 2010 on a 30 m spatial resolution within Dinamica EGO.

#### Changes to the provision of ES

In this study, we analysed changes to the provisioning (wood provision), regulating (landslide regulation) and cultural (biodiversity provision) ecosystem services in the Subcarpathians of Buzau County. The description of ecosystem services and the methodologies to analyse the changes are described in the following paragraphs. The changes to all ecosystem services were assessed through a spatially explicit pixel based approach, where future forest scenarios were compared to the existing forest cover in a GIS environment (Quantum GIS Development Team 2013). The conceptual methodology of changes to the provisioning of ecosystem services in our study is summarised in Table 1.

#### Provisioning services: Wood provision

Subcarpathian ecosystems provide the communities at a local and regional scale with many resources, among which wood is the most important. This is being demonstrated by a vital part of the local economy, which now depends on wood harvesting and processing (MADR 2012). Since 1989, forest management has been experiencing difficulties due to changes in the legislation of forest harvesting and ownership. The past trends suggest that wood provision might change in the future due to growing demands for wood and expected changes in forest legislation (Malek et al 2014). Therefore we have analysed possible future changes to wood provision by comparing the ability of future forest scenarios to provide wood compared to the current situation. If an area experienced forest expansion, this was identified as gain in the provision of wood. Our assumption was based on the fact that an increase in forest cover leads to more forest growing stock, therefore enabling more wood that can potentially be used as a resource according to the Romanian forest legislation (Giurgiu 2004). The new potential growing stock was calculated using the extent of the new projected forest and the value for a mean annual increment of young mixed forest (with an age of 0 to 30 years), which is defined as 8 $m^3$/ha by the regional forest authorities. In the case of deforestation, this was identified as a loss of wood provision, as clear cutting leads to a loss of an area that could contribute to the net annual increment. Clear cutting, as a type of forest harvesting with short term economic gains, decreases the potential of an area to provide a steady and continuous supply of wood. Here, the potential loss of a net annual increment was calculated using the areal extent of deforestation and the value of 6 $m^3$/ha for the increment of mature mixed forests older than 80 years. Due to the unavailability of more detailed forest data (such as forest quality, tree heights and spatial distribution of prevalent species such as spruce, beech and pine), we had to assign a mean value to all forest areas based on expert opinion. This was also the case in defining the higher net annual increment for younger forests, as compared to older, mature forest stands. Another assumption in our assessment was, that if the forest remained the same, there was no change to wood provision. This way we only focused on the possible consequences of the forest cover change scenarios.

**Cultural services: Biodiversity provision**

Subcarpathian high nature value (HNV) grasslands are low intensity agricultural habitats that are amongst most biologically rich and diverse ecosystems (Bignal and McCracken 1996). The concept of HNV was developed to identify areas in Europe where agricultural land use supports high species and habitat diversity (Andersen et al 2003). Thus, we used HNV grasslands as a proxy for the ecosystem service of habitat and biodiversity provision. Land abandonment and forest overgrowth have a negative effect on habitat and biodiversity provision, as they threaten the maintenance of HNV grasslands. The provision of supporting ecosystem services was assessed based on the losses of HNV grasslands due to forest expansion. To map HNV grasslands, we first extracted all built up areas, forests, bare lands and water bodies from the 2010 land cover map generated through the LANDSAT classification by Malek et al. (2014). This was followed by the manual identification of HNV grasslands among the remaining agricultural and grassland areas using the HNV region definition (MADR 2012) and areas with high proportion of semi-natural vegetation. Therefore, we also excluded intensive agricultural areas. A mosaic was also produced of low intensity agricultural areas, including small scale natural elements such as riparian vegetation (Paracchini et al 2008).

**Regulating services: potential for landslide regulation**

Regulating services allow mountain areas to be habitable and are key to the safety of numerous settlements and communication lines, maintaining access to these areas. Life conditions in mountain areas are determined by physical processes, related to gravity (natural hazards), such as erosion, landslides, avalanches and rockfall (Körner et al 2005). In the observed case study area, one of the most important local ecosystem services is the regulation of landslides. A healthy vegetation cover can affect slope stability through erosion control and water regulation, especially in a landslide prone area such as the Buzau Subcarpathians (Swift et al 2004). As the data on landslide hazard and risk is relatively scarce in this case study area, we have generated a landslide susceptibility map to identify areas that have the highest susceptibility of landslides. Later we have run the landslide susceptibility model with the future forest cover scenarios, to study the effects of land-use changes on the landslide susceptibility. Here we have extracted the areas where landslide susceptibility had increased, and translates to a loss in regulating services. Areas where landslide suceptibility decreased indicated a gain in regulating services.

Landslide susceptibility analysis was performed using Weights of Evidence (WoE) a statistical data-driven Bayesian probability model (Bonham-Carter 1994). It is based on the spatial association between known occurrences (observed landslide scarp points) used as training dataset, and a series of evidential themes, in order to determine a predictive output represented by a post-probability map. For each class of every individual explanatory variable positive and negative weights were calculated on the basis of the positive and negative correlation with the training dataset. This approach has been widely used in many scientific fields and it has been proved to give good performances in predicting spatial probability of landslide occurrence in many different areas (Lee et al 2002; van Westen et al 2003; Lee and Choi 2004; Thiery et al 2007; Regmi et al 2010; Ozdemir and Altural 2013) but also in the case study here presented (Hussin et al. 2013; Zumpano et al. 2013; Zumpano et al. 2014).

Eight explanatory variables were selected to perform the analysis: digital elevation model (DEM) derivates such as altitude, aspect, planar curvature, profile curvature, slope and internal relief, and a soil and land use map (Zumpano et al. 2014). We chose to use the soil map to represent the characteristics of the materials involved in the failures that are mainly shallow to medium seated landslides. This was due to the fact, that previous studies have shown that the replacement of the lithological map with the soil map gives significantly better performances, probably due to the fact that the variable "soil" represents better the material involved in these failures (Hussin et al 2013; Zumpano et al 2013; Zumpano et al 2014). The DEM derived maps were reclassified in 10 classes using quantiles, except for the aspect which was reclassified in 9 classes according to the main compass directions plus one class defining flat areas. The soil and the land-use maps were reclassified, based on expert judgment. The landslide inventory derived from archive data (Institute of Geography, Romanian Academy, Buzău County Inspectorate for Emergency Situations) consists of 1518 observed failures. Landslide scarps were represented with centroid points, then split using a random selection into two equal subsets and used for training and prediction.

Table 1: Definition of gains and losses to ecosystem services provisioning

| Ecosystem service | Gain | Loss |
|---|---|---|
| Provisioning:<br><br>wood provision | Increase of forest cover (ha) * 8 $m^3$/ha | Deforested areas (ha) * 6 $m^3$/ha |
| Cultural:<br><br>biodiversity provision | No gain analysed | Forest expansion on the account of HNV grassland and a consequent loss |
| Regulating:<br><br>regulating landslides | Decrease in the level of the area's landslide susceptibility | Increase in the level of the area's landslide susceptibility |

**Results**

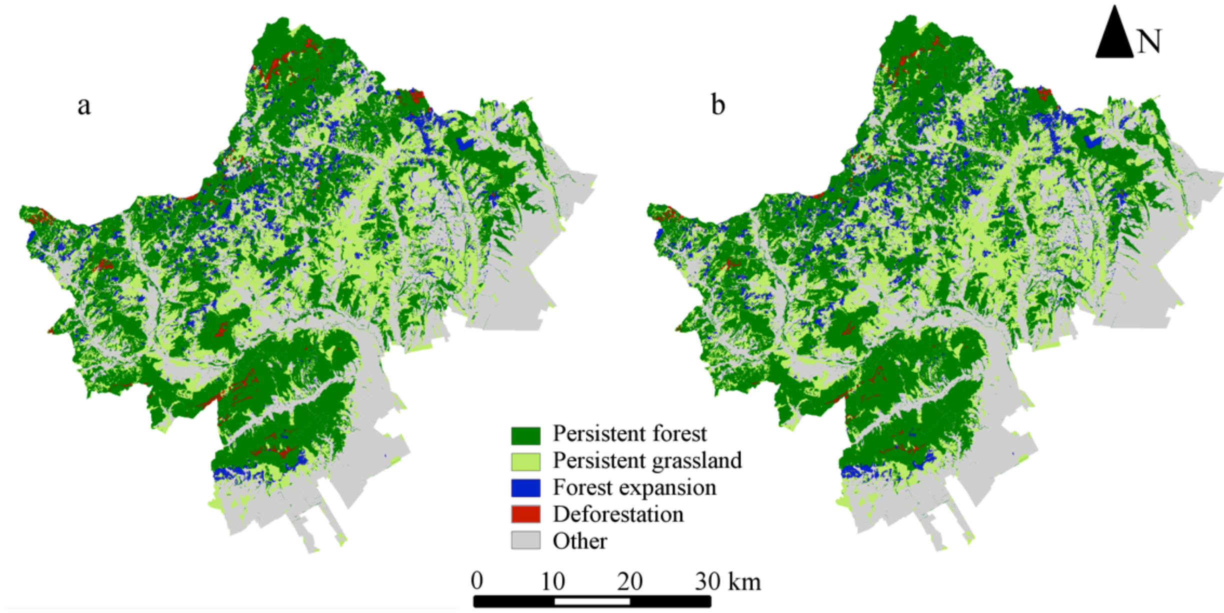
**Forest cover change scenarios**

Based on the two scenarios, future changes to forest cover were extracted. The alternative scenario of maximizing forest harvesting resulted in 21.41 $km^2$ of deforestation, whereas the business as usual scenario (the forest harvesting policy remains the same) resulted in only 12.84 $km^2$ deforestation. Both scenarios have the same extent of forest expansion (99.93 $km^2$), as this transition was based solely on the spatial and biophysical characteristics of the area, excluding protected areas under the Natura 2000 network. The spatial distribution of future forest cover scenarios is summarized in Fig. 2. These two scenarios served as land cover maps when performing the analysis of changes to ES.

**High Nature Value Grasslands**

The total agricultural land, grasslands and other vegetation types cover an area of 116450 ha (48 % of the study area). From this, HNV grasslands cover 54680 ha, or 47 % of the current maximum potential HNV grassland extent (all areas that are not built-up, bare or covered by forests or water). Most of the grasslands in the hilly areas of the Subcarpathians are classified as HNV grassland, whereas this is not the case for valley and lowland grasslands (Fig. 3).

Fig. 2: Spatial distribution of the alternative deforestation scenario (a) and business as usual scenario (b) for the year 2040 modified from Malek et al. (under prep).




## Landslide susceptibility

The majority of areas are characterized by low landslide susceptibility. However, most of the areas with a low susceptibility to landslides are on the valley floor and less steep areas. Areas with more than a 50 % of landslide susceptibility (characterized as medium, high and very high susceptibility) are mostly present on steeper slopes that are not covered by forests. In this example, more than 90 % of forests are defined with a susceptibility value below 50 %. The fact that it is less likely that a landslide occurs on a forested area is not surprising, as evidence shows the positive influence of vegetation for soil reinforcement (Schmidt et al. 2001).

Fig.3: High Nature Value (HNV) Grasslands in the Buzau Subcarpathians

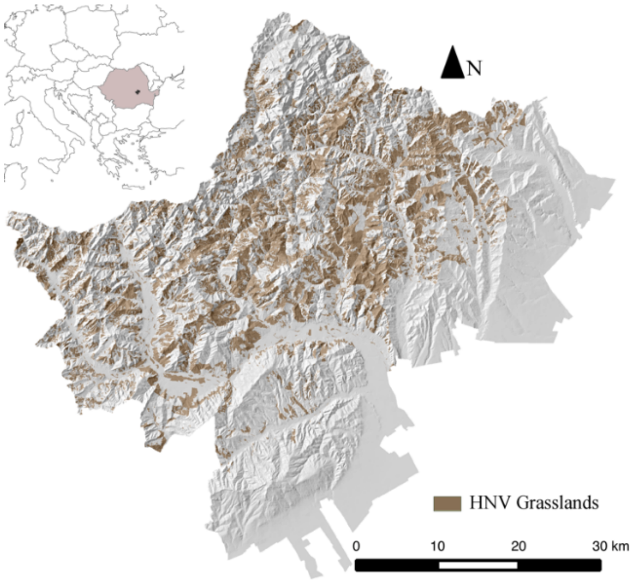
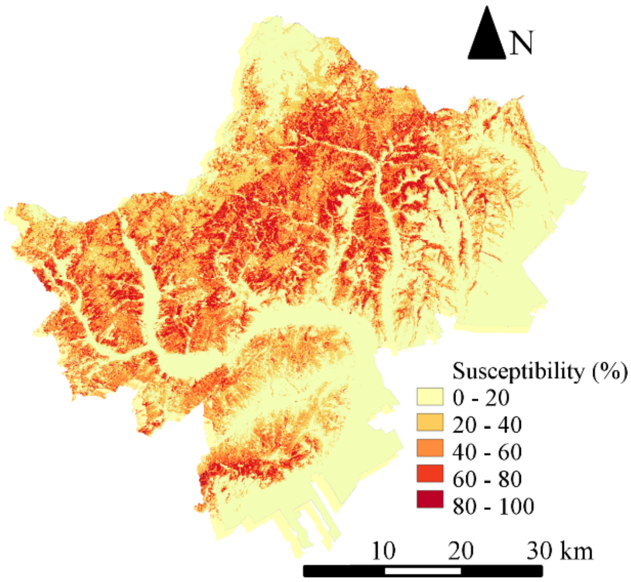



Fig.4: Buzau Subcarpathians Susceptibility Map



### Changes to ecosystem service provisioning

The results of changes to ecosystem service provisioning are spatially explicit and are also described in quantitative terms (Fig.5 and Table 2). As observed on the maps in Fig.5, changes occur in locations that are similar for all groups of ecosystem services and for both scenarios. This can be attributed to the application of the same spatial suitability model and spatial data (topography, distance to settlements, slopes…) when simulating both scenarios (Malek et al. under prep). Still, the surface areas describing the changes to ecosystem service provisioning differ between the two scenarios. Presenting numbers and locations for both gains and losses instead of net values that do not consider spatial variation is important, as some areas might experience only gains, while other experience only losses. Also, the spatial explicitness can inform us of potential critical areas (e.g. side catchments) that might experience significant loss to a particular ecosystem service.

In terms of wood provisioning, the 2040 scenarios do not differ in terms of gains. This is due to the fact that the projected forest expansion is the same for both scenarios. The scenarios however differ drastically in terms of losses to wood provision. More deforestation is projected in the alternative forest harvesting scenario, resulting in a bigger loss of the potential for forest harvesting, which is defined by the loss in mean net annual increment per year.

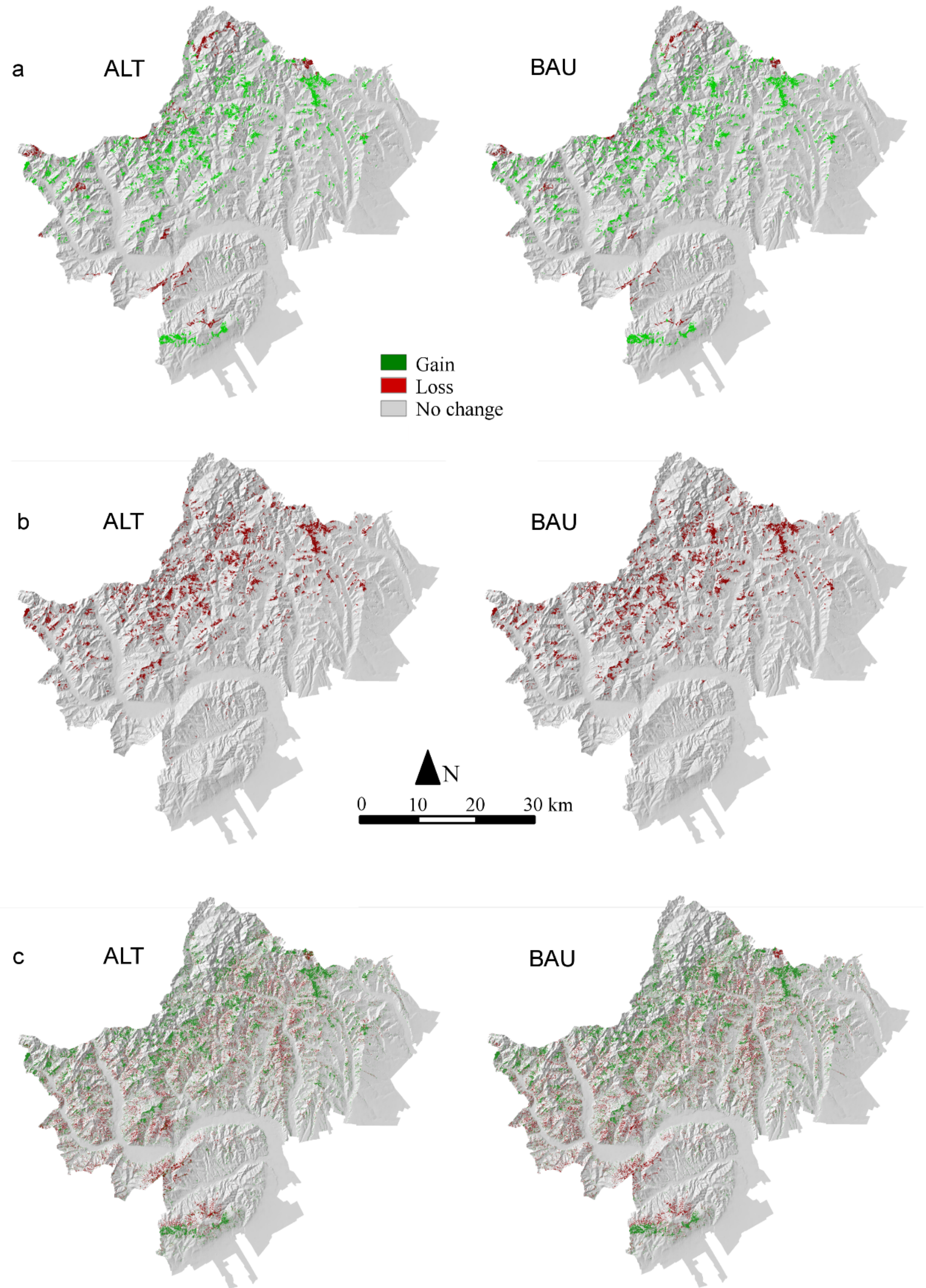
When looking at the changes to biodiversity support, both scenarios result in a 16.4 % loss of HNV grasslands due to forest expansion. Most of the forest expansion occurred on areas at higher altitudes and steeper slopes currently classified as grasslands or low intensity agriculture, which have been subject to high abandonment rates in the last 25 years (Malek et al 2014). These areas also contain a considerable presence of HNV grasslands, resulting in their rather high loss. As the expansion of low intensity agriculture and semi-natural grasslands was not addressed in the modeled scenarios, there were no gains of biodiversity provision analysed.

The two scenarios differ slightly in terms of gains to landslide regulation: 6.1% of the whole area in the alternative, and 6.2% in the business as usual scenario are projected to experience a decrease of the level of landslide susceptibility. The difference between the scenarios is more obvious when looking at the areas subjected to an increased level of landslide susceptibility. Here, 4.4% of the total study area in the alternative and 4.1% in the business as usual scenario experienced an increase of the level of landslide susceptibility. When looking at regional net gains, the alternative scenarios results in 4068 ha, and the business as usual in 5228 ha of net gains for landslide regulation in the form of the decrease landslide susceptibility. Even though it appears, that on the regional level, the area will experience a net gain for landslide regulation, there is a considerable amount of zones that are subject to loss of landslide regulation (Fig. 4). In a landslide prone area like the Buzau Subcarpathians, such local scale changes are significant, as they can result in a local increase of occurrence and intensity of landslides.

Table 2: Gains and losses to ecosystem services provisioning under two 2040 scenarios of forest cover change

| | Alternative scenario | | Business as usual | |
|---|---|---|---|---|
| Ecosystem service | Gain | Loss | Gain | Loss |
| Wood provision (gains and losses in net annual increment per year) | 9993 ha * 8 m3/ha = 79944 m3 | 2141 ha * 6 $m^3$/ha = 12846 $m^3$ | 9993 ha * 8 $m^3$/ha = 79944 $m^3$ | 1284 ha * 6$m^3$/ha = 7704 $m^3$ |
| Biodiversity provision (ha of HNV grasslands lost) | No gain analysed | 8967 ha | No gain analysed | 8967 ha |
| Landslide regulation (decreases (gain) eases (loss) in the level of landslide susceptibility) | 14744 ha | 10676 ha | 15060 ha | 9835 ha |

Fig.5: Changes to the three ecosystem services for the alternative deforestation (ALT) and business as usual (BAU) scenario: (a) wood provision, (b) biodiversity support and (c) landslide regulation potential.



## Discussion

In this study we analysed future changes to the provisioning of ecosystem services in the Subcarpathians of Buzau County in Romania. Based on future forest cover scenarios under changes to the forest harvesting policy, we focused on three ecosystem services: wood provision, biodiversity support and landslide regulation potential. As it is a relatively data poor area, it was necessary to use a set of proxies and assumptions for all three ecosystem services. Similar studies on potential future changes to ecosystem service provisioning in the Carpathian region are rare. Existent research on land cover changes in the Carpathian region showed that their driving forces and possible consequences are complex (Griffiths et al 2012). This study complements the understanding of a variety of possible consequences of forest cover changes, and also addresses the spatial component of this issue.

The spatial assessment differs from other similar scale studies on ecosystem services. This study aims at quantification of potential future changes to ecosystem services. Using two scenarios based on a set of changes to the Romanian forest policy, we aimed at improving the understanding on how future changes to the forest cover can result in either gains or losses to ecosystem services. On the other hand, previous studies have assessed ecosystem services, usually focusing only on current land cover.

This study offers an explanation on the consequences of increasing forest harvesting in the area. Seen as a means to improve the regional economic development, forest harvesting can result in a variety of different consequences. First of all, deforestation due to clear-cut forest harvesting results in short term financial gains, but at the same time decreases the potential of the forest to provide a steady and continuous flow of wood resources. The alternative scenarios result in a 66.7 % higher loss of forest areas. This affects the potential for wood provision in the form of traditional forest harvesting methods more than the business as usual scenario.  Secondly, deforestation can result in a local increase of landslide risk, posing a threat to livelihoods and infrastructure. This was analysed by modeling the changes to landslide susceptibility using the same static variables (elevation, slope, geology), while changing the land cover according to future forest scenarios. The business as usual scenario resulted in a 7.9% lower loss and a 28.5% higher net gain of the landslide regulation potential when compared to the alternative scenario. Our results indicate that short-term gains from forest harvesting can have negative consequences in the form of increased landslide risk.

Forest expansion as the dominant future land-use change in the area has positive and negative consequences to human well-being. On one hand, it can result in the decrease of high nature value grasslands, leading to lower biodiversity levels, loss of significant habitats and a more homogeneous landscape (MacDonald et al 2000; Fischer et al 2008; Zimmermann et al 2010). On the other hand, it can result in a lower risk to landslides, as areas covered with forests have a lower landslide susceptibility than areas covered with grasslands or low intensity agricultural areas. Reforestation has the ability to increase slope stability, which is considered as a landslide risk reduction measure (Phillips and Marden 2005). This is a good trade-off between increased safety and economic gains (e.g. lower damages on infrastructure), and a lower cultural value of the landscape.

Using a spatially explicit pixel based approach we were able to identify the spatial distribution of the gains and losses to ES. Areas that have witnessed these changes are however subjected to a level of uncertainty. The uncertainty in this study is related to several aspects of the input data and the models used. Firstly, uncertainty is defined by the accuracy of the classified land cover maps serving as an input in forest change simulation. Despite the fact that the maps have more than a 90% accuracy, a statistical error of the area estimation suggests that the location accuracy can still vary from 4 to 30 % (Olofsson et al 2013; Malek et al 2014). Secondly, the accuracy of the future forest change allocation model implies that locations of future changes have up to a 16 % spatial disagreement when validated with past data (Malek et al. under prep.). However, the projected future scenarios are considered acceptable, as their accuracy is comparable with other high resolution land cover change models (Soares-Filho et al 2002; Maeda et al 2011). Moreover, our susceptibility model is also characterised by a certain level of uncertainty, defined both by the model and the mapped landslide data used in the analysis. Finally, due to data scarcity our approach dealing with assessing the changes to wood and biodiversity provision is based on expert opinion. All these errors are aggregated in final maps presenting the changes to ecosystem service provisioning. Therefore, the results have to be analysed through the prism of possible inconsistencies and errors when looking at the exact locations of changes to ecosystem services provisioning. We suggest the results should be discussed as suggestions for most plausible areas, where changes to ecosystem services provisioning might occur in the future.

For future research we suggest an additional, more thorough analysis of changes to ecosystem service provisioning. In case of resource provision, this could be performed with more detailed data and spatial distribution of forest types, age and quality. Moreover, data regarding the ownership and economic value of forests could improve the assessment of potential trade offs of future forest harvesting and forest expansion. In terms of biodiversity provision, deforestation and forest expansion can also have other consequences than the loss of HNV grassland, like changes to habitat fragmentation and landscape connectivity (Körner et al 2005; Millenium Ecosystem Assessment 2005). This might affect vital habitats of large European carnivores present in the area, like the wolf (*Canis lupus*) and brown bear (*Ursus arctos*) (van Maanen et al 2006). When analyzing potential changes to landslide regulation potential, improved spatial and temporal resolution of landslide data could allow the use of more elaborate runoff models. Improving the data and the models can lead to prioritization of locations where measures for regulation of ecosystem services degradation can be considered. These can be performed as reforestation or technical measures, or grassland protection together with incentives for low intensity agriculture. Through more accurate results, the approach could so fully utilize its decision support potential and could lead to more informed grassland and forest management decisions.

The application of future forest change scenarios, together with the assessment of changes to ecosystem services provisioning is continuously being studied at different scales and study areas. These studies can provide additional understanding on possible consequences for forest harvesting, habitat conservation and risk management. This study improves the understanding of possible future gains and losses of ecosystem services provisioning as a consequence of different forest management in the Carpathian region.

## Conclusion

This study aims at improving the understanding of possible future changes to the provision of ecosystem services in the Romanian Carpathians. As the area is subject to increased pressures for forest harvesting, we focused on two future scenarios of changes to the forest cover. Both scenarios have considered forest expansion following historic observation and deforestation as a consequence of clear-cut forest harvesting practices. Both forest transitions can have a variety of effects to the environment, which is why we analysed the changes to the provision of three ecosystem services: wood provision, biodiversity support and landslide regulation. The changes were analysed by comparing two 2040 forest cover scenarios with the 2010 forest cover.

The two scenarios described as (1) alternative forest harvesting and (2) business as usual, try to project the state of the Buzau Subcarpathian forests and grasslands in 2040. Both scenarios had the same extent of forest expansion, however were different in terms of areas subjected to deforestation. To analyse the changes to ecosystem services provisioning in this data scarce area, we applied three proxy indicators, describing the gains and losses of a particular ES.

Wood provision is defined by the extent of new forest areas due to forest expansion as a gain, and by the extent of deforested areas as a loss to ES provisioning. The alternative scenario projected a 66.7% higher deforestation, therefore resulting in a higher loss for wood provisioning due to a decrease in the potential of the forest to provide a steady supply of wood. Biodiversity support is defined by the extent of high nature value grasslands in the area. These low intensity agricultural areas are characterized by high biodiversity levels. Both scenarios result in the loss of biodiversity support due to their prevalent transition of forest expansion. Changes in landslide regulation potential were analysed by observing the changes to landslide susceptibility of the area. The gains are described by lower levels, and losses by higher levels of landslide susceptibility. The business as usual scenario results in a 7.9% lower loss of landslide regulation potential compared to the alternative scenario, as a result of deforestation. On the other side, it also results in a 28.5% higher regional net gain of landslide regulation potential compared to the alternative scenario, as a consequence of the simulated forest expansion.

Despite the uncertainties of the data and models applied, the comparison of the two scenarios provides valuable information on the consequences of future forest harvesting. This helps to enable vital decision support when assessing forest harvesting policies and informing decision makers on potential gains and losses of future development. Finally, the approach supports the prioritization of areas where losses to ecosystem service provisioning are more likely to occur.

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## References

Andersen E, Baldock D, Bennet H, et al (2003) Developing a High Nature Value indicator. 76.

Baumann M, Kuemmerle T, Elbakidze M, et al (2011) Patterns and drivers of post-socialist farmland abandonment in Western Ukraine. Land Use Policy 28:552–562. doi: 10.1016/j.landusepol.2010.11.003

Bignal EM, McCracken DI (1996) Low-Intensity Farming Systems in the Conservation of the Countryside. J Appl Ecol 33:413–424. doi: 10.2307/2404973

Bonham-Carter G (1994) Geographic information systems for geoscientists: modelling with GIS. Pergamon, Oxford; New York

Burkhard B, Kroll F, Müller F (2010) Landscapes' Capacities to Provide Ecosystem Services – a Concept for Land-Cover Based Assessments. Landsc Online 1–22. doi: 10.3097/LO.200915

Castro AJ, Martín-López B, García-LLorente M, et al (2011) Social preferences regarding the delivery of ecosystem services in a semiarid Mediterranean region. J Arid Environ 75:1201–1208. doi: 10.1016/j.jaridenv.2011.05.013

De Groot R (2006) Function-analysis and valuation as a tool to assess land use conflicts in planning for sustainable, multi-functional landscapes. Landsc Urban Plan 75:175–186.

Egoh B, Reyers B, Rouget M, et al (2008) Mapping ecosystem services for planning and management. Agric Ecosyst Environ 127:135–140. doi: 10.1016/j.agee.2008.03.013

Fischer M, Rudmann-Maurer K, Weyand A, Stöcklin J (2008) Agricultural Land Use and Biodiversity in the Alps. Mt Res Dev 28:148–155. doi: 10.1659/mrd.0964

Fisher B, Turner RK, Morling P (2009) Defining and classifying ecosystem services for decision making. Ecol Econ 68:643–653. doi: 10.1016/j.ecolecon.2008.09.014

Giurgiu V (2004) Gestionarea durabilă a pădurilor României. Silvologie, vol. III B. The Publishing House of the Romanian Academy, Bucharest

Grêt-Regamey A, Bebi P, Bishop ID, Schmid WA (2008) Linking GIS-based models to value ecosystem services in an Alpine region. J Environ Manage 89:197–208. doi: 10.1016/j.jenvman.2007.05.019

Griffiths P, Kuemmerle T, Kennedy RE, et al (2012) Using annual time-series of Landsat images to assess the effects of forest restitution in post-socialist Romania. Remote Sens Environ 118:199–214. doi: 10.1016/j.rse.2011.11.006

Hussin H, Zumpano V, Sterlacchini S, et al (2013) Comparing the predictive capability of landslide susceptibility models in three different study areas using the Weights of Evidence technique. EGU Gen. Assem. Conf. Abstr. Vienna, p 12701

INSSE (2013) Romanian National Institute of Statistics Data Portal. http://www.insse.ro/. Accessed 11 May 2013

Körner C, Ohsawa M, Spehn E, et al (2005) Mountain Systems. Ecosyst. Hum. Well-Curr. State Trends Find. Cond. Trends Work. Group Millenn. Ecosyst. Assess. pp 681–716

Kozak J, Estreguil C, Troll M (2007) Forest cover changes in the northern Carpathians in the 20th century: a slow transition. J Land Use Sci 2:127–146. doi: 10.1080/17474230701218244

Kuemmerle T, Müller D, Griffiths P, Rusu M (2008) Land use change in Southern Romania after the collapse of socialism. Reg Environ Change 9:1–12. doi: 10.1007/s10113-008-0050-z

Lee S, Choi J (2004) Landslide susceptibility mapping using GIS and the weight-of-evidence model. Int J Geogr Inf Sci 18:789–814. doi: 10.1080/13658810410001702003

Lee S, Choi J, Min K (2002) Landslide susceptibility analysis and verification using the Bayesian probability model. Environ Geol 43:120–131. doi: 10.1007/s00254-002-0616-x

Lerman Z, Csaki C, Feder G (2004) Evolving farm structures and land use patterns in former socialist countries. Q J Int Agric 43:309–336.

MacDonald D, Crabtree J., Wiesinger G, et al (2000) Agricultural abandonment in mountain areas of Europe: Environmental consequences and policy response. J Environ Manage 59:47–69. doi: 10.1006/jema.1999.0335

MADR (2012) Programul Naţional de Dezvoltare Rurală 2007-2013. National Rural Development Program. Ministry of Agriculture and Rural Development of Romania

Maeda EE, de Almeida CM, de Carvalho Ximenes A, et al (2011) Dynamic modeling of forest conversion: Simulation of past and future scenarios of rural activities expansion in the fringes of the Xingu National Park, Brazilian Amazon. Int J Appl Earth Obs Geoinformation 13:435–446. doi: 10.1016/j.jag.2010.09.008

Malek Ž, Scolobig A, Schröter D (2014) Understanding Land Cover Changes in the Italian Alps and Romanian Carpathians Combining Remote Sensing and Stakeholder Interviews. Land 3:52–73. doi: 10.3390/land3010052

Mathijs E, Swinnen JFM (1998) The economics of agricultural decollectivization in East Central Europe and the former Soviet Union. Econ Dev Cult Change 47:1–26. doi: 10.1086/452384

Micu M, Bălteanu D (2013) A deep-seated landslide dam in the Siriu Reservoir (Curvature Carpathians, Romania). Landslides 10:323–329. doi: 10.1007/s10346-013-0382-8

Millenium Ecosystem Assessment (2005) Ecosystems and human Well-Being: Synthesis. Island Press, Washington, DC

Muică N, Turnock D (2008) A Toponomical Approach to the Agrarian History of the Pătârlagele Depression (Buzău Subcarpathians, România). Hum. Geogr. - J. Stud. Res. Hum. Geogr. 2:

Müller D, Kuemmerle T, Rusu M, Griffiths P (2009) Lost in transition: determinants of post-socialist cropland abandonment in Romania. J Land Use Sci 4:109–129. doi: 10.1080/17474230802645881

Nedkov S, Burkhard B (2012) Flood regulating ecosystem services—Mapping supply and demand, in the Etropole municipality, Bulgaria. Ecol Indic 21:67–79. doi: 10.1016/j.ecolind.2011.06.022

Olofsson P, Foody GM, Stehman SV, Woodcock CE (2013) Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation. Remote Sens Environ 129:122–131. doi: 10.1016/j.rse.2012.10.031

Oszlányi J, Grodzińska K, Badea O, Shparyk Y (2004) Nature conservation in Central and Eastern Europe with a special emphasis on the Carpathian Mountains. Environ Pollut 130:127–134. doi: 10.1016/j.envpol.2003.10.028

Ozdemir A, Altural T (2013) A comparative study of frequency ratio, weights of evidence and logistic regression methods for landslide susceptibility mapping: Sultan Mountains, SW Turkey. J Asian Earth Sci 64:180–197. doi: 10.1016/j.jseaes.2012.12.014

Paracchini ML, Petersen J-E, Hoogeveen Y, et al (2008) High nature value farmland in Europe. European Commission Joint Research Centre, Institute for Environment and Sustainability, Ispra

Phillips C, Marden M (2005) Reforestation Schemes to Manage Regional Landslide Risk. In: Glade T, Anderson lcolm, Crozier MJ (eds) Landslide Hazard Risk. John Wiley & Sons, Ltd, pp 517–547

Quantum GIS Development Team (2013) Quantum GIS Geographic Information System. Open Source Geospatial Foundation Project

Regmi NR, Giardino JR, Vitek JD (2010) Modeling susceptibility to landslides using the weight of evidence approach: Western Colorado, USA. Geomorphology 115:172–187. doi: 10.1016/j.geomorph.2009.10.002

Scheffer M, Brock W, Westley F (2000) Socioeconomic Mechanisms Preventing Optimum Use of Ecosystem Services: An Interdisciplinary Theoretical Analysis. Ecosystems 3:451–471. doi: 10.1007/s100210000040

Schmidt, K.M. et al. 2001. The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. Canadian Geotechnical Journal, 38(5), pp.995–1024.

Schröter D, Cramer W, Leemans R, et al (2005) Ecosystem Service Supply and Vulnerability to Global Change in Europe. Science 310:1333 –1337.

Soares-Filho BS, Cerqueira GC, Pennachin CL (2002) Dinamica—a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. Ecol Model 154:217–235. doi: 10.1016/S0304-3800(02)00059-5

Swift MJ, Izac A-MN, van Noordwijk M (2004) Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? Agric Ecosyst Environ 104:113–134. doi: 10.1016/j.agee.2004.01.013

Taff GN, Müller D, Kuemmerle T, et al (2009) Reforestation in Central and Eastern Europe After the Breakdown of Socialism. In: Nagendra H, Southworth J (eds) Reforesting Landsc. Springer Netherlands, Dordrecht, pp 121–147

Thiery Y, Malet J-P, Sterlacchini S, et al (2007) Landslide susceptibility assessment by bivariate methods at large scales: Application to a complex mountainous environment. Geomorphology 92:38–59. doi: 10.1016/j.geomorph.2007.02.020

Troy A, Wilson MA (2006) Mapping ecosystem services: Practical challenges and opportunities in linking GIS and value transfer. Ecol Econ 60:435–449. doi: 10.1016/j.ecolecon.2006.04.007

Van Maanen E, Predoiu G, Klaver R, et al (2006) Safeguarding the Romanian Carpathian ecological network. A vision for large carnivores and biodiversity in Eastern Europe. Icas Wildlife Unit, Brasov

Van Westen CJ, Rengers N, Soeters R (2003) Use of Geomorphological Information in Indirect Landslide Susceptibility Assessment. Nat Hazards 30:399–419. doi: 10.1023/B:NHAZ.0000007097.42735.9e

Verburg PH, de Koning GHJ, Kok K, et al (1999) A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. Ecol Model 116:45–61. doi: 10.1016/S0304-3800(98)00156-2

Zimmermann P, Tasser E, Leitinger G, Tappeiner U (2010) Effects of land-use and land-cover pattern on landscape-scale biodiversity in the European Alps. Agric Ecosyst Environ 139:13–22. doi: 10.1016/j.agee.2010.06.010

Zumpano V, Ciurean R, Micu M, et al (2013) Uncertainty associated with regional landslide risk analysis - a case study in Buzau County, Romania. EGU Gen. Assem. Conf. Abstr. p 9306

Zumpano V, Hussin HY, Reichenbach P, et al (2014) A landslide susceptibility analysis for Buzau County, Romania. Romanian J Geogr 58:9–16.

# Appendix E: Scenarios of land cover change and landslide susceptibility: an example from the Buzau Subcarpathians, Romania

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# Scenarios of land cover change and landslide susceptibility: an example from the Buzau Subcarpathians, Romania

**Žiga Malek[1,2], Veronica Zumpano[3], Dagmar Schröter[4], Thomas Glade[2], Dan Balteanu[3], Mihai Micu[3]**

[1] International Institute for Applied Systems Analysis, Schlossplatz 1, 2361 Laxenburg, Austria

[2] Department of Geography and Regional Research, University of Vienna, Universitätsstrasse 7, 1010 Vienna, Austria

[3] Romanian Academy, Institute of Geography, 12 Dimitrie Racovita, 023993 Bucharest, Romania

[4] Transdisciplinarity Lab, Department of Environmental Systems Science, ETH Zürich, Sonneggstrasse 33 SOL F4, Zürich 8092, Switzerland

contact: ziga.malek@gmail.com

Since 1990 the Subcarpathians in Buzau County, Romania have witnessed substantial socio-economic changes and resulting changes in the land cover. Influenced by the interplay of poor economic conditions, land ownership reforms, and institutional difficulties, these changes have been difficult to manage, resulting in a dispersal of built-up areas. Even though, the spatial extent of land cover changes has not reached critical levels as similar areas in the Carpathians, our analysis suggests that in the future the area might experience more extreme land cover changes. Moreover, the litho-structural traits and the high relief energy of the Romanian Subcarpathians favored the occurrence of various types of mass movements, imposing different levels of risk to people, buildings and infrastructure. Increase of human influence in form of expansion of built-up areas in the area could therefore result in slope instability and changes in the temporal and spatial patterns of hydro-meteorological hazards. This study shows, that possible future changes in land cover will not have a major influence on hazards, however risk might increase due to the increased value and number of elements at risk.

Keywords: Land cover change, Scenarios, GIS, Landslide susceptibility.

# 1. Introduction

In mountain areas even minor land cover changes can aggravate the consequences of hydro-meteorological hazards such as landslides, avalanches, and flash floods. Whereas most of conditioning factors for landslides (e.g. topography, geology, hydrology) can be considered as stationary, land cover can change in a relatively short time span, therefore directly affecting the landslide spatial distribution occurrence. Our research addresses the possible land cover changes in form of expansion of built-up areas in the Romanian Carpathians, under a set of scenarios of socio-economic change. Through our research, we tried to evaluate how different land cover change scenarios might result in changes in landslide susceptibility and in which susceptibility classes the major changes might happen.

## *1.1 Study area*

The study area lies in the Buzau County Carpathians and Subcarpathians, in South East Romania. It covers an area of about 3300 km$^2$. The Carpathians are rising up to 1772 m, with the geology being represented mainly by Paleogene flysch deposits. Landslides cover large areas in the case study site, in some parts more than two-thirds of the total area (Muică and Turnock 2009). Landslides are quite often connected with floods (especially flash-flood) throughout the small, high erosive potential tributary catchments. Slope undercut during the frequent flash flood episodes commonly causes rotational, retrogressive landslides that might reach the mid and even upper-slope sector. The effects of channel-slope coupling are potentially enhanced by the area's overall high seismicity (3 major events of more than 7 Mw per century). After land ownership reforms since the 1990s, poor socio-economic conditions, and institutional difficulties, the pressure on the environment in form of deforestation and expansion of built up areas has increased. As discussed by the involved stakeholders, a further increase in economic activities and living standard is expected.

# 2. Methods

## *2.1 Land cover change*

The evaluation started with the classification of several LANDSAT images between 1989 and 2010, to identify the land cover trends in the last 20 years. For future land cover scenario modeling we used Dinamica EGO, to develop a spatially explicit cellular automata based model (Soares-Filho et al. 2002). The spatial allocation module of the model generates a land cover change probability map by weighting the defined landscape attributes (elevation, slope, distance to settlements, roads and main employment centers, and protected areas) of past land cover changes. The demand for built-up areas is calculated by the non-spatial scenario module, where the amount of new built-up areas is defined as a function of population change and increase in the living standard. For GDP growth and population change rates we used projections provided by the Romanian National Statistics Institute and IIASA (INSSE 2012; IIASA 2012). We generated land cover scenarios until 2035, for two scenarios of population decrease (a projected trend in Romania), and added another scenario where population remains stable. The year 2035 presents a medium term interest, suitable for local scale land cover analysis in rural areas.

### *2.2 Landslide susceptibility*

Landslide hazard assessment at regional scale is very often performed through susceptibility analysis. This is due to the fact that very often the information related with the temporal probability is missing, as it is in our case. Hence in this work the susceptibility analysis was performed instead, in order to assess the spatial probability of the landslides occurrence. The analysis was executed using the weight of evidence (*WofE*) modeling technique, very well documented and widely applied in many scientific fields (van Westen et al. 2003; ; Duke & Steele 2010; Sterlacchini et al. 2011). WofE is a log-linear form of the data-driven Bayesian probability model that uses known occurrences as training points to derive a predictive output (response theme). The method is based on the calculation of positive and negative weights (W+ and W−) by which the degree of spatial association among training points and each explanatory variable class may be modeled (Sterlacchini et al. 2011). For the analysis 8 explanatory variables were used (altitude, aspect, profile and planar curvature, slope, lithology, soil, internal relief and land cover).

## 3. Results and discussion

### *3.1. Land cover scenarios*

The 3 future scenarios are described in terms of population change and built-up areas in Table 1. The scenarios also differ in the spatial pattern of land cover changes, an example of expansion of built-up land in a smaller area is shown in Fig. 2. We assumed that depopulation has a limiting effect on the expansion of built-up areas, as there is less demand for new land even though the living standard will increase. Therefore, both depopulation scenarios result in fewer new built-up areas. Still, in all scenarios, built-up areas increased. This is mainly due to the assumption that the projected growth of GDP would result in urbanization of the region and new economic activities.

### *3.2. Changes in the landslide susceptibility classes*

The analysis was run using the three different land cover scenario maps in order to obtain different susceptibility set-ups. Due to the fact that the scenarios used as input address only changes in the built-up areas, few changes can be observed comparing the susceptibility map for the actual and modeled land cover. As expected, the human impact (attributed to the increase of built-up areas) is not influencing the slope instability substantially, but more probably the related exposure of the elements at risk. It is also important to underline that less than 1% of the whole area is projected to change. Such changes are not sufficient to be observed from the analysis with a low level of sensitivity. Furthermore, we analyzed the occurrence of projected changes in each susceptibility class for the three scenarios. The results are summarized in Fig. 1, which highlights, that the major changes occur in the low susceptibility class.

## 4. Conclusion

Looking at the foreseen 2035 scenarios, no considerable expansion of human settlement can be expected in areas with high slope instability. Nevertheless, even though projected land cover changes might seem unimportant, it has to be taken into account that the number and value of elements at risk might rise, which would lead to an increase in risk.

**Acknowledgement**

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## References

Duke, C., Steele, J., 2010. Geology and lithic procurement in Upper Palaeolithic Europe: a weights-of-evidence based GIS model of lithic resource potential. *Journal of Archaeological Science*, 37(4), pp.813–824.

IIASA, 2012. Shared Socioeconomic Pathways (SSP) Database. Available at: https://secure.iiasa.ac.at/web-apps/ene/SspDb/ [Accessed May 24, 2012].

INSSE, 2012. Romanian National Institute of Statistics Data Portal. Available at: http://www.insse.ro/ [Accessed May 11, 2012].

Muică, N., Turnock, D., 2009. Historical geography of settlements in the Patarlagele depression: The cartographic evidence from the late nineteenth and twentieth centuries. *Romanian Journal of Geography*, 54.

Soares-Filho, B.S., et al., 2002. Dinamica—a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. *Ecological Modelling*, 154(3), pp.217–235.

Sterlacchini, S. et al., 2011. Spatial agreement of predicted patterns in landslide susceptibility maps. *Geomorphology*, 125(1), pp.51–61.

Van Westen, C.J., Rengers, N., Soeters, R., 2003. Use of Geomorphological Information in Indirect Landslide Susceptibility Assessment. *Natural Hazards*, 30(3), pp.399–419.

## Tables and Figures

**Table 1: Land cover scenario results**

| Year - Scenario | Population | Urban areas (km$^2$) |
|---|---|---|
| 1990 | 187404 | 203.70 |
| 2010 – baseline | 168513 | 211.84 |
| 2035 high depopulation | 138945 | 226.58 |
| 2035 low depopulation | 157054 | 230.51 |
| 2035 constant population | 168513 | 237.95 |

6

**Fig. 1: Land cover changes distribution in susceptibility classes**

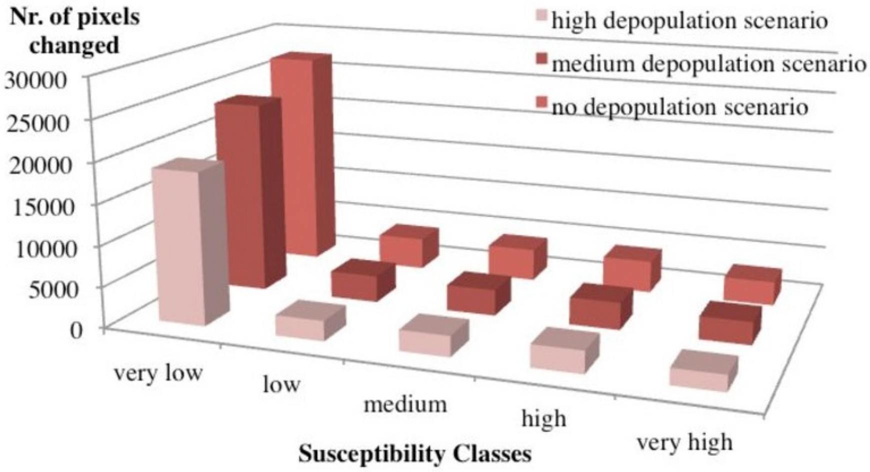
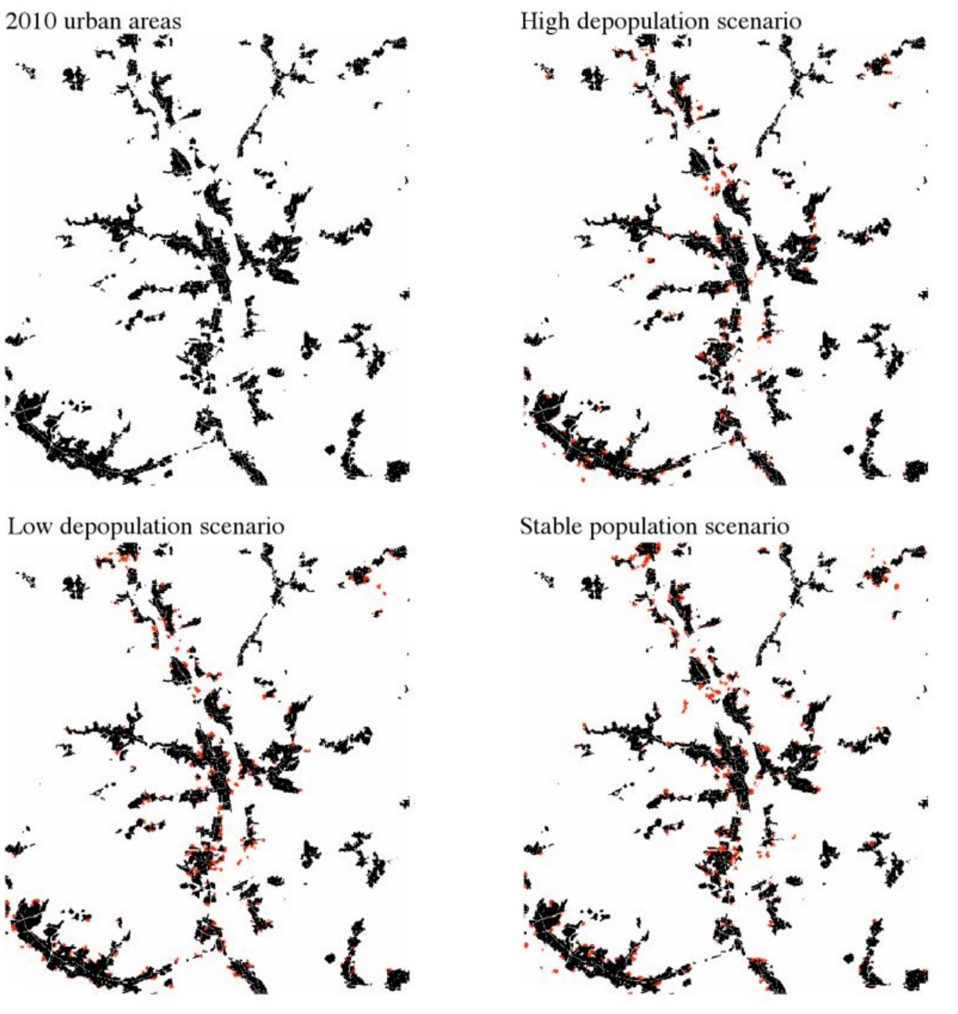


**Fig. 2: Example of land cover scenarios**



# Appendix F: Fuzzy-logic Cognitive Mapping: Introduction and overview of the method

Malek Ž.

In: Gray S, Jordan R, Pallisimio M, Gray S. Including Stakeholders in Environmental Modeling: Considerations, Methods and Applications

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**Abstract** Lack of information and large uncertainties can constrain the effectiveness and acceptability of environmental models. Fuzzy-logic cognitive mapping (FCM) is an approach, able to deal with these limitations by incorporating existing knowledge and experience. It is a soft-knowledge approach for system modeling, where components of a system and their relationships are identified and semi-quantified in a participatory way. Its usefulness has been manifested through applications in a variety of disciplines, from engineering, information technology, business, and medicine. This chapter introduces FCM as a simple, transparent and flexible participatory method to model complex social-ecological systems based on expert and stakeholder knowledge. It describes the evolution of FCM to environmental modeling due to its ability to facilitate public participation, data generation and systems thinking. Numerous actors can be involved when studying environmental issues: experts, scientists, decision makers and other stakeholders. Thus, a wide range of opinions and perceptions can be taken into account, providing a platform for discussion and negotiation among different actors. Moreover, data otherwise inaccessible can be gathered through FCM. Finally, one of the most significant characteristics of the method is the possibility to study causal relationships and feedback loops. This way, FCM supports decision-making by simulation and scenario studies.

### Chapter Highlights

*Approach:* This chapter presents fuzzy-logic cognitive mapping as a participatory method for modeling social-ecological systems. The overview of the method is discussed through its evolution, suitability for application in environmental modeling, and examples in environmental research.

*Participant Engagement:* Fuzzy-logic cognitive mapping facilitates interactive stakeholder involvement throughout the entire modeling process, offering a possibility for discussion, negotiation, consensus building, and social learning.

*Models/Outcomes:* Final outcome are semi-quantitative models representing most significant components and their relationships of a social-ecological system. These can be used to increase understanding of a particular issue, analyse possible changes to the system, and project future scenarios, or serve as a communication or perception analysis tool.

*Challenges:* The results of this semi-quantitative method can only be interpreted comparing to other components in the model, and cannot be taken as absolute real-value outcomes. Also, to overcome the possible biases, subjectivity and difficulties in assigning weights to interconnection in the model, numerous stakeholders need to be involved.

## 1. Introduction

When addressing environmental issues, we often come across gaps in knowledge, limitations in data and uncertainties in understanding. Not having enough information to apply analytical models therefore poses a growing need for alternative models that allow improving the knowledge and generate solutions starting from stakeholders' perceptions (Hurtado 2010). Indeed, the use of both expert and local stakeholders' knowledge has been growing in environmental modeling (Özesmi & Özesmi 2004). Still, participatory environmental modeling can be challenging, due to several reasons. First of all, environmental issues involve numerous actors with different perspectives and conflicting interests, and are characterized by intangible causes and key uncertainties (Mingers & Rosenhead 2004). Furthermore, participatory environmental modeling can be extensive, complicated and inapprehensible to stakeholders otherwise unfamiliar with modeling. This is also demonstrated by the clear gap between the demands of researchers and their quantitative simulation models, and the stakeholders' needs for simple decision support tools (van Kouwen et al. 2008). Finally, information provided by the experts can be unclear, incomplete and subject to personal bias (Krueger et al. 2012; Page et al. 2012).

Fuzzy-logic cognitive mapping (FCM) can serve as a means for clear, transparent participatory modeling, and improving otherwise lengthy and complicated procedures of gathering expert based data. It is a soft-knowledge methodology, where a number of identified concepts and the relations between them are depicted in a form of a graph. This allows a semi-quantitative description of various interactions within a system, and enables visualizing causal reasoning. Thus, significant information about a system can be encoded and visualized, helping to reduce uncertainties and exceed limitations in knowledge and data (Hobbs et al. 2002). Since its emergence from cognitive mapping, FCM evolved into a means to confront uncertainty, offering simulation besides only description and visualization. FCM can be used to develop simple qualitative models of a particular system, to quantify causal relationships of measureable physical variables, or to model abstract and complex theories. Therefore it is suitable for modeling a variety of systems, and has been applied in several disciplines, among others banking, information technology, and engineering.

This chapter introduces fuzzy-logic cognitive mapping as a participatory environmental modeling approach, able to overcome the unknown in knowledge and data. It presents its evolution into a method for identifying key issues and modeling system structure. Moreover, being a transferable modeling approach applied to a number of environmental issues, its application in environmental modeling and decision support will be presented.

## 2. Description

Fuzzy-logic cognitive maps are semi-quantitative, mental models of a given system. They are graphical representations representing the behavior of complex systems based on expertise and understanding of a particular domain (Kosko 1986). Due to their ability to represent complex models, they are considered as an alternative to other system modeling approaches. A fuzzy-logic cognitive map consists of numerous concepts representing components of a system, and the causal links between these concepts, describing how different concepts are influencing each other. The concepts and relationships are represented in graphical form, allowing easy visualization and control of the system.

The graphical representation of the system consists of a directed graph: nodes connected with edges in the form of arrows. The nodes represent concepts, which are the most significant components of the system as defined by the experts involved. They can either be vague or abstract ideas, such as aesthetics or satisfaction, or measurable physical quantities such as precipitation or percentage of a vegetation cover (Özesmi & Özesmi 2003). Moreover, they can represent logical propositions (thresholds of a specific process), state variables (quality, abundance), rare events (weather extremes), and decisions (harvest quotas), and can thus describe the management of a particular system (Hobbs et al. 2002). Directed edges connecting the nodes, represent the causal relationships between different concepts. The assigned weights of the edges quantify how the concept at the beginning of the edge influences the concept at the other end (McNeill & Thro 1994). Fig. 1 shows a simplified FCM as a graph consisting of nodes and weighted connections. For modeling complex systems the edges can be defined as feedback loops, therefore FCM could be considered as a system dynamics approach (Kok 2009). The mathematical representation of a Fuzzy-logic Cognitive Map is represented by the numerical values of nodes and edges and the vector matrix calculation (van Vliet et al. 2010). The numerical values of nodes range between 0 and 1, and edges between -1 and 1, thus describing the value of concepts, and strength and direction of the causal relationships. A positive relationship means an increase (decrease) of the first concept leads to an increase (decrease) in the other, and the negative relationship means an increase (decrease) in the first concept leads to a decrease (increase) in the other. A weight with a value 0 indicates no relationship between the two concepts. Whereas numerical values for edges are defined by expert opinion or empirical data, the values of nodes can either be calculated by the model, or are fixed boundary conditions (Hobbs et al. 2002).

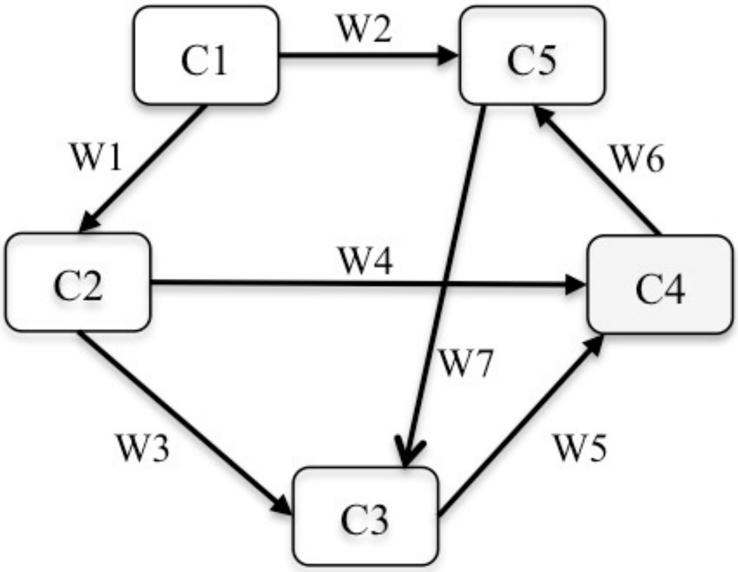
Constructing a fuzzy-logic cognitive map demands the involvement of experts or stakeholders, as the method takes advantage of their knowledge and experience. The first step in the construction process is the identification of concepts by the involved stakeholders. Afterwards, the stakeholders identify causal relationships among these concepts and describe them as negative or positive, allowing the draft of the first versions of the directed graph. Finally, these relationships are estimated and ranked as numerical values, or defined as a set of linguistic variables than can later be transformed to values between -1 and 1 (from negatively very very strong, to positively very very strong…). The constructed FCM can be later modified and altered at any time. The concepts and their relationships can be either constructed through interviews, group sessions, questionnaires, or document interpretation (Ülengin & Topçu 1997). The approach is semi-quantitative in spite the possibility of quantifying the values of nodes and edges supported by empirical data. This is due to the fact, that the quantification is performed based solely on the relationships between the concepts, and that the outcomes can only be compared within the system. Also, the concepts, their relationships and assigned weights are subjective, by reflecting the perspectives and opinions of participants. Still, they are not random due to an involvement of a group of experts with knowledge in the domain of the system (Tan & Özesmi 2006). A FCM can be constructed by a single expert. Involving a group of experts however improves the reliability of the FCM, as the approach allows a simple knowledge aggregation from multiple sources (Stach et al. 2005). Constructing a FCM collectively through a group meeting, can minimize misunderstanding and improve knowledge, and accelerate the constructing process (Hobbs et al. 2002).

## 3. Evolution of FCM

Fuzzy-logic cognitive mapping evolved from concept and cognitive mapping, studying structures, interconnections and causal relationship of a particular issue. The development of the approach went hand in hand with the recognized deficiency of other methods to deal with complex systems, related to model causal relationships and feedback loops. Originally meant to model social, economic and political systems, FCM has developed into a tool for modeling systems, and analyse decisions and processes in different scientific areas.

**Fig. 1** An example of a fuzzy-logic cognitive map: a) the graphical representation of FCM, b) relationship vector matrix as a mathematical representation of FCM. Nodes Cx represent concepts with a state value. The weights and arrows of the causal relationships Wx represent the influence one concept has on another.

**a**




**b**

| | **C1** | **C2** | **C3** | **C4** | **C5** |
|---|---|---|---|---|---|
| **C1** | 0 | W1 | 0 | 0 | W2 |
| **C2** | 0 | 0 | W3 | W4 | 0 |
| **C3** | 0 | 0 | 0 | W5 | 0 |
| **C4** | 0 | 0 | 0 | 0 | W6 |
| **C5** | 0 | 0 | W7 | 0 | 0 |

The concept of semi-quantitative representation of a system origins from the graph theory that has been formulated by Euler in 1736 and has witnessed drastic development by mathematicians since (Biggs et al. 1999). The methods of graph theory are used to analyse the structural properties of a graph, such as a fuzzy-logic cognitive map (Özesmi & Özesmi 2003). With its help we can understand the complexity of the modeled system, for example by describing the centrality and density of its graph, thus providing quantitative indicators about the graph's characteristics. The term cognitive mapping (CM) was already coined in 1948 by Tolman, however adopted by Axelrod to model decision-making processes using directed graphs where a set of nodes are connected by directed edges. The theory of directed graphs has been developed in the 20th century for structural studies, e.g. in anthropology (Hage & Harary 1983). The goal of CM was to construct a graphical representation of a person's belief about an issue on a conceptual, qualitative level (Axelrod 1976). Besides being a participatory technique, CM went beyond simple listing of ideas by organizing them into a map showing the interactions between these ideas, thus structuring them (Mendoza & Prabhu 2006). CM has been used to capture different mental models and deal with strategy making (Ackermann & Eden 2004). It can however result in large and inapprehensible models difficult to analyze, and does not take into account indirect variables, feedback loops and time lags (Jetter & Schweinfort 2011). To overcome these limitations, (Kosko 1986) modified cognitive maps with fuzzy logic. Unlike Axelrod's CMs, where the relationships are described by the discrete values 0 or 1, the strengths of causal relationships in Kosko's FCM are fuzzy and range between -1 and 1. By being defined as positive or negative, they describe the direction and type of causality. Moreover, causal relationships in FCM are dynamic, meaning that altering one node affects all nodes in the path, allowing the study of feedback loops. The fuzzy-logic and consideration of causality proved to be useful when incorporating vague and qualitative knowledge (Rotmans 1998).

The flexibility of the tool is manifested through its diverse applications. In engineering, FCM has been widely used for controlling and supporting, as well as projecting future outcomes of changes to processes. It has been applied for supervision of manufacturing systems (Stylios & Groumpos 1999), human reliability in industrial facilities (Bertolini 2007), and safety evaluation (Enrique Peláez & Bowles 1996) to name a few. In information technology (IT), FCM has been applied mostly to support IT project management. Applications in IT range from evaluating investments in information systems (Irani et al. 2002), knowledge-based data mining of information from the internet (Hong & Han 2002), automatic generation of semantics for scientific e-documents (Zhuge & Luo 2006), modeling the success of IT projects (Rodriguez-Repiso et al. 2007), to predicting software reliability (Chytas et al. 2010). FCM have also been used in medicine, e.g. for aiding medical diagnosis (Innocent & John 2004) and tumor grading (Papageorgiou et al. 2006). Due to their usefulness for decision-support FCM has found its way to business, where it was used for analyzing market needs and potential, idea and concept development and evaluation, as steps in developing a new product (Jetter 2006). In social and political sciences FCM has served to model strategic issues and decision-support, as well as complex social and economical systems. Among others, it has been applied to study political development (Taber 1991), and the influence of police presence on theft occurrence (Carvalho 2013). FCM have thus proved to be a suitable tool for system modeling and decision making support, paving the way for application in environmental issues.

## 4. Fuzzy-logic cognitive mapping in the environmental modeling context

Being already applied in numerous applications throughout several disciplines, fuzzy-logic cognitive mapping was also introduced to the research of social-ecological systems. First, the need for application of FCM in environmental modeling and decision-making was demonstrated by the growing demands for participatory approaches when addressing environmental issues. Secondly, FCM emerged as a means to incorporate expert knowledge when modeling complex systems facing uncertainties in data and knowledge. Moreover, due to their ability to study feedback loops and causal relationships, FCM have been applied numerous times to study the consequences of changes to the environment, e.g. under different conditions of the system or decisions, thus enabling scenario studies.

### 4.1. Facilitating public participation

Numerous actors such as experts, scientists, decision makers and other stakeholders are involved when addressing environmental issues. In the past however, managing these issues has mostly been assigned to experts, with marginal involvement of local communities or a wider range of stakeholders. Due to the ineffectiveness of this traditional top-down approach to deal with the challenges of sustainable environmental management, the need for participatory management has arisen (Mendoza & Prabhu 2006). However, instead of facilitating a “one-way” participation, more interactive processes providing the chance for discussion, deliberation, negotiation and consensus building have become acknowledged as a major component of dealing with environmental issues (Patel et al. 2007). Fuzzy-logic cognitive mapping enables the involvement of experts and public throughout the entire modeling process. This is mainly due to its transparent development process, as the experts and other stakeholders need to be involved to construct the model from its beginning: identifying the concepts, their relationships and the strength of these relationships. This way, the acceptability of the final model is improved (Stach et al. 2005). Furthermore, FCM can promote cognitive learning.

FCM facilitates participation in way, that it supports all 4 arguments for public participation: normative, substantive, instrumental and social learning (von Korff 2007). Numerous experts and other stakeholders (e.g. members of the public) can be involved in FCM, which can lead to a wide variety of opinions on environmental issues. This way FCM reflects a broad spectrum of public and professional values, following normative reasons for participation. The substantive argument claims, that the involvement of a wider group of people can offer detailed local information, uncover mistakes or lead to alternative clarifications (Beierle & Cayford 2002). Through FCM we can thus gather more and improved information. For example, this is of high importance when identifying relationships in an ecosystem. Von Korff (2007) furthermore describes the instrumental argument, which states that participation can legitimize the final decision. Stakeholders can so consider the final social-ecological model as a more relevant and reliable. The concluding argument of public participation describes the idea of social learning. Active stakeholder involvement promotes learning for (and from) all involved parties, and leads to better knowledge about other participants' views and values. FCM has indeed proven to serve as a successful learning and communication tool, e.g. in the case of forest management (Mendoza & Prabhu 2006). Besides supporting decision-making and problem solving, it also serves as a tool for learning and negotiation (Eden et al. 1992).

Despite its easily apprehensible visually guided construction of a model, FCM can still be difficult to understand to the public not used to flow diagrams. Nevertheless, experts are normally familiar with conceptual models thus being able to understand FCM (Vennix 1996; Pahl-Wostl & Hare 2004). There are several reasons for using FCM as a participatory tool instead of other semi-quantitative methods (van Vliet et al. 2010). First of all, they are easy to teach and explain. Secondly, all stakeholders should be able to understand them, as the basics are comprehensible. Moreover, FCM have a high level of integration, which is particularly needed for complex environmental issues. Also, the construction of a FCM can be completed in a short time, leading to lower costs and less consumed time of the stakeholders (Kosko 1992). Lastly, the method results in a description of a system, providing sufficient complexity to explain a wide variety of environmental issues (Wainwright & Mulligan 2013).

### 4.2. Expert knowledge to deal with data and knowledge limitations

Solving environmental issues is often more difficult also due to large uncertainties or incomplete data and knowledge. Detailed scientific data might be unavailable for a particular case study, or it does not suffice the expected level of detail needed to perform an analysis. Usually, there are also limitations of a definite cost on obtaining information about the system – this can be demonstrated by the case of collecting field data, usually restricted both by time and money. Especially in environmental studies, there might however be abundant local knowledge of experts or the public, familiar with the environmental issue (e.g. a particular ecosystem).

There is still a big challenge to incorporate this local knowledge, as typical models have no means to achieve this (Özesmi & Özesmi 2004). FCM does not result merely in a list of ideas or perceptions: they result in a semi-quantitative model, based on people's knowledge. No hard data is needed to construct the model, however it can also be taken into account when identifying concepts and assigning weights to relationships. FCM can help to identify qualitative variables, and even relate them to quantitative variables. Additionally, important intangibles can be identified, thus leading to a possible incorporation of socio-economic driving forces and consequences. All this does not only lead to improved data, as it can also be used as a means of communication between stakeholders and scientists, and more importantly, for support of further model development (van Vliet et al. 2010).

As mentioned before, fuzzy-logic cognitive maps (FCMs) can be constructed by using different approaches, from interviews and group discussions, to document analysis. This flexibility allows the researcher to apply the suitable involvement approach, also depending on the availability and preferences of the stakeholders. Reviewing, editing and comparing single fuzzy-logic cognitive maps, as well as aggregating them into a single model is also easy and fast. The final map can be constructed jointly in a group session, or by aggregation of numerous individual FCMs. This goes for any number of maps, thus leading to easy integration also for a large set of individual FCMs (Jetter & Schweinfort 2011). The flexibility of the approach is also due to the fact, that they can easily be edited or extended by adding new concepts and establishing new relationships between them at any time of the construction process. The graphic part can easily be translated into a vector matrix, containing all information about the relationships between the concepts. This way, the burdensome and long lasting task of filling out a matrix can be avoided, spending less time on the parameterization of the model (De Jouvenel 2000). Moreover, no particular modeling software is needed to calculate the output of a fuzzy-logic cognitive map, as traditional statistical and spreadsheet software suffice.

A two-way communication with a group of experts can also serve as a possibility to validate FCMs. In spite of the difficulties of validation in terms of traditional historical data and statistical validation, it is possible to test the approach using other procedures. FCMs can be compared to other models representing the same or similar social-ecological issue. Secondly, experts can evaluate whether the model logic and its results are reasonable. Through evaluating if the changes to concepts result in realistic changes in the results, a sensitivity analysis can be performed. The symbolic representation of FCMs can also be matched to a real life issue, e.g. a decision process or workflow. Additionally, it is possible to test, whether a model run over a certain number of iterations results in reasonable changes to the concepts. FCMs can so be tested in several commonly employed validation procedures in order to provide information on the acceptance of a model (Rykiel Jr. 1996).

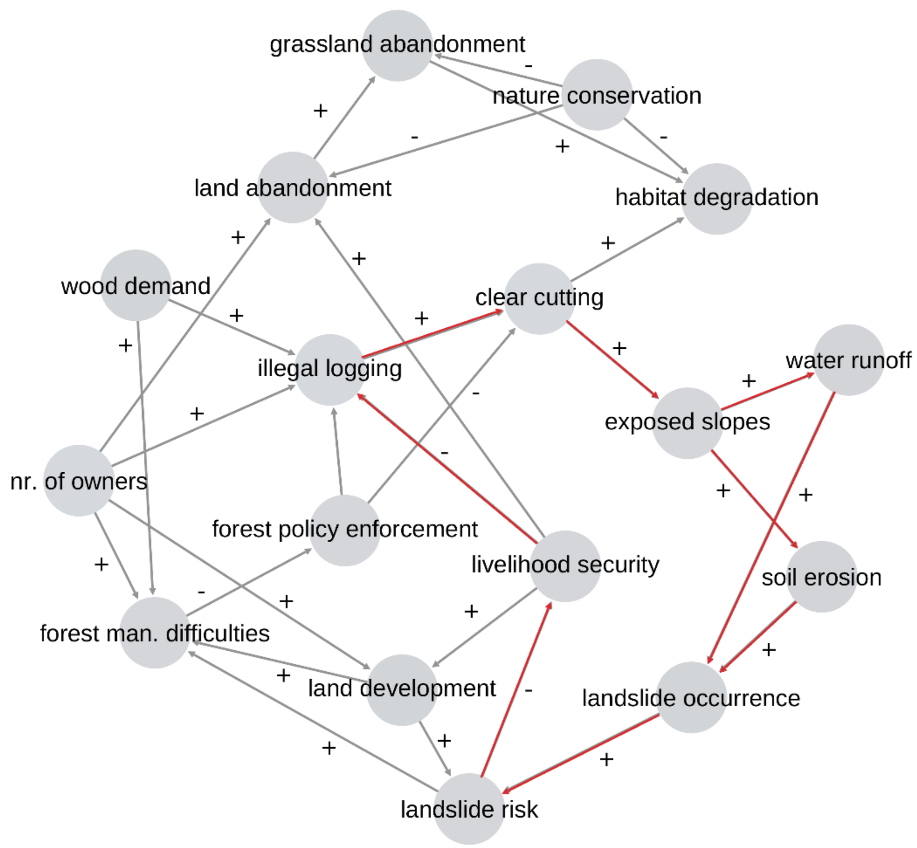
### 4.3. Simulating changes to the system and decision outcomes

Social-ecological systems are dynamic, evolving through changes of its components or relations between them. Feedback has to be taken into account when updating the condition of the components, and propagation of causal relationships. Fuzzy-logic cognitive mapping allows feedback loops, thus being able to handle this complexity and help to understand short and long-term dynamics (Kok 2009).

The basic concept of FCM is established as a semi-quantitative system dynamics approach involving feedback. A change to a single concept results in the changes to all concepts it directly affects. Through a network of causal relationships, other concepts are subsequently subject to change. Consequently, changes in other concepts can affect the concept initiating these changes (Kosko 1986). An example of a feedback loop is presented in Fig 2, on an example of deforestation in a rural mountainous area. FCMs are therefore not static, and can be used to study changes to the social-ecological system, either in form of changing conditions in the environment (e.g. precipitation), socio-economic driving forces (e.g. population, demand for resources), or management decisions (e.g. changes to harvest technique or quantity). Therefore, FCM offers much more than just an explanatory use, and can be applied to project and evaluate a possible future. This can be done either by identifying key future issues or guiding the exploration of plausible future scenarios (Probst & Gomez 1992; Ackermann & Eden 2004).

Revealing key feedbacks is one of the strongest points of FCM, not only as it enables the study of “what if” scenarios, but also as it leads to aggregating information of simulation models to the level of decision-making (van Kouwen et al. 2008). People’s difficulties of understanding complex systems are usually an obstacle when discussing the results of quantitative environmental simulation models. Among others, people tend to focus on a limited number of variables, ignoring feedbacks and overlooking the temporal dimension when thinking about future changes (Senge 1990; Acar & Druckenmiller 2006; Jetter & Schweinfort 2011). By involving the experts and stakeholders in constructing the model from the beginning on, the model and its simulation results are in their domain. Also, the simple and transparent construction method improves the trust of all the involved stakeholders in scenario analysis, impact assessments, and final decision evaluation and choice (Mendoza & Prabhu 2006).

**Fig. 2** Feedback loop on a simplified example of deforestation in a rural area in the Romanian Carpathians, modified from Malek et al. (2014). The feedback marked with red, depicts how a decrease in livelihood security triggered by the external fall of communism in the late 1980s affected illegal logging, with a consequent increase in landslide risk due to forest clear cutting on slopes. Finally, the increased landslide risk resulted as a negative feedback to livelihood security.




## 4.4. Examples of FCM in environmental research

Fuzzy-logic cognitive mapping has been used to model how different social-ecological systems operate. One of the first applications of FCM in environmental sciences, were ecological models based on expert and stakeholders knowledge. Radomski and Goeman (1996) applied FCM to improve decision-making in sport fisheries by involving fisheries biologists and fisheries managers. Hobbs et al. (2002) used FCM to define management objectives for the complex ecosystem of Lake Erie. They involved numerous scientists, managers, and the public to construct a complex model of an ecosystem. The work of Özesmi and Özesmi includes applications of FCM to obtain opinions of different stakeholders when establishing a national park, solving the conflict of population displacement due to a hydro plant construction, facilitating participatory wetland management, comparing the perception of different stakeholder groups regarding a salt lake ecosystem, and identifying needs for ecosystem conservation strategies (Özesmi & Özesmi 2003; Özesmi & Özesmi 2004; Tan & Özesmi 2006). Gras et al. (2009) have applied FCM to develop an individual-based predator model. In their model, the behavior of individual agents is modeled by FCM, allowing the evolution of the agent behavior. Kontogianni et al. (2012) analysed the perception of Ukrainian stakeholders for risks for the marine environment of the Black Sea. They used FCM to generate a model for environment management based on laymen perception on ecosystem resilience, risk management and possible future scenarios. Gray et al. (2012) applied FCM on a case of fishery management to integrate stakeholder knowledge. By collecting representations of stakeholders' mental models they aimed to evaluate similarities and differences of their perceptions of the same social-ecological system. Another example is the application of FCM to support Long Term Socio Ecological Research by Wildenberg et al. (2014). They applied FCM in 5 case studies to explore, analyze and communicate the perceptions of key stakeholders affected by conservation management.

Fuzzy-logic cognitive mapping has proven to be successful in forest management, where decision-making is characterized by high uncertainty due to the variety of social-ecological interactions. Skov and Svenning (2003) combined FCM with GIS-based spatial operations to predict ground flora species richness. This approach based on standard forestry maps together with expert knowledge was shown to be an efficient way of predicting the spatial pattern of species diversity under a set of different forest management scenarios. Carvalho et al. (2006) have combined FCM with voronoi cellular automata to simulate the propagation of forest fires. They used rule based FCM used to model the dynamic behavior of individual forest fire cells. Mendoza and Prabhu (2006) used FCM for participatory forest management. They applied it to an Indonesian case study area, where a stately owned forest was subject to large pressures in form of deforestation for urban and agricultural expansion and tourism. Ramsey et al. (2012) modeled forest response to deer control in New Zealand using a Bayesian algorithm to train their FCM. Their aim was to extract expert knowledge on the response of growth rates of tree seedlings to lower deer densities.

Besides forest management, fuzzy-logic cognitive mapping has been applied to management of other natural resources, such as water and soil, as well as to agriculture and conservation. Giordano et al. (2005) identified issues in water resources conflict in south of Italy using FCM. Here, FCM was used to structure the issues of drought, and inform the involved participants about water management alternatives. Ramsey and Norbury (2009) developed a model to assist decision-making on pest management relying on qualitative information. They used FCM to develop a complex food webs model and applied it to a dryland ecosystem in New Zealand. Papageorgiou et al. (2009) applied FCM for cotton yield management in precision farming. Their FCM modeled the behavior of cotton yield under a set of key factors in cotton crop production as recognized by the experts. Ortolani et al. (2010) analysed the Belgian farmers' perceptions of agri-environmental measures with FCM. They extracted causal relationships between environmental management measures and numerous socio-economic and biophysical variables from questionnaires and interviews with farmers. Murungweni et al. (2011) applied FCM to analyse livelihood vulnerability in the Great Limpopo Conservation Area in Southern Africa. Their emphasis was on evaluating feedback mechanisms in social-ecological systems to reveal possible changes to a livelihood system under different scenarios. In the study of Văidianu et al. (2014), FCM was applied to examine stakeholders' perception for improving the management of the Danube Delta Biosphere Reserve in Romania. The key concepts were gathered for supporting future communication on sustainable development and biodiversity conservation of the area.

## 5. Limitations of fuzzy-logic cognitive mapping

Owing to its rather broad and semi-quantitative methodology, fuzzy-logic cognitive mapping is a flexible approach, transferable to basically any problem. On the other side, also its main weaknesses are connected to the methodology. Whereas some drawbacks related to its subjective and qualitative nature can be improved easily by involving additional experts, other issues cannot be resolved and have to be taken into account when interpreting the results.

The minor drawbacks of FCM are related to the graphical representation and stakeholder involvement. First, the simple and open structure of the symbolic representation of the system offers a suitable framework for participation of non-expert stakeholders. This vagueness however, can serve as a concern for more technical experts and researchers, especially as results gathered through participation can have a lower degree of accuracy (Mendoza & Prabhu 2006; Gray et al. 2012). Secondly, the stakeholders involved need to have adequate knowledge on the analysed topic to be able to estimate the strength of relationships between the concepts. This can result in the exclusion of some stakeholders, which could otherwise provide great value to the process (Kok 2009). Furthermore, all biases of involved stakeholders are encoded in the maps as well (Kosko 1992). Nevertheless, the subjectivity and robustness of the model generated through FCM can be improved by involving numerous experts and informed stakeholders.

The major limitations are related to the methodology of the approach itself. Firstly, relationships in FCM are only semi-quantified, as they are not described by real-value parameter estimates (Craiger et al. 1996). This limits the interpretation of results. Secondly, despite providing information on values of concepts after a defined number of iterations, these cannot be directly converted into time steps. Still, this issue can be solved, if the processes studied all operate at the same temporal scale (Kok 2009). Another weakness of the method lies in the process of defining the weights of the semi-quantified relationships. The methodology is based on gathering opinions and representing the belief system of the involved stakeholders. To overcome this limitation, numerous stakeholders need to be involved. This way, the final fuzzy-logic cognitive map represents an agreement between different opinions. Agreement can be achieved through combining multiple fuzzy-logic cognitive maps, or constructing one map in a workshop setting. This limitation, however can also be used to understand how different stakeholders view the important concepts and relationships of a system (Özesmi & Özesmi 2003).

## 6. Conclusion

Fuzzy-logic cognitive mapping has emerged as a useful participatory instrument for modeling of complex social-ecological systems. Moreover, through successful applications in numerous domains, it has become established as an effective technique for decision-making support in environmental issues.

The rising demand for participatory approaches in environmental issues is well acknowledged, and FCM has proven to be an effective approach for discussing, planning, negotiating and building consensus. FCM leads to a semi-quantitative, graphical representation of a behavior of a complex system. Its graphical and semi-quantitative nature allows effortless and quick visualization and control of the analysed system. It can combine expertise from scientists, experts, decision-makers, and other stakeholders from different disciplines, thus being able to include a broader spectrum of public and expert opinion. Therefore it can help to bridge the gap between science and decision-making. It can offer more and improved information, available on a detail otherwise impossible to achieve with other techniques.

This is especially significant in environmental issues, where hard data is often unavailable or knowledge of a system is uncertain. Due to the complexity of social-ecological system, it is sometimes difficult to identify important intangibles or establish relationships between socio-economic and physical variables. As the key stakeholders have been involved throughout the complete model construction process, FCM lead to a more reliable and relevant model outcomes. Moreover, the method has proven as a successful learning and communication tool, facilitating the exchange of ideas and opinions between different stakeholders. Due to its ability to model feedback loops, FCM has great potential in future environmental research, studying consequences of environmental changes or decisions regarding a particular social-ecological system.

## 6. References

Acar W, Druckenmiller D (2006) Endowing cognitive mapping with computational properties for strategic analysis. Futures 38:993–1009. doi: 10.1016/j.futures.2005.12.018

Ackermann F, Eden C (2004) The Practice of Making Strategy: A Step-by-Step Guide. SAGE, London

Axelrod RM (1976) Structure of Decision: The Cognitive Maps of Political Elites, 1st Paperback Edition edition. Princeton Univ Pr, Princeton, N.J.

Beierle TC, Cayford J (2002) Democracy in Practice: Public Participation in Environmental Decisions. Resources for the Future

Bertolini M (2007) Assessment of human reliability factors: A fuzzy cognitive maps approach. Int J Ind Ergon 37:405–413. doi: 10.1016/j.ergon.2005.12.009

Biggs NL, Lloyd EK, Wilson RJ (1999) Graph Theory 1736-1936. Oxford University Press, Oxford Oxfordshire ; New York

Carvalho JP (2013) On the semantics and the use of fuzzy cognitive maps and dynamic cognitive maps in social sciences. Fuzzy Sets Syst 214:6–19. doi: 10.1016/j.fss.2011.12.009

Carvalho JP, Carola M, Tome JAB (2006) Forest fire modelling using rule-based fuzzy cognitive maps and voronoi based cellular automata.

Chytas P, Glykas M, Valiris G (2010) Software Reliability Modelling Using Fuzzy Cognitive Maps. In: Glykas M (ed) Fuzzy Cogn. Maps. Springer Berlin Heidelberg, pp 217–230

Craiger JP, Weiss RJ, Goodman DF, Butler AA (1996) Simulating organizational behavior with fuzzy cognitive maps. Int J Comput Intell Organ 120–123.

De Jouvenel H (2000) A Brief Methodological Guide to Scenario Building. Technol Forecast Soc Change 65:37–48. doi: 10.1016/S0040-1625(99)00123-7

Eden C, Ackermann F, Cropper S (1992) The Analysis of Cause Maps. J Manag Stud 29:309–324. doi: 10.1111/j.1467-6486.1992.tb00667.x

Enrique Peláez C, Bowles JB (1996) Using fuzzy cognitive maps as a system model for failure modes and effects analysis. Inf Sci 88:177–199. doi: 10.1016/0020-0255(95)00161-1

Giordano R, Passarella G, Uricchio VF, Vurro M (2005) Fuzzy cognitive maps for issue identification in a water resources conflict resolution system. Phys Chem Earth Parts ABC 30:463–469. doi: 10.1016/j.pce.2005.06.012

Gras R, Devaurs D, Wozniak A, Aspinall A (2009) An Individual-Based Evolving Predator-Prey Ecosystem Simulation Using a Fuzzy Cognitive Map as the Behavior Model. Artif Life 15:423–463. doi: 10.1162/artl.2009.Gras.012

Gray S, Chan A, Clark D, Jordan R (2012) Modeling the integration of stakeholder knowledge in social–ecological decision-making: Benefits and limitations to knowledge diversity. Ecol Model 229:88–96. doi: 10.1016/j.ecolmodel.2011.09.011

Hage P, Harary F (1983) Structural Models in Anthropology. Cambridge University Press

Hobbs BF, Ludsin SA, Knight RL, et al. (2002) Fuzzy cognitive mapping as a tool to define management objectives for complex ecosystems. Ecol Appl 12:1548–1565. doi: 10.1890/1051-0761(2002)012[1548:FCMAAT]2.0.CO;2

Hong T, Han I (2002) Knowledge-based data mining of news information on the Internet using cognitive maps and neural networks. Expert Syst Appl 23:1–8. doi: 10.1016/S0957-4174(02)00022-2

Hurtado SM (2010) Modeling of Operative Risk Using Fuzzy Expert Systems. In: Glykas M (ed) Fuzzy Cogn. Maps. Springer Berlin Heidelberg, pp 135–159

Innocent PR, John RI (2004) Computer aided fuzzy medical diagnosis. Inf Sci 162:81–104. doi: 10.1016/j.ins.2004.03.003

Irani Z, Sharif A, Love PED, Kahraman C (2002) Applying concepts of fuzzy cognitive mapping to model: The IT/IS investment evaluation process. Int J Prod Econ 75:199–211. doi: 10.1016/S0925-5273(01)00192-X

Jetter A, Schweinfort W (2011) Building scenarios with Fuzzy Cognitive Maps: An exploratory study of solar energy. Futures 43:52–66. doi: 10.1016/j.futures.2010.05.002

Jetter AJ (2006) Fuzzy Cognitive Maps for Engineering and Technology Management: What Works in Practice? Technol. Manag. Glob. Future 2006 PICMET 2006. pp 498–512

Kok K (2009) The potential of Fuzzy Cognitive Maps for semi-quantitative scenario development, with an example from Brazil. Glob Environ Change 19:122–133.

doi: 10.1016/j.gloenvcha.2008.08.003

Kontogianni A, Papageorgiou E, Salomatina L, et al. (2012) Risks for the Black Sea marine environment as perceived by Ukrainian stakeholders: A fuzzy cognitive mapping application. Ocean Coast Manag 62:34–42. doi: 10.1016/j.ocecoaman.2012.03.006

Kosko B (1986) Fuzzy cognitive maps. Int J Man-Mach Stud 24:65–75. doi: 10.1016/S0020-7373(86)80040-2

Kosko B (1992) Fuzzy Associative Memory Systems. Fuzzy Expert Syst.

Krueger T, Page T, Hubacek K, et al. (2012) The role of expert opinion in environmental modelling. Environ Model Softw 36:4–18. doi: 10.1016/j.envsoft.2012.01.011

Malek Ž, Schröter D, Glade T, Boerboom LGJ (2014) Effects of possible forest management scenarios in the Romanian Carpathians.

McNeill FM, Thro E (1994) Fuzzy Logic: A Practical Approach. Academic Press Professional, Inc., San Diego, CA, USA

Mendoza GA, Prabhu R (2006) Participatory modeling and analysis for sustainable forest management: Overview of soft system dynamics models and applications. For Policy Econ 9:179–196. doi: 10.1016/j.forpol.2005.06.006

Mingers J, Rosenhead J (2004) Problem structuring methods in action. Eur J Oper Res 152:530–554. doi: 10.1016/S0377-2217(03)00056-0

Murungweni C, van Wijk MT, Andersson JA, et al. (2011) Application of Fuzzy Cognitive Mapping in Livelihood Vulnerability Analysis. Ecol Soc. doi: 10.5751/ES-04393-160408

Ortolani L, McRoberts N, Dendoncker N, Rounsevell MD. (2010) Analysis of Farmers' Concepts of Environmental Management Measure: An Application of Cognitive Maps and Cluster Analysis in Pursuit of Modelling Agents' Behaviour. Fuzzy Cogn. Maps Adv. Theory Methodol. Tools Appl.

Özesmi U, Özesmi S (2003) A Participatory Approach to Ecosystem Conservation: Fuzzy Cognitive Maps and Stakeholder Group Analysis in Uluabat Lake, Turkey. Environ Manage 31:0518–0531. doi: 10.1007/s00267-002-2841-1

Özesmi U, Özesmi SL (2004) Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. Ecol Model 176:43–64. doi: 10.1016/j.ecolmodel.2003.10.027

Page T, Heathwaite AL, Thompson LJ, et al. (2012) Eliciting fuzzy distributions from experts for ranking conceptual risk model components. Environ Model Softw 36:19–34. doi: 10.1016/j.envsoft.2011.03.001

Pahl-Wostl C, Hare M (2004) Processes of social learning in integrated resources management. J Community Appl Soc Psychol 14:193–206. doi: 10.1002/casp.774

Papageorgiou EI, Markinos A, Gemptos T (2009) Application of fuzzy cognitive maps for cotton yield management in precision farming. Expert Syst Appl 36:12399–12413. doi: 10.1016/j.eswa.2009.04.046

Papageorgiou EI, Spyridonos PP, Stylios CD, et al. (2006) Advanced soft computing diagnosis method for tumour grading. Artif Intell Med 36:59–70. doi: 10.1016/j.artmed.2005.04.001

Patel M, Kok K, Rothman DS (2007) Participatory scenario construction in land use analysis: An insight into the experiences created by stakeholder involvement in the Northern Mediterranean. Land Use Policy 24:546–561. doi: 10.1016/j.landusepol.2006.02.005

Probst GJB, Gomez P (1992) Thinking in Networks to Avoid Pitfalls of Managerial Thinking. In: Maruyama M (ed) Context Complex. Springer New York, pp 91–108

Radomski PJ, Goeman TJ (1996) Decision Making and Modeling in Freshwater Sport-fisheries Management. Fisheries 21:14–21. doi: 10.1577/1548-8446(1996)021<0014:DMAMIF>2.0.CO;2

Ramsey DSL, Forsyth DM, Veltman CJ, et al. (2012) An approximate Bayesian algorithm for training fuzzy cognitive map models of forest responses to deer control in a New Zealand adaptive management experiment. Ecol Model 240:93–104. doi: 10.1016/j.ecolmodel.2012.04.022

Ramsey DSL, Norbury GL (2009) Predicting the unexpected: using a qualitative model of a New Zealand dryland ecosystem to anticipate pest management outcomes. Austral Ecol 34:409–421. doi: 10.1111/j.1442-9993.2009.01942.x

Rodriguez-Repiso L, Setchi R, Salmeron JL (2007) Modelling IT projects success with Fuzzy Cognitive Maps. Expert Syst Appl 32:543–559. doi: 10.1016/j.eswa.2006.01.032

Rotmans J (1998) Methods for IA: The challenges and opportunities ahead. Environ Model Assess 3:155–179. doi: 10.1023/A:1019019024003

Rykiel Jr. EJ (1996) Testing ecological models: the meaning of validation. Ecol Model 90:229–244. doi: 10.1016/0304-3800(95)00152-2

Senge PM (1990) The Fifth Discipline: The Art & Practice of The Learning Organization. Doubleday, New York

Skov F, Svenning J-C (2003) Predicting plant species richness in a managed forest. For Ecol Manag 180:583–593. doi: 10.1016/S0378-1127(02)00646-1

Stach W, Kurgan L, Pedrycz W, Reformat M (2005) Genetic learning of fuzzy cognitive maps. Fuzzy Sets Syst 153:371–401. doi: 10.1016/j.fss.2005.01.009

Stylios CD, Groumpos PP (1999) A Soft Computing Approach for Modelling the Supervisor of Manufacturing Systems. J Intell Robot Syst 26:389–403.

Taber R (1991) Knowledge processing with Fuzzy Cognitive Maps. Expert Syst Appl 2:83–87. doi: 10.1016/0957-4174(91)90136-3

Tan CO, Özesmi U (2006) A Generic Shallow Lake Ecosystem Model Based on Collective Expert Knowledge. Hydrobiologia 563:125–142. doi: 10.1007/s10750-005-1397-5

Ülengin F, Topçu İ (1997) Cognitive map: KBDSS integration in transportation planning. J Oper Res Soc 48:1065–1075. doi: 10.1057/palgrave.jors.2600444

Văidianu MN, Adamescu MC, Wildenberg M, Tetelea C (2014) Understanding Public Participation and Perceptions of Stakeholders for a Better Management in Danube Delta Biosphere Reserve (Romania). In: Papageorgiou EI (ed) Fuzzy Cogn. Maps Appl. Sci. Eng. Springer Berlin Heidelberg, pp 355–374

Van Kouwen F, Schot PP, Wassen MJ (2008) A framework for linking advanced simulation models with interactive cognitive maps. Environ Model Softw 23:1133–1144. doi: 10.1016/j.envsoft.2008.02.006

Van Vliet M, Kok K, Veldkamp T (2010) Linking stakeholders and modellers in scenario studies: The use of Fuzzy Cognitive Maps as a communication and learning tool. Futures 42:1–14. doi: 10.1016/j.futures.2009.08.005

Vennix J (1996) Group Model Building: Facilitating Team Learning Using System Dynamics, 1 edition. Wiley, Chichester ; New York

Von Korff Y (2007) Re-focusing research and researchers in public participation. Proc. CAIWA

Wainwright J, Mulligan M (2013) Introduction. Environ. Model. Find. Simplicity Complex.

Wildenberg M, Bachhofer M, Isak KGQ, Skov F (2014) Use and Evaluation of FCM as a Tool for Long Term Socio Ecological Research. In: Papageorgiou EI (ed) Fuzzy Cogn. Maps Appl. Sci. Eng. Springer Berlin Heidelberg, pp 221–236

Zhuge H, Luo X (2006) Automatic generation of document semantics for the e-science Knowledge Grid. J Syst Softw 79:969–983. doi: 10.1016/j.jss.2005.08.022

# CHANGES research project

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The CHANGES network aims to develop an advanced understanding of how global changes (related to environmental and climate change as well as socio-economical change) will affect the temporal and spatial patterns of hydro-meteorological hazards and associated risks in Europe; how these changes can be assessed, modelled, and incorporated in sustainable risk management strategies, focusing on spatial planning, emergency preparedness and risk communication. My part in the project was to analyse past and model future scenarios of land use and land cover changes, partly presented in the dissertation. More information on the CHANGES project: www.changes-itn.eu

# Curriculum Vitae


| | |
|---|---|
| Name | Žiga Malek |
| Nationality | Slovenian |
| Contact | Steinbauergasse 11/10, 1120 Wien, Austria |
| | ziga.malek@gmail.com |


## Education

| | |
|---|---|
| 2011 - | PhD in Physical Geography<br>Faculty of Earth Sciences, Geography and Astronomy<br>University of Vienna, Austria |
| 2005 – 2010 | University Degree in Landscape Architecture<br>Biotechnical Faculty, University of Ljubljana, Slovenia |

## Additional Education

| | |
|---|---|
| 2013 | Certificate in Geo-Information Science and Earth Observation: Scenario Development and Decision Support in Spatial planning. Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, The Netherlands |
| 2013 | Protecting Mountains Society from Natural Hazards: Plans or Dams? FORMOSE Post-graduate Intensive Course, Barcelonette, France |
| 2012 | Environmental Hazards and Sustainable Development in Mountain Regions. International Summer School, Magura, Romania |
| 2012 | Hyper-Temporal Earth Observation Data Analysis for Food Security and Biodiversity Assessment. SENSE – Research School for Socio-Economic and Natural Sciences of the Environment, Summer |

| | |
|---|---|
| | Academy 2012. Enschede, The Netherlands |
| 2012 | Multi-hazard Risk Assessment. Technical Skills Course. Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, The Netherlands |

**Work experience**

| | |
|---|---|
| August 2011 - | Research Assistant |
| | Risk, Policy and Vulnerability Program. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. |
| January 2012 - | PhD Student |
| | Faculty of Earth Sciences, Geography and Astronomy, Institute of Geography and Regional Research, University of Vienna, Austria |
| February 2013 - | Visiting Scientist |
| July 2013 | Faculty of Geo-Information Science and Earth Observation (ITC) of the University of Twente, Enschede, The Netherlands |
| November 2010 - | Environmental and Spatial Planning Associate |
| August 2011 | TrafCons Traffic Planning, Engineering and Consulting, Ljubljana, Slovenia |
| April 2010 - | Landscape Architecture Intern (Erasmus) |
| July 2010 | Neumann Gusenburger Landschaftsarchitekten, Berlin, Germany |

**Publications**

Malek Ž, Zumpano V, Schröter D, Glade T, Balteanu D, Micu M. 2014. Scenarios of land cover change and landslide susceptibility: an example from the Buzau Subcarpathians, Romania. In: Lollino G, Manconi A, Guzzetti F, Culshaw M, Bobrowsky P, Luino F. Engineering Geology for Society and Territory – Volume 5: Urban Geology, Sustainable Planning and Landscape Exploitation (IAEG XII Congress, Torino, Italy)

Malek Ž, Scolobig A, Schröter D. 2014. Understanding Land Cover Changes in the Italian Alps and Romanian Carpathians Combining Remote Sensing and Stakeholder Interviews. Land: 3(1): 52–73

Malek Ž, Patt A, Schröter D. 2012. Identification of changes to ecosystem services in the Subcarpathians of Buzău County in Romania. In: Forum Carpaticum 2012: From Data to Knowledge – from Knowledge to Action. Proceedings. Boltižiar, M. (Ed.). Institute of Landscape Ecology, Slovak Academy of Sciences, Bratislava, Branch Nitra

Ciurean RL, Malek Ž, Schröter D, Glade T. 2012. Vulnerability Assessments for Natural Disaster Reduction: Frameworks, Applications and Future Challenges. Deliverable for the CHANGES Work Package 2: Evaluating Changes in Exposed Elements at Risk and their Vulnerability

**Conference Oral Presentations**

Malek Ž. 2014. Future land change scenarios for risk assessment: Linking participatory modelling and geosimulation. International Conference: Analysis and Management of Changing Risks for Natural Hazards. Padova, Italy.

Zumpano V, Malek Ž, Reichenbach P, Micu M, Balteanu. 2014. Urban area exposure to landslides under landuse changes scenarios: application in a discontinuous data environment. International Conference: Analysis and Management of Changing Risks for Natural Hazards. Padova, Italy.

Zumpano V, Malek Ž. 2014. The consequences of forest management in the Curvature Carpathians: analysing the relation between forest cover change and landslide susceptibility in Buzău County, Romania. International Geographical Union – Commission on Land Use and Cover Changes 2014 Symposium: Land use-Land cover Changes and Land Degradation, Bucharest, Romania

Malek Ž, Schröter D, Glade T, Boerboom L. 2014. Hydro-meteorological risk and socio-economic development: future land cover scenarios of an alpine valley. 2014 Global Land Project Open Science Meeting, “Land transformations: between global challenges and local realities”, Berlin, Germany

Malek Ž, Schröter D, Glade T. 2013. Land use/cover changes in European mountain areas: global driving forces and local destinies. Hochgebirge im Globalen Wandel, Arbeitskreis Hochgebirge, 22. Jahrestagung 2013, Bonn, Germany

Malek Ž, Patt A, Schröter D, Glade T. 2012. Changes to the provision of ecosystem services in the Subarpathians in Buzău County in Romania. Forum Carpaticum 2012, Tatranska Lomnica, Slovakia

Malek Ž. 2012. Effects of global changes on mountain land use patterns and ecosystem services in a comparative case study: Italian Alps and Romanian Carpathians. Research proposal presentation. GI_forum 2012, Salzburg, Austria

**Conference Poster Presentations**

Malek Ž. 2014. Combining participatory modelling and land change simulation for generating spatially explicit scenarios of future tourism development: example in the Italian Alps. International Scientific Committee on Research in the Alps (ISCAR) Forum Alpinum '14. Darfo Boario Terme, Italy

Malek Ž, Balteanu D, Micu M. 2014. Land Use and Cover Changes in the Bend Carpathians and Subcarpathians. International Geographical Union – Commission on Land Use and Cover Changes 2014 Symposium: Land use-Land cover Changes and Land Degradation, Bucharest, Romania

Malek Ž, Schröter D, Glade T, Boerboom L. 2014. Spatial pattern of forest management in the Romanian Carpathians under a set of forestry policy scenarios. 2014 Global Land Project Open Science Meeting, "Land transformations: between global challenges and local realities", Berlin, Germany

Malek Ž, Schröter D, Glade T. 2013. Land use/cover changes in European mountain areas: identifying links between global driving forces and local consequences. European Geosciences Union General Assembly 2013, Vienna, Austria

Malek Ž, Schröter D, Glade T. 2012. Effects of global changes on mountain land use patterns and ecosystem services in a comparative case study: Italian Alps and Romanian Carpathians. IIASA 40th Anniversary Conference 2012, Vienna, Austria

Malek Ž, Patt A, Schröter D, Glade T. 2012. Analyzing land use change and the effects on the provision of ecosystem services in European mountain areas: Case studies from the Romanian Carpathians and the Italian Alps. ECOCHANGE final conference, Zürich, Switzerland

**Seminars, Presentations**

Land use/cover change scenario model development with Dinamica EGO. Invited presentation, Help, Consultation and Guidance of MSc students at the Department of Natural Resources, Faculty of Geo-information science and Earth Observation – ITC, University of Twente, Enschede, The Netherlands. January 2014

A framework for local scale land use/cover change scenario development. Invited presentation at the Department of Geoinformatics, University of Salzburg. January 2014

Exploring land use/ cover changes in European mountain areas: global driving forces have local consequences. Invited presentation at the Department of Earth System Analysis, Faculty of Geo-information science and Earth Observation – ITC, University of Twente, Enschede, The Netherlands. April 2013