SOCIAL-ECOLOGICAL MODELING OF ALPINE ECOSYSTEM SERVICES

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Das Schönste, was wir erleben können, ist das Geheimnisvolle. Es ist das Grundgefühl, das an der Wiege von wahrer Kunst und Wissenschaft steht. Wer es nicht kennt und sich nicht wundern, nicht mehr staunen kann, der ist sozusagen tot und sein Auge erloschen.

Albert Einstein
SOCIAL-ECOLOGICAL MODELING OF ALPINE ECOSYSTEM SERVICES

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Summary

Mountain social-ecological systems (SESs) deliver critical ecosystem services (ES) to more than half of the world’s population. At the same time, mountain SESs are highly sensitive to socio-economic, ecological, and political changes from the global to the local scale. In recent decades, these changes have accelerated fundamental transformations in land use across mountain regions and put the provision of vital ES at risk. As the evidence and our knowledge of the consequences of large-scale drivers for local mountain environments and well-being increase, so does the concern of policy-makers and scholars about how to change the course of the observed development. Given the uncertainty of future global change, a new generation of social-ecological models is required to address these worries and support negotiations on sustainable development pathways. These models need to be able to (1) capture the complexity of temporal and spatial dynamics of mountain SESs across scales (i.e., generate system knowledge), (2) evaluate the impact of different policy and management strategies under various boundary conditions given an envisioned target (i.e., provide target knowledge), and (3) identify transformation pathways toward sustainability (i.e., develop transformation knowledge). However, the setup and application of such models is especially challenging in mountain regions: data to drive them may be sparse or unavailable and the small number of interested stakeholders complicates transdisciplinary research processes, which are urgently needed to achieve the aspired outcomes. Furthermore, due to their marginality, complexity, and remoteness, mountain regions often have less priority in national policy arenas.

The goals of this thesis are to develop a social-ecological model that integrates ES supply and demand, to apply it to a real-world mountain case study to advance our understanding of global change impacts on mountain SESs, and to evaluate alternative policy strategies with regard to an envisioned level of ES. Results should fuel the scientific, political, and societal debate on sustainable development pathways of mountain regions by unraveling important trade-offs related to alternative courses of action. Specifically, the following research questions were addressed:

1. How can the integration of normative and explorative methods support our understanding of the future dynamics of mountain SESs?
2. Which global and regional drivers are key sources of uncertainty in the future provision of demanded ES across the case study region?
3. Which policy strategies foster a desirable development of the mountain region against a wide range of global pressures and pulses?

These questions were elaborated in three research articles that have been published in renowned scientific journals.

Paper I describes the inter- and transdisciplinary development process of the integrative social-ecological modeling system BackES. In particular, it explains how a choice experiment and an agent-based land-use model were linked via a utility function to integrate ES demand and supply in a theoretical consistent manner based on welfare economic theory. Applied to a case study region in the Swiss Alps, Paper I illustrates how an integration of explorative and normative methods can support our understanding of mountain SES dynamics and how, where, and when ES are coproduced by the social and ecological parts of the system. It unravels the dynamic relationships among global boundary conditions, policy interventions, land use, and ES supply and demand in the mountain case study region, as well as infers which components most strongly affect future ES benefits. Furthermore, the paper discusses relevant assumptions about and limitations of the modeling system.

In Paper II, an extensive scenario analysis was conducted to quantify and map uncertainties in the future ES provision resulting from uncertainties in climatic and socio-economic driving forces and societal values. Results show that future gains in ES benefits occur predominantly in the valley bottom but are prone to high uncertainties, whereas in remote areas, losses in ES occur quite consistently across various assumed global and regional change scenarios. In more urban areas, the magnitude of changes in benefits is substantially influenced by global and national socio-economic drivers and demand for services. By contrast, regional drivers, e.g., the farming structure will determine how much land is given up and thus, how high the loss of ES is in remote sites. In both areas of the case study, climate change drives the pattern of future ES delivery. These insights highlight where management and policy-making have to deal with high levels of uncertainty to secure the provision of demanded ES and where the investment of limited resources might become inefficient in future.

In Paper III, the (mis)match between ES supply and demand was simulated in different scenarios of global change and by implementing various potential policy
strategies to infer clear policy recommendation on when and how to intervene in the system for reaching envisioned ES benefits. Results show that, without interventions, the mountain SES is not resilient enough to provide desired ES against global change. Policy strategies that simultaneously tackle several important system stressors are required to mitigate the pronounced loss of highly valued cultural ES. Robust strategies combine timely spatial planning restrictions with more targeted direct payments to support young farmers and traditional mountain management practices. Evaluating the robustness of policy action in different boundary settings and deriving milestones for intervention are crucial to decision-making in the current era of highly uncertain future global change.

Overall, the results of this thesis suggest that different trade-offs will emerge in our mountain case study in the future. Most pronounced is the increasing gap between a high demand for cultural services, including aesthetics, and a decreasing number of farms managing the landscape and maintaining the supply of these ES. In addition, trade-offs between single services (e.g., between the cultural heritage and the habitat service or between the former and the aesthetics of grassland) will become more pronounced. My findings illustrate that the strength of these trade-offs will substantially depend on global boundary conditions and on policy actions taken. These factors furthermore determine how the costs of maintaining the desired ES delivery are distributed among society and farmers. If no policy actions are taken, land-use changes observed in the past decades will likely continue and determine the development pathway of the SES for the next 20 years. Specifically, in a strong globalization and liberalization scenario, the rate of farm and grassland abandonment will accelerate, and settlement and forest growth will substantially increase. However, if adequate policies are implemented, then the resilience of the system to a range of pressures can be maintained to a high degree, and the provision of ES might remain within critical thresholds. This resilience will depend on a large extent on the current farming structure, which comprises mostly part-time businesses and a highly subsidized agricultural sector. The results indicate that better cooperation among agricultural policy, nature conservation, and spatial planning might be a promising strategy to maintain ES in the case study and potentially across European mountain regions. In addition, measures should support an agriculture that adapts the supply of ES to societal demands and harmonizes supply and demand in a spatially explicit manner.

However, meeting the demand for cultural ES in our mountain case study in the future is becoming increasingly difficult and will be related to high societal costs. Society therefore has to address the questions of whether maintenance of the (currently preferred) *status quo* ES provision is efficient, sustainable, and desirable in the longer term and whether it is useful to continue the chosen pathway of high governmental financial aid for farmers and reliance on their second income from tourism. Such a discourse is especially relevant in the longer term because socio-economic, political, or climatic shocks might accumulate, or unpredictable shifts in the ecological or societal part of the system may occur. To provide support for negotiations on longer-term sustainable development pathways, the modeling system *BackES* needs several advancements: Trade-offs among ES demand of different stakeholder groups and at different scales as well as the dynamics in the societal perception and valuation of ES should be integrated and simulated. Furthermore, (cross-scale) feedback mechanisms should be better represented to account for off-site effects, non-linear processes in SESs and trade-offs between desirability and ecological viability of ES provision.

In summary, this thesis contributes to methodological innovations with regard to the integration of positive and normative approaches in ES research, spatially and temporally explicit modeling of mountain SESs, uncertainty analyses in combination with scenario approaches, and the operationalization of resilience in a SES context. Furthermore, it generates system, target, and potentially transformation knowledge with regard to mountain SESs. In particular, this thesis provides insights into global and regional change effects, key sensitivities, ES trade-offs, resilience-building factors, and useful policy strategies in a mountain case study that can be indicative for other similar mountain SESs.
Zusammenfassung


Die Ziele dieser Doktorarbeit bestehen darin, ein sozioökologisches Modell zu entwickeln, das sowohl das Angebot an als auch die Nachfrage nach ÖSL integriert, und es in einem Fallstudiengebiet anzuwenden, um vertiefte Erkenntnisse der Auswirkungen vom global Wandel im Berggebiet zu gewinnen und alternative Politikmassnahmen im Bezug auf eine gewünschte Versorgung an ÖSL zu evaluieren. Die Resultate sollen zu der wissenschaftlichen, politischen und gesellschaftlichen Debatte über nachhaltige Entwicklungsstrategien von Berggebieten beitragen, indem sie wichtige Abwägungen aufzeigen, die mit verschiedenen Strategien verbunden sind. Insbesondere wurden die folgenden Forschungsfragen bearbeitet:

1. Wie kann die Integration von normativen und explorativen Methoden unser Verständnis von zukünftigen Mensch-Umwelt-Interaktionen im Berggebiet fördern?
2. Welche globalen und regionalen Faktoren tragen entscheidend zu der Unsicherheit in der zukünftigen Bereitstellung von ÖSL im Fallstudiengebiet bei?
3. Welche Politikmassnahmen stärken eine erwünschte Entwicklung des Berggebietes gegen eine Bandbreite an möglichen zukünftigen globalen Stressfaktoren?

Die Forschungsfragen wurden in drei Artikeln abgehandelt, die in anerkannten wissenschaftlichen Zeitschriften publiziert wurden.


In der zweiten Publikation wurde eine umfassende Szenarioanalyse durchgeführt, um Unsicherheiten in der zukünftigen Bereitstellung von ÖSL auf Grund von Unsicherheiten in klimatischen und sozioökonomischen Einflussfaktoren und gesellschaftlichen Werten zu quantifizieren und kartieren. Die Resultate zeigen, dass Nutzen von ÖSL in der Zukunft vor allem in Talregionen


Meine Analysen zeigen aber auch, dass es immer schwieriger wird und mit immer mehr gesellschaftlichen Kosten verbunden sein wird, die gewünschten ÖSL im Berggebiet bereitzustellen. Die Gesellschaft als Ganzes muss sich deswegen fragen, ob eine Erhaltung des (gegenwärtig bevorzugten) Status quo effizient, nachhaltig und erwünscht ist und ob es sinnvoll ist, den eingeschlagenen Weg mit umfangreichen Landwirtschaftssubventionen und der Abhängigkeit der Bauern auf ein Einkommen aus dem Tourismus weiterzuverfolgen. Dieser Diskurs ist insbesondere auf längere Sicht wichtig, weil sozioökonomische, politische oder klimatische Schocks allenfalls vermehrt auftreten werden und unvorhergesehen, einschneidende Veränderungen in Ökosystemen und gesellschaftlichen Normen und Werten auftreten können. Um Diskussionen über längerfristige nachhaltige Entwicklungsstrategien besser unterstützen zu können, muss das Modellsystem

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Over every mountain there is a path, although it may not be seen from the valley.

Theodor Roethke
1. Introduction

1.1. Motivation
Mountains cover about 24% of the earth’s land surface and half of the world’s population depends, directly or indirectly, on the resources provided by these regions. Because of their unique features, such as compressed topographies, steep vertical gradients, or remoteness, mountain ranges are repositories of biological and cultural diversity that deliver a suite of services across multiple scales (e.g., Macchi, 2010; Altaweel et al., 2016; Foggin, 2016). Locally, mountain ecosystems prevent and mitigate natural hazards and provide diverse food and energy resources to dwellers. At the regional or national scale, mountains often have high cultural significance, and scenic landscapes and clean air make them target destinations for recreation and tourism. In addition, they are of global significance due to their key role in the water cycle, climate regulation, biodiversity protection, and carbon sequestration (e.g., Körner et al., 2005; Grêt-Regamey et al., 2012; Flury et al., 2013). The provision of these ecosystem services (ES) depends largely on land use and management, which itself is shaped by the long-established interactions of mountain populations with their environment. These tightly coupled mountain social-ecological systems (SESSs) have developed a high diversity of cultures, traditional ecological knowledge, and sustainable resource management practices that have persisted under sometimes extreme environmental and social conditions and that were adapted to the natural variability over time (Messerli, 1983; Ostrom, 2009; Rouncevell et al., 2012; Verburg et al., 2013).

In recent decades, however, economic globalization and climatic changes have impacted many of the sensitive mountain SESSs around the world and accelerated fundamental land-use and land-cover changes with far-reaching consequences for the provision of ES (Tovar et al., 2013). For example, agricultural intensification and cropping have decreased biodiversity and soil fertility, resulting in a loss of food production potential. Or, urbanization and changes in forest cover have altered the identity of mountain cultural landscapes and major biogeochemical cycles, with mostly negative effects on water availability and carbon storage capacity (Lambin et al., 2001; Schirpke et al., 2012; Westhoek et al., 2013). The topographic complexity and physical and political remoteness exacerbate the vulnerability of mountains and constrain opportunities for adaptation (Altaweel et al., 2016). A spatial analysis of past land cover across mountain ranges of the world demonstrates that changes in land cover were slow and similar in all mountain massifs between 1700 and 1900 but have accelerated and started to differ among mountain ranges since the mid- to late 1960s (Figure 1.1).

Agricultural lands, especially pastures, have decreased in the mountain regions of many industrialized countries (e.g., by approximately 10% in the Alps or the Iberian Peninsula; Figure 1.1a). Given the challenging conditions of climate and terrain, mountain agriculture has become less and less competitive, and rapid economic growth has pulled labor from the primary sector (MacDonald et al., 2000; Munroe et al., 2013). Traditional farming systems in these regions could only be retained due to considerable subsidies (Bender et al., 2011). The abandonment of marginal agricultural land has led to an expansion of forest, particularly marked in the Alps (Figure 1.1c), and caused a loss of cultural landscapes and related ES, including aesthetic, recreation, and habitat services (Bernerés et al., 2014). In less developed countries without institutions to provide technology, capital, or access to markets, farmers could not improve land productivity and have expanded the areas under cultivation to secure the livelihoods of a rapidly growing population, mainly at the cost of forests (Rudel et al., 2005), as evident in the Himalaya or the Andes (Figure 1.1a, b, c). In these regions, the loss of old-growth forests is related to a decrease in biodiversity and many ES, such as spiritual and regulation services (Saxena et al., 2003). Urban areas occupy less than 1.2% of the mountain land surface, so changes in urban land may therefore not appear to be key for the sustainability of mountain regions (Figure 1.1d). However, urbanization fragments mountain landscapes and threatens both habitat and aesthetic services (Lambin et al., 2001; Bender et al., 2011). Furthermore, the transformation of urban-rural linkages drives changes not only in ES supply, but also in the socio-economic and cultural structure of and demand for ES in mountain regions.

As the evidence and our knowledge of the consequences of global drivers, such as climatic changes, economic interconnectedness, population growth, and migration, for local mountain environments and human well-being increases, policy-makers and scholars are increasingly concerned about how to change the course of the observed development (Gurung et al., 2012). Accordingly, the attention given to mountains in policy debates and policy-making has increased significantly since the early 1990s, from the global to the national level (Price, 1998; Castelein, 2006; Balsiger and Debarbieux, 2015). In 1992, mountains achieved recognition in the global arena with the inclusion of a specific chapter in Agenda 21, the
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A plan of action for sustainable development endorsed by the United Nations (UN) at the Earth Summit in Rio de Janeiro, Brazil. Since then, mountains have been specifically considered in the UN Framework Convention on Climate Change, in the Convention on Biological Diversity, and in the Millennium Ecosystem Assessment, as well as through the designation of the year 2002 as the “International Year of Mountains”. At the European Union (EU) level, eight Alpine states and the European community ratified the Alpine Convention between 1991 and 1994, and at the same time, the Association of Elected Representatives from Mountain Areas was established. Currently, there is no single, sectorally and territorially integrated policy framework for Europe’s mountains. Instead, the EU legislative framework includes measures relating to agriculture, rural and regional development, and nature conservation, whereas numerous other relevant and interacting policy domains exist (Hazeu et al., 2010). Similarly, the majority of European countries address mountain development in a complex mixture of sectoral policies, although with differences in the degree of consolidation (Schuler et al., 2004). As an increasing amount of political and financial capital is invested in designing frameworks and instruments to deal with the socio-economic and environmental challenges associated with mountain development, diverse actors, including scholars, local communities, intergovernmental organizations, and EU policy-makers, have expressed the need to evaluate the impact of these strategies and interventions on the sustainability of mountain regions (Balsiger and Debarbieux, 2015; Gjøersen et al., 2016; Imperiale and Vanclay, 2016).

Policy-makers and managers striving for sustainable development, however, face considerable challenges. In mountains, as in all parts of the world, human and

Figure 1.1. Historical land-cover changes in mountain ranges of the world. (a) pasture area, (b) crop area, (c) forest area, (d) urban area. Note: The historical analysis of land-cover changes is based on linking the GTOPO30 global digital elevation model (USGS, 1996), used to characterize mountain ranges based on slope and elevation (Körner et al., 2005), with the HYDE historical land-cover data set at 0.5° x 0.5° resolution (Chini et al., 2014). The HYDE data show historical reconstructions of the percentage cover of urban, pasture, and crop areas, and primary and secondary lands (i.e., vegetation-covered lands undisturbed by human activities and disturbed by human activities but recovering, respectively), as well as on wood harvest based on a global land-use model (Furtel et al., 2006). Land cover shares in all grid cells located in mountain regions were analyzed in 50-year intervals between 1700 and 1950 and in 10-year intervals thereafter. The results of the spatial analysis were then aggregated for 10 of the most important mountain ranges in the world. Unproductive land, assumed to be constant over time, was not considered in the analysis.
environmental dimensions have become inextricably intertwined. The pathways in Figure 1.1 demonstrate that the effects of drivers increasingly depend on the place-based, social-ecological contexts in different mountain ranges. Therefore, uniform policies or generalized management strategies solely based on mountains’ biophysical conditions will no longer suffice. Rather, sustainable development needs to be addressed in a complex reality of interrelated social, economic, and ecological processes (Carpenter et al., 2009; Ostrom, 2009; Müller et al., 2010; Sohl et al., 2010). As the increasing pressures create more and more conflicts among competing land-use demands, stakeholders’ interests, and policy agendas at different scales, contradictory land management goals become evident and necessitate multiple trade-offs. Decision-makers thus need to continuously uncover differing perspectives and negotiate on what constitutes a sustainable and desirable development (Sayer et al., 2013).

Science that supports decision-making and addresses the complexity outlined previously requires an understanding of the interactions among social, economic, and ecological components in mountain systems and their dynamic changes over time and space (Gurung et al., 2012; Huber et al., 2013a). This suggests a demand for a new generation of social-ecological models that are able to capture the temporal and spatial dynamics of mountain SESs and that can be applied to specific contexts in real-world case studies (e.g., Cowling et al., 2008; Ash, 2010; Bateman et al., 2013; Maes et al., 2013; Verburg et al., 2015). However, unforeseeable shocks accompanying ongoing global change and the complexity of feedbacks shroud the future trajectory of SESs in uncertainty. Policy-makers and managers thus would benefit from making decisions that are robust and foster sustainable and desirable development under various potential circumstances. Therefore, science for decision-making has to account for the many uncertainties involved in the dynamics of SESs and include normative approaches that bring societal values into the evaluation and negotiation of sustainable development options (e.g., Ascough II et al., 2008; Polasky et al., 2011; Voinov et al., 2014; Martinez-Harms et al., 2015; Verburg et al., 2015).

Understanding these complex dynamics and the sustainability of mountain SESs and their services has become the core topic of several research cooperations, including the Mountain Research Initiative, the Ecosystem Services Partnership’s Biome Working Group on Polar Regions and High Mountains, the Mountain Sentinels, and the Mountain Partnership, as well as of journals such as Mountain Research and Development and Mountain Science. As a common mission, the initiatives envision a world in which policy-making, management, and governance at all scales conceive the social, environmental, and economic resources of mountain regions, unravel and negotiate trade-offs among these dimensions, and transform the trade-offs into widely shared responses to current pressures.

To realize this goal, research in mountain regions has to be advanced in three knowledge domains: (1) knowledge about what is (system knowledge), (2) knowledge about what should be (target knowledge), and (3) knowledge about how we come from where we are to where we should be (transformation knowledge).

1.2. Research challenges, gaps, and needs

The science of system, target, and transformation knowledge in mountain regions is evolving. However, many fundamental research challenges remain. These challenges are briefly outlined in the following paragraphs.

(1) System knowledge: Understanding the dynamics within mountain SESs

In the past decades, many scientific studies have investigated the dynamics of mountain environments at different scales, but for a long time the emphasis was mainly on the ecological system (Gurung et al., 2012). Obtaining a differentiated understanding of mountain ecosystems and their change in space and time was - and still is - crucial but not sufficient. It is equally important to enhance knowledge of how changes in mountain ecosystems influence humans living in and downstream of mountain regions through changes in ES and how societal values and human preferences shape and drive changes in the mountain ecosystems and their services (Körner et al., 2005).

With the emergence of conceptual frameworks on how to study human-nature interactions (Holling, 2001; MA, 2005; Folke, 2006; Ostrom, 2009), the body of literature that adopts an integrated systems approach to understanding the dynamics and processes within and between the social and ecological systems in mountain regions has been growing (e.g., Castella and Verburg, 2007; Bajracharya et al., 2010; Manfredi et al., 2010; Boone et al., 2011; Briner et al., 2012; Nolin, 2012; Huber et al., 2013a; Rammer and Seidl, 2015). These studies highlight the need for more inter- and transdisciplinary research that integrates different expertise and perspectives of stakeholders in coherent approaches. Furthermore, across all studies, modeling plays a key role in integrating
knowledge across disciplines, stakeholders, time, and scales for a better understanding of dynamics in mountain SESs.

Models, as simplified mechanistic representations of the structure and processes of the real world, can help obtain a better understanding of complex mountain SESs. However, validation of these models and data scarcity are key challenges in mountain regions: Models require data to drive them, but the data may be sparse or unavailable, low quality, or not spatially or temporally representative, problems particularly pronounced in mountains (Gurung et al., 2012). Furthermore, mountain systems change rapidly through local and global system feedbacks and will eventually reach tipping points in the social, ecological, or both systems, which is not easy to capture in models (Walker and Meyers, 2004; Schouten et al., 2009). That is, adequate representation and integration of causal processes, feedback effects, and cross-scale interactions in and between social and ecological parts of models remain a big challenge (Parker et al., 2008; Huber et al., 2013b).

In summary, to improve our understanding of mountain SES dynamics, there is a need for research approaches that coherently link methods from different disciplines and that apply process-oriented and calibrated models in both natural and social science domains (Rounsevell et al., 2012; Huber et al., 2013a; Verburg et al., 2015).

(2) Target knowledge: Setting development targets and evaluating system dynamics with regard to these targets

Many scientific studies have investigated the consequences of ongoing global changes for local mountain environments (e.g., Mottet et al., 2006; Huber et al., 2013b; Tvar et al., 2013; Munteanu et al., 2014) and demonstrated the pronounced vulnerability of mountain regions to these pressures (Grêt-Regamey et al., 2012; Haida et al., 2015). However, although the core business of scientists is to supply fundamental knowledge concerning natural and social processes, and their connections in SESs, policy-making and management processes may well benefit from scientific support for incorporating normative targets of future development (Bryson et al., 2010). The integration of normative approaches and explorative system analysis enables the investigation of both the outcomes that are most beneficial to society and the processes that might produce those outcomes (Brown et al., 2013). Targets may be derived from the analysis of ecological thresholds, existing policy goals and regulations, or participatory methods engaging different stakeholders (Iverson Nassauer and Corry, 2004; Grêt-Regamey and Brunner, 2011; Wiek and Iwaniec, 2014). Most of the studies analyzing SESs lack in formulating and considering visions of desired future outcomes and in interpreting predictions with regard to such targets (Rounsevell et al., 2012; Wolff et al., 2015).

The evaluation of system dynamics with regard to targets is complicated by the substantial uncertainties related to how global and local changes will evolve and affect SESs (Stürck et al., 2015). Such uncertainties in future drivers are poorly investigated in existing studies of mountain environments (Gurung et al., 2012). Scenario approaches have evolved as reliable methods of providing insight into a range of potential future changes of driving factors and their impact on ecosystems and their services (Rounsevell and Metzger, 2010). Scenario analyses are particularly helpful in illustrating emerging synergies or trade-offs among different ES of mountain regions (e.g., Schirpke et al., 2012; Briner et al., 2013) and in facilitating strategic conversations with stakeholders (Rounsevell et al., 2012). However, existing scenario approaches are mostly environmentally focused and barely integrate insights from studies on preferences in mountain landscapes (e.g., Hunziker et al., 2008; Lindemann-Matthies et al., 2010; Huber et al., 2011; Bieling, 2013). Furthermore, explicit quantifications and visualizations of uncertainty in global change projections for mountain regions are rare (Grêt-Regamey et al., 2013a). As extreme biophysical gradients within mountain landscapes create unique vulnerabilities to disturbance and provision of ES, it is crucial to assess the uncertainty of future global change impacts on mountain SESs in a spatial manner (Hou et al., 2014). The explicit consideration and communication of spatial uncertainties can support a spatial targeting of management and policy actions in a heterogeneous mountain environment given limited resources (Bateman et al., 2013; Briner et al., 2013; Stürck et al., 2015).

In summary, to make global change research more meaningful for supporting ES management and policy-making, an integration of positive and normative approaches is necessary. Such integrated approaches should project the impact of global change on local mountain environments and evaluate the impact with regard to a target, as well as inform on the inherent and spatially explicit uncertainties of these predictions accounting for uncertainties in ecological and social components of mountain systems (Grêt-Regamey et al., 2013b; Schägner et al., 2013; Schulp et al., 2014).

(3) Transformation knowledge: Identifying transformation towards sustainability
Current mountain research is mainly geared toward the first two knowledge domains. However, this research cannot yet offer major insights that would advise and empower mountain societies to adequately respond to global change, nor can it trigger sufficient innovation in this regard (Gurung et al., 2012). Consequently, calls for research that facilitates choices among a range of alternative policy and management options that stimulate public discussion on and induce transformation toward sustainable mountain futures have become more frequent in recent years (Rueff et al., 2015).

To identify potential transformations toward sustainability requires in a first step, as outlined previously, a negotiation on what constitutes a desirable, sustainable future and an evaluation of the distance to such a target to derive information on the current state and on the necessity of transformative actions (Moldan et al., 2012). Even though, at present, the term sustainability has become so widespread and well-known that we may take it as common sense1, when it comes to decision-oriented research the rather vague definition needs more precise specification (Hak et al., 2012). Recent literature defines sustainability as a normative vision that guides development in a constant process of uncovering and negotiating social, economic, and ecological perspectives and that necessitates multiple trade-offs (CDE, 2016). Thus, setting targets for sustainable development is a challenging task. The perspectives are not only numerous and contradictory, but they are also prone to change over time (Voinov et al., 2014). For example, in mountain landscapes, society’s demand for ES has changed and diversified over the past century (Vos and Meekes, 1999), and cultural ES such as recreation, cultural heritage, or aesthetics have gained in importance (Sayadi et al., 2009; van Zanten et al., 2014). These changes suggest that society needs to be involved in the discussion on and visioning of which properties and services, and ultimately which indicators, of ecosystems will be used to measure our progress and plan future actions (Hak et al., 2012).

In a second step, alternative development pathways describing necessary policy decisions and management actions to bring about the desirable future have to be explored (Rounsevell et al., 2012). The majority of current scenario approaches to tackle this question are limited in providing information detailed enough to identify critical pathways and infer explicit policy recommendations. They often tend to be static representations of the future and lack the necessary temporal resolution to adequately capture the different time frames of short-term policy and management decisions and longer-term environmental and socio-economic trends. Furthermore, they open the space of potential options but seldom narrow down the infinite spectrum of possible policy actions to a bandwidth of relevant and sustainable policy and management choices (Cash et al., 2006; Bryson et al., 2010; Rounsevell and Metzger, 2010). Developing strategies that mitigate global change effects and pave the way to a sustainable future requires novel methods that go beyond traditional scenario analysis and are tailored to policy contexts. The need for such approaches is particularly pronounced in mountain regions that, due to their marginality, complexity, and remoteness, often have less priority in national policy arenas (Maru et al., 2014; Rueff et al., 2015).

Ideally, these research processes should be aligned to real-world decision-making cycles and consider input from and discussions with practitioners throughout the entire process, from the identification of the problem and evaluation of alternative actions to negotiating choices and even monitoring the societal and ecological impacts of these choices (Voinov and Bousquet, 2010). Only then can real transformation knowledge be generated and policy and management changes on the ground be triggered (Hou et al., 2013). However, there are multiple obstacles to such transdisciplinary research processes (Lang et al., 2012). In mountain regions, particular challenges arise from smaller populations, and thus available stakeholders, a very high heterogeneity of opinions across stakeholders or a pronounced amount of general skepticism toward academic research (Kreutzmann, 2001; Huber and Rigling, 2014).

In summary, from a sustainability perspective, there appears to be an urgent need and scientific obligation to engage stakeholders and explicitly integrate their values in different stages of a research project to foster co-learning and co-management and to provide policymakers with feasible pathways for possible developments before the degradation and effects of global change become entirely irreversible in mountain landscapes (Huber et al., 2013b).

1.3. Major research questions

The overarching goal of this thesis is to advance the understanding of global change impacts in mountain regions using social-ecological modeling and to fuel the scientific and policy debate on whether and which

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1 The most frequently quoted definitions are from the World Conservation Strategy (IUCN et al., 1980) - “for development to be sustainable it must take account of social and ecological factors, as well as economic ones” - and the Brundtland Report (WCED, 1987) - “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.  

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interventions are needed to guarantee an envisioned level of mountain ES, given the uncertainty of future global change. The research gaps highlighted in Section 1.2 are addressed by three key research questions and were elaborated in three corresponding research articles. Each article, however, covers more than one knowledge domain to a varying degree. More specifically, this thesis addresses the following research questions:

(1) How can the integration of normative and explorative methods support our understanding of the future dynamics of mountain SESs?

The first research question was approached in research article I (Chapter 5), in which an integrative social-ecological modeling system was developed in an inter- and transdisciplinary research process and applied to a case study region in the Swiss Alps. The article addresses the need for innovative modeling approaches that coherently link methods from natural and social sciences calibrated to understand dynamics in real mountain case studies (system knowledge) while integrating normative social evaluation criteria (target knowledge). The article reveals relevant model sensitivities, discusses advantages and limitations of the modeling system, and illustrates its potential to explore interactions within SESs over time. In particular, it unravels the dynamic relationships among policy interventions, land use, and ES supply and demand in the mountain case study region.

(2) Which global and regional drivers are key sources of uncertainty in the future provision of demanded ES across the case study region?

The second research question was tackled in research article II (Chapter 6), in which uncertainties in the future provision of ES resulting from uncertainties in climatic and socio-economic driving forces and societal demand for ES were quantified and mapped. The article provides system and target knowledge by evaluating the spatial effects of regional and global changes on mountain SESs with regard to a desirable future while accounting for uncertainties in ecological and social system components. Results of the study offer insights into the magnitude and location of changes in ES caused by different drivers and highlight where management and policy-making have to deal with high levels of uncertainty to secure the provision of demanded ES.

(3) Which policy strategies foster a desirable development of the mountain region against a wide range of global presses and pulses?

The third research question was addressed in research article III (Chapter 7), in which the (mis)match between ES supply and demand was modeled in different scenarios of global change and given various potential sectoral and intersectoral policy strategies. The article specifically contributes to the generation of target and transformation knowledge by inferring policy recommendations that ensure desirable transition pathways of the mountain case study. The article identifies types and timing of interventions that help maintain regionally demanded ES and that are robust under the assumed global change scenarios.

1.4. Project embedment of the thesis
This doctoral thesis was embedded in the interdisciplinary European project Operational Potential of Ecosystem Research Applications (OPERAs; Box 1.1) as part of the European Union’s 7th Framework Programme and the transdisciplinary research project MOUNTLAND financed by the Competence Center Environment and Sustainability, an institution within the Eidgenössische Technische Hochschule (ETH) domain (Box 1.2). The

Box 1.1. OPERAs. OPERAs is a European research project, running from 2012 to 2017, and comprising scientists and practitioners from 28 different organizations, that are helping to put cutting-edge ecosystem science into practice. The OPERAs research infers whether, how, and under what conditions the concept of ES can move beyond the academic domain and toward practical implementation in support of sustainable management and policy strategies. OPERAs aims to improve the overall understanding of how ES contribute to human well-being in different SESs across various contexts, sectors, scales, and time. Based on an assessment of knowledge gaps and requirements for new policy options, improved or novel tools and instruments are developed and tested in practice in 12 exemplar case studies in Europe. Research in the exemplars explores, demonstrates, and validates mechanisms, instruments, and best practices that serve to maintain and enhance sustainable flows of ES. As an outcome, OPERAs will provide improved operational methods to quantify, map, value, and visualize ES and produce best practice guidelines to support policy and decision-making. Available resources and tools are brought together in a web-based portal that is co-developed by scientists and practitioners and that represents different interests and perspectives on the development, communication, and implementation of the ES concept (http://oppla.eu/).
rationales and objectives of these projects framed the research approach and questions of this doctoral thesis, and results were fed back into the projects to contribute to different work packages, goals, and iterative discussions. Being embedded in both projects offered various opportunities to exchange, discuss, and reflect on selected approaches, methods, and results. Furthermore, research conducted in this thesis was influenced by and could profit from experiences and expertise of the group Planning of Landscape and Urban Systems, which is part of ETH Zurich.

The OPERAs project provided a more conceptual frame to this thesis through its objectives to expand and exploit the operational potential of the ES concept and to address challenges in integrating the concept of ES into different instruments and in mainstreaming new and improved instruments. The MOUNTLAND project framed the thesis with regard to the methodology by its vision to follow a backcasting approach and by providing an existing land-use change modeling framework for further adaptations to the research context. In both projects, the consideration of transdisciplinary knowledge and the engagement with practitioners and society were crucial. Furthermore, both projects promoted the empirical testing of the developed method to derive policy and management strategies for a real case study. The case study region in the Swiss Alps served as 1 exemplar out of 12 exemplar case studies across Europe in OPERAs, and as 1 out of 3 mountain case studies in Switzerland in MOUNTLAND. Whereas MOUNTLAND was set up to derive insights into regional dynamics and solutions adapted to the Swiss national policy context, the European orientation of OPERAs encouraged a reflection of the results with regard to European mountain regions and policy recommendations in general.

1.5. Structure of the thesis
The remainder of the thesis is organized into three parts. The first part, consisting of Chapters 2 through 4, offers theoretical, methodological, and contextual background information relevant to the conducted analyses. Chapter 2 provides an introduction into the concept of ES, decision-making processes and decision-support modeling, and presents the conceptual framework of the thesis. In Chapter 3, methodological issues are discussed (i.e., the inter- and transdisciplinary development of the social-ecological modeling system is outlined and methods to analyze the supply of and demand for ES are evaluated). Chapter 4 describes relevant biophysical and socio-economic aspects of the mountain case study region, identifies major actors within the SES, and summarizes the relevant policy framework in Switzerland.

The second part of the thesis consists of three individual articles which address the specific research questions formulated in Section 1.3:  
• Chapter 5: A backcasting approach for matching regional ecosystem services supply and demand  
• Chapter 6: Mapping uncertainties in the future provision of ecosystem services in a mountain region in Switzerland  
• Chapter 7: Policy strategies to foster the resilience of mountain social-ecological systems under uncertain global change

The third part of the thesis (Chapter 8) summarizes the key findings of the articles, discusses cross-cutting issues that emerged throughout the analyses, outlines policy implications and the societal relevance of the thesis, and identifies the need for future research.

Box 1.2. MOUNTLAND. MOUNTLAND was a Swiss transdisciplinary research project that was conducted from 2012 to 2016 by scientists from three institutions across the ETH domain. The project explored management and policy strategies to promote and improve sustainable development in mountain regions. To infer such strategies, the vision of MOUNTLAND went beyond traditional scenario analysis by applying a backcasting approach that started from a defined vision and looked backward to predict future development. MOUNTLAND aimed to better understand land-use transition processes and their resilience to expected changes in mountains, provide a set of policy and management alternatives to achieve future desired states of ES given these changes, and empower stakeholders to actively participate in the elaboration of desired futures and the negotiation of development strategies. The project built on an existing research network in three mountain case studies in Switzerland and on a validated land-use change modeling framework, both of which were established in a forerunner project. Researchers in MOUNTLAND collaborated to refine the existing model framework to suit the backcasting context and project objectives. They also worked together to establish a structured inter- and transdisciplinary process that generated capacity and robust knowledge among stakeholders to enable them to better adapt to expected changes and transform their region toward a desirable future.
Probleme kann man niemals mit derselben Denkweise lösen, durch die sie entstanden sind.

Albert Einstein
2. Theoretical background

2.1. The concept of ecosystem services

2.1.1. Evolution of a concept

Over the past decades, ecosystem services (ES) have become an established concept for linking the natural environment to human well-being and for communicating the value of ecosystems to stakeholders (Farley, 2008). The interconnectedness of humans and the environment has been acknowledged for thousands of years, but only in the middle of the last century have we started to recognize the extent to which they are interrelated (Daily, 1997). As the knowledge of this relationship grew, so did the awareness of the importance of ecosystems to maintain and improve human well-being (Nahlik et al., 2012). In this context, the idea of ES was first raised in the late 1970s. It started with the utilitarian framing of beneficial ecosystem functions as “services” as a means to increase public interest in biodiversity conservation (Westman, 1977; Ehrlich and Ehrlich, 1981; De Groot, 1987; Gómez-Baggethun et al., 2010). In the following two decades the concept was discussed primarily in the scientific arena, in the 1980s in the sustainable development debate (WCED, 1987), and in the 1990s with an increased focus on methods to estimate the economic value of ES (Costanza et al., 1997). In 2005, the publication of the Millennium Ecosystem Assessment (MA, 2005) placed ES for the first time on the policy agenda (Gómez-Baggethun et al., 2010). Since then, the literature on ES has grown exponentially (Fisher et al., 2009) and different slightly nuanced definitions of the concept have evolved (Braat and de Groot, 2012). In this thesis, I will stick to The Economics of Ecosystems and Biodiversity (TEEB) study which, as a follow-up of the Millennium Ecosystem Assessment, provided an in-depth insight into the economic significance of ecosystems and which defined ES as the “direct and indirect contributions of ecosystems to human well-being” (TEEB, 2010).

In recent years, the ES concept has firmly transcended the academic arena and been adopted in several high-level policy frameworks (Schleyer et al., 2015). In particular, the global strategic plan for biodiversity for the period 2011-2020 of the Convention of Biological Diversity complements the previous, conservation-based biodiversity targets with the addition of ES (Maes et al., 2013). Following the global agreement, the EU has taken up ES as a complement to the conservation approach into their Biodiversity Strategy to 2020 (EU, 2011). In addition, other policy sectors in the EU have begun to integrate the ES concept into their programs. For example, the new proposal for the EU’s Common Agriculture Policy identifies “restoring and preserving ES” as one of the six priorities for rural development (EU, 2013). Obligated by the EU Biodiversity Strategy, member states of the EU are currently assessing and mapping ES in their national territory to include them in their accounting systems by 2020. These assessments and the design, implementation and management of new ES-based policies require reliable frameworks and methods to estimate the current state of and future trends in ES provision (Maes et al., 2012).

2.1.2. The development of a framework

The social and ecological factors, and their interactions, that create and alter ES are inherently complex (Carpenter et al., 2009; Scholes et al., 2013). Measuring and managing ES therefore requires a sophisticated system-based approach that accounts for how these services are generated by interconnected social-ecological systems (SESs), how these services interact with each other, how changes in the services influence human well-being, and how changes in human well-being feedback and affect the generation of ES (Reyers et al., 2013). In the various publications on ES, several frameworks have evolved to conceptually and visually describe the links between ecosystems, their services and human well-being (Nahlik et al., 2012; Bennett et al., 2015). Initially suggested frameworks, e.g., from the Millennium Ecosystem Assessment (MA, 2003), or the so called ‘cascade model’ by Haines-Young and Potschin (2010) described unidirectional flow of services from the ecosystem to the human, socio-economic domain of a system and helped systematize and organize ES. Later on, they were extended to include feedbacks and impacts from management and policy decisions on the ecosystem in order to mainstream ES into the social arena (e.g., Cowling et al., 2008; Turner and Daily, 2008; TEEB, 2010; Wainger and Mazzotta, 2011; van Oudenhoven et al., 2012). While each framework has its own specific objectives, they all highlight the fact that per definition ES only exist when there is a demand or use by stakeholders (Paetzold et al., 2010; Villa et al., 2014; Geijzendorffer et al., 2015).

To answer the research questions in this thesis, I have developed a framework based on three existing policy-relevant frameworks describing ES provision in SESs (Ostrom, 2009; TEEB, 2010; van Oudenhoven et al., 2012; Figure 2.1). The framework conceptualizes the environment as an open system consisting of ecological and social processes which are linked through ES and interactions such as resource use, management practices and policy-making (Virapongse et al., 2016). These processes act as direct drivers of ES dynamics and...
are separated in the framework through the boundary of the SES from indirect drivers, which represent broader scale forces that influence the system (Rounsevell et al., 2010). Within the SES, ES flow from the ecological part, the ecosystem, on the left to the social part on the right side. ES benefits denote the gain in human well-being through delivered ES, which depends on the value people give to different services (van Oudenhoven et al., 2012). While value perception can alter ES benefits through increasing or decreasing demand for a service, it can also serve as a normative frame inducing changes in policy-and decision-making. Finally, policy-making, as well as indirect drivers such as population growth or changes in the economy act upon land use and management, which then, in combination with climatic changes, alter the ecosystem and the services they provide.

The framework in this thesis is anchored in economic theory based on the assumption that ES benefits capture the contribution of ES to human well-being and arise from preferences of people (Polasky and Segerson, 2009). While multiple non-commensurable value dimensions for ES co-exist, commonly divided into biophysical, socio-cultural and economic dimensions (e.g., de Groot et al., 2002; Farber et al., 2002; Martínez et al., 2013), I chose the latter one, as it is considered to be particularly relevant to policy-making (Fisher et al., 2008; Polasky and Segerson, 2009; TEEB, 2010; Bateman et al., 2011). Especially, the economic language is perceived as a powerful persuasive means of communicating the importance of what nature provides us, and of measures to protect it, to a wider audience (Atkinson et al., 2012). However, the selection of one value domain in an ES framework constrains and ultimately defines the value attached to the services. Ideally all three value domains should be integrated into decision-making processes (Tallis and Polasky, 2009; de Groot et al., 2010b). Comprehensive frameworks that draw upon the complementary perspectives are currently being developed (Martín-López et al., 2014), but such an all-encompassing valuation is beyond the scope of this thesis. In the next paragraph, I therefore lay out the assumptions underlying the economic value perspective as a frame in which the results of this thesis should be understood and discussed.

2.1.3. Economic valuation of ecosystem services
Economic approaches to value ES aim at making explicit to society in general, and policy-making in particular, that the degradation or depreciation of ES has associated costs to society (Fisher et al., 2008). If these costs are not accounted for in decision-making, society might be worse off due to a misallocation of resources (TEEB, 2010). In this context, economic valuation of ES can help in determining whether an intervention that alters an ecosystem delivers net benefits to society, in prioritizing funding, in choosing between competing land uses or in communicating the value of the environment to society (Liu et al., 2010). Accordingly, economic assessments of ES are usually applied in the context of policy evaluation measuring net benefits of ES across alternative policy options (Braat and de Groot, 2012; Kumar et al., 2013).

![Figure 2.1. Framework used for addressing the research questions in this thesis, based on van Oudenhoven et al. (2012), MA (2005) and Ostrom (2009).](image)
Ecosystems and their services have economic value for society because they contribute to human well-being. This is because people derive utility from their actual or potential use and, also, because they value services for reasons not connected with use, such as altruistic, bequest, and stewardship motivations (Hein et al., 2006). Thus, while an economic approach is always anthropocentric and limited to capturing the value of ES to human well-being (Farber et al., 2002), it is important to note that this value may include preferences individuals or groups of people have that relate to the well-being of animals, plants or the pure knowledge that their natural environment is maintained. These individual or shared values are not perfectly or even partially reflected in market prices, although there is a widespread misconception that these prices equal the economic value of a service (Bateman et al., 2011). As this is only true under a set of fairly restrictive assumptions, eliciting economic values requires the application of advanced valuation techniques, which are discussed in more detail in Section 3.3.

The economic value of an ES is a reflection of what people are willing to trade off to conserve the service (TEEB, 2010). The underlying hypothesis is that people make decisions in order to optimize their utility, which always takes place in the presence of constraints such as income, time, wealth or resource supply (Farber et al., 2002). Consequently, values of ES are mirrored in people’s willingness to pay to attain them or in their willingness to accept compensation to forego them (Bateman et al., 2011). It is important to note that in neo-classical economics the concept of change is fundamental to defining values. That is, economic valuation attempts to elicit public preferences for changes in the state of an ecosystem from a baseline to an alternative rather than valuing an entire system (Polasky and Segerson, 2009). Valuing an entire ecosystem as done for example in the seminal study by Costanza et al. (1997) can be consistent with an economic approach if it compares human well-being with and without the ecosystem. However, usually, eliminating the ecosystem is neither a policy-relevant change, nor a sensible comparison (Toman, 1998; Daily, 2000; Bateman et al., 2011).

There are several assumptions underlying economic valuation which constrain its application and challenge valuation methods. Economic valuation assumes that individuals are rational, have well-defined preferences and can best judge what is in their interest. It also presupposes that people’s preferences are valid regardless of how they are viewed by others or of moral obligations (Polasky and Segerson, 2009). However, the public may not fully understand the contributions of ecosystems nor have consistent preferences. Therefore, providing adequate information on ES benefits prior to a valuation task is crucial (Bateman et al., 2011). At the same time, preferences of people depend greatly on the ecological and socio-economic context in which valuation takes place (Pearce, 1998). Therefore, estimates of economic value only reflect the current choice pattern given a multitude of conditions such as the distribution of wealth, the state of the natural environment or expectations about the future (Barbier et al., 2009). Economic values should therefore always be discussed in relation to these boundary conditions, and both assessing long-term dynamics within values and upscaling these values remain highly challenging tasks (Farber et al., 2002; Kumar et al., 2013).

One of the most complex contextual aspects of economic values is that the stock that produces the ES may affect the value of changes in ES (Bateman et al., 2011). Usually, where stocks are abundant, marginal values remain more or less constant with respect to changes in stocks (TEEB, 2010). However, if the stock decreases and the level of the services declines and approaches a threshold beyond which they cannot be provided any longer, marginal values begin to rise steeply. Hence, over this range of service provision the use of constant marginal values to assess changes in ES could result in large valuation errors (Farley, 2008). The uncertainty related to where these thresholds lie and when in time they might be crossed makes it difficult to determine when marginal analysis ceases to be appropriate (Farley, 2012). Another problem when approaching thresholds is the inherent assumption of substitutability between ES, which underlies the economic approach. Even the economic concept of the existence value of species is not defined in terms of an intrinsic right to exist, but rather in terms of the amount of other ES that an individual is willing to give up to ensure its existence (Polasky and Segerson, 2009). Such an approach might be legitimate if these species are abundant, but again, hardly applicable if critical thresholds for minimum viable populations are passed (Fisher et al., 2008).

In summary, economic values are anthropocentric, contextual and time specific and should thus be assessed and used spatially and temporally explicit at scales meaningful for policy processes (Braat and de Groot, 2012). In such a clearly outlined setting, they can provide useful information about the effect of alternative policy actions on human well-being, especially with regard to localized impacts that are fairly well known and far from ecological thresholds (Kumar et al., 2013). Ideally,
however, economic valuation approaches should be used
to complement, but not substitute ethical or scientific
arguments relating to policy and conservation actions
(Turner and Daily, 2008).

2.2. Environmental decision-making

Calls for operational methods and instruments linking
conceptual scientific understanding of SESs and ES
to practice are widespread (Daily et al., 2009; Ash,
2010; Goldstein et al., 2012). The question how to best
operationalize ES remains elusive (Primmer and Furman,
2012) and large international research projects have
been launched to tackle this challenge, for example
OpenNESS, OPERAs, or GreenSurge, all under the
umbrella of the EU 7th Framework Programme for
Research and Technological Development (see e.g. Box
1.1). Several authors recommend that ES research should
address the various stages in decision-making, from
problem identification to policy evaluation and capacity
building and highlight the need for participatory and
transdisciplinary research processes (Cowling et al., 2008;
Turner and Daily, 2008; de Groot et al., 2010b; Martinez-
Harms et al., 2015). The following paragraphs give a
short overview of the different phases of environmental
decision-making processes and involved uncertainties as
a basis to introduce social-ecological models as decision-
support tools in Section 2.3.

2.2.1. The policy cycle

Environmental decision-making is extremely complex
and context-dependent, but includes some core steps
that can be usefully applied to nearly any environmental
planning, management or policy decision (Gregory et al.,
2012b). Figure 2.2 shows a schematic of an environmental
policy cycle in three main phases based on suggestions by
Martinez-Harms et al. (2015) and Ascough II et al. (2008).

The problem structuring phase involves defining the
environmental problem and outlining the social-
ecological context in which a decision is embedded.
A comprehensive evaluation of the social-ecological
context includes the identification of stakeholder
preferences, for example for different ES, the appraisal
of broader political and governance regimes and the
recognition of access to capital and labor. Furthermore,
objectives relating to the aspired outcomes have to be
set and performance measures have to be derived. These
measures serve as metrics to evaluate and report how
well alternative courses of actions perform. Ideally, many
different stakeholders are involved during the first phase
of the policy cycle (Martinez-Harms et al., 2015).

Once the problem has been firmly elaborated, a list
of potential solutions has to be generated. Usually,
alternative actions need to be created rather than
discovered and be iteratively compared and refined. They
should represent real, practicable and context-specific
choices and be robust to key uncertainties that are likely
to impact the SES over time (see Section 2.2.2; Gregory
et al., 2012b). Analytical methods, e.g., integrated social-
ecological models, serve as useful means to estimate the
consequences of the alternatives on the performance
measures. This task is undertaken by experts, usually a
combination of scientists from different disciplines and
local knowledge holders. The performance outcomes
then need to be compared, visualized and - depending
on the number of generated alternatives - be broken
down to a feasible subset of potential candidate options
(Ascough II et al., 2008).

The third phase starts with the selection of a preferred
alternative. As usually there will be a number of competing
objectives, this choice involves trade-offs and negotiation
processes among stakeholders. Decision-support tools
are a valuable means to help guide such processes (see
Section 2.3). Once an action is selected, it needs to be
implemented through internalization in policy, plans
or management strategies. An ideal decision process
should then include careful evaluation and reassessment
of the implemented alternative to promote learning and
build capacity to make better decisions in future (Polasky
et al., 2011a).
2.2.2. Decision-making under uncertainty

Global climatic and socio-economic changes, including rising connectedness of regions and markets and increased mobility of people, make regional management and policy-decisions and their outcomes increasingly dependent on such larger scale factors (Young et al., 2006). The uncertainty related to global change is large, due to the complexity of cross-scale effects, the rapid rate of change and the lack of a historical analog. Consequently, decision-making has to deal with an ever growing amount of uncertainty (Polasky et al., 2011a). I do not attempt to provide an encompassing typology of different uncertainties (see e.g., Burgman, 2005; Gregory et al., 2012a), but concentrate on outlining in which phases of the policy cycle the consideration of uncertainties is most critical (Figure 2.2).

Although often ignored, uncertainty should be considered already when identifying objectives in the problem structuring phase. The space of desired future states should be imagined as broad as possible and go beyond what is currently considered probable (Sutherland and Woodroof, 2009; Wintle et al., 2010). Such a freeing of constraints provides a flexible enough starting point for developing a set of strategies that might be robust against future uncertain changes (Grêt-Regamey and Brunner, 2011). Furthermore, analyses that take a broad view of the space of plausible outcomes can generate a richer understanding of complex system dynamics, a more accurate and comprehensive assessment of uncertainties and deeper insights into potential threats to human well-being (Biggs et al., 2009).

In the second phase, as stated above, the consideration of uncertainties in global change and SES dynamics can help find strategies that are robust or likely to reduce uncertainties over time. Dependent on the project goals, timeline and resources, attempts to reduce uncertainty may include collecting additional information, advancing predictive modeling tools, or eliciting judgments about the range of potential outcomes from experts (Gregory et al., 2012b). When using social-ecological models to evaluate different alternatives (see Section 2.3), the model itself is often a key source of uncertainty as it is only one plausible and often highly simplified representation of the system (Ascough II et al., 2008). Therefore, two aspects are crucial when evaluating potential solutions: Firstly, guidance to decision-makers should rely on a broad set of alternatives, data and models (Polasky et al., 2011a). Such an approach might not result in an accurate prediction of the future, however, it can unravel major vulnerabilities in the system, which helps prioritize effective and robust actions (Sarewitz, 2010). Secondly, an honest and accurate representation and communication of uncertainty related to both methods and results is essential (Gregory et al., 2012b).

However, even if uncertainties of alternatives are outlined well, decision-making based on unclear outcomes remains difficult. A formal commitment to review the decision when new information is available and the development of a flexible frame for implementing strategies can be key to agreeing on a course of action and furthermore foster social learning over time (Grêt-Regamey and Brunner, 2011).

2.3. Model-based decision support

Models of SESs are simplified mechanistic representations of the structure and processes of the real world (Schlüter et al., 2014). As such, they can serve a number of purposes that might provide information relevant to decision-making processes (de Groot et al., 2010b; Rounsevell et al., 2012; Crossman et al., 2013; Schüttler et al., 2014; Turner et al., 2016). For example, they allow to obtain a better understanding of complex SESs and to explore the response of the system to global and regional drivers and perturbations (system knowledge). They can be used to explore decision spaces and to assess decision robustness to uncertain future settings with regard to a normative vision (target knowledge). Or, they potentially support a productive dialogue between stakeholders about future policy and management strategies and suitable development pathways (transformation knowledge). While a variety of techniques and methods to model SESs and criteria to categorize them exist (see Section 3.4 and reviews by Schaldach and Priess, 2008; Kelly et al., 2013; Verburg et al., 2015), at a very fundamental level, they can be distinguished into two main categories – explorative approaches and goal-oriented normative approaches (McIntosh et al., 2006; Rounsevell et al., 2012), which are briefly introduced in the context of ES research in the following paragraphs.

2.3.1. Explorative: forecasting

The majority of existing integrated social-ecological modeling studies use forecasting approaches to develop a mechanistic understanding of processes in SESs and to predict future ES provision given changes in different drivers (e.g., Nelson and Daily, 2010; Polasky et al., 2011b; Bagstad et al., 2013c; Briner et al., 2013a; Schirpke et al., 2016). While simple trend extrapolation is very limited to forecast complex and uncertain system behavior assuming a continuous path of social, ecological and technical development from the past towards the future, scenario studies provide insight into the range and uncertainty of future ES changes (Rounsevell et
al., 2012; Grêt-Regamey et al., 2013a; Figure 2.3). They organize complex information into coherent storylines to help people conceptualize the future and provide useful information to guide policy development and land management (Metzger et al., 2010; Polasky et al., 2011a). Foresight scenario analyses are particularly helpful to illustrate emerging synergies and trade-offs among ES (e.g., Nelson et al., 2009; Schirpke et al., 2012; Reed et al., 2013) and between economic development and ES (Metzger et al., 2006; Goldstein et al., 2012). They, however, have several constraints: Firstly, our ability to predict the future is strongly limited. There is fundamental uncertainty about future events resulting from the lack of knowledge about system conditions, underlying dynamics, potential innovations and the intentional nature of human decision-making. Thus, our ability to predict the likelihood of alternative outcomes for complex systems is seriously comprised (Dreborg, 1996). Secondly, the most plausible futures may not be the most feasible ones and exploring the desirability of alternative futures may be more important than their coherence (Robinson, 2003). Finally, scenarios usually describe the state of a system at a fixed future point in time and are of limited value for analyzing the dynamic response of a system to alternative policy options (Rounsevell and Metzger, 2010). In particular, the time horizon of scenarios seldom matches the short-term nature of policy cycles that affect actions of decision-makers (Bryson et al., 2010). Thus, forecasting scenarios often fail to provide clear information on how specific policy alternatives will influence future ES provision and how this provision relates to policy or sustainability goals.

### 2.3.2. Normative: backcasting

Backcasting has been proposed as a complementary approach to forecasting. Backcasting starts from a future normative vision, then looks back to identify how this desirable future could be achieved and proceeds to define robust follow-up activities, strategies and pathways leading to the desired future state (Robinson, 1982; Figure 2.3). Hence, the focus is shifted away from predicting plausible future developments to inferring possible solutions to current and future problems based on predefined desirability criteria and goals (Robinson, 1982; Robert, 2005; Höjer et al., 2011). Backcasting focuses on determining the freedom of policy action with respect to desirable futures rather than on evaluating policy implications along a certain path or trend (Wilson et al., 2006). Backcasting methods are especially valuable for strategic planning, for example in the fields of sustainability (e.g., Dreborg, 1996; Holmberg, 2000), transportation (e.g., Robert, 2005; Mattila, 2011), conservation (Gordon, 2015) or spatial development (Haslauer, 2015). Furthermore, they can integrate stakeholders in local sustainability planning and the development of policy and management strategies (e.g., Carlsson-Kanyama et al., 2008; Höjer et al., 2011; Kok et al., 2011; Quist et al., 2011; Berkel and Verburg, 2012). One drawback of backcasting is that it does often not sufficiently account for global change processes that influence regional scale system dynamics (Kok et al., 2011). Forecasting scenarios can, however, be used to include such processes. Thus, an integrated perspective can profit from the complementarities of the two approaches.

![Figure 2.3](image_url) **Figure 2.3.** Forecasting and backcasting perspectives: in forecasting the focus is on diverging towards different exploratory futures, in backcasting the focus is on converging to identify robust elements for ensuring desired transformation pathways (adapted from Kok et al., 2011).
A combination of normative visions with explorative modeling approaches based on a thorough understanding of system functioning could help identify leverage points, problems and barriers to achieving such a vision in light of the unprecedented global change (Verburg et al., 2015). Although pleas have been made to use models in such ways (Rounsevell et al., 2012; Brown et al., 2013), very few actual examples are available in literature (Castella et al., 2007; Seppelt et al., 2013; van Berkel and Verburg, 2014).

2.3.3. Requirements for decision-support systems
In order to enable clear communication and effective decisions in real-world case studies, social-ecological models are increasingly embedded into decision-support systems (Klein et al., 2015). Decision-support systems are computerized systems that provide a user friendly platform for entering input, viewing output and analyzing results to support group or individual decision-making (van Delden et al., 2011). They assist in the interpretation of scientific results with regard to policy-relevant questions and in the comparative assessment and selection of options to change (McIntosh et al., 2006; Volk et al., 2010; McIntosh et al., 2011; van Delden et al., 2011; Sojda et al., 2012; Bagstad et al., 2013b). These studies emphasize three major points crucial for a successful application of these tools: (1) Understanding user needs and ensuring legitimacy. Ascertaining user needs and eliciting policy-makers’ perceptions, experiences and expectations is one of the key issues in building a good decision-support system. They should be tailored to the actual decision problem and be clear in the purpose they serve and the context in which it is applied. (2) Working collaboratively. It is important for tool developers to understand the process of a decision and to engage with those in charge of it. Expertise should be built up collaboratively through dialogue between interested parties and this learning process may finally be as significant as the software. Ideally, stakeholders would get the opportunity to contribute to and challenge model assumptions. (3) Establishing and maintaining credibility and trust. It is vital, however, often very challenging that decision-support tools build both social and scientific credibility. In any decision-making process some of the actors need to be convinced of the benefits of using the tools. To be scientifically credible, tools should be transparent, validated and peer-reviewed. To be socially credible, developers must establish trust with end-users, the tool should adequately reflect local circumstances and underlying assumptions need to be disclosed. Both scientific and social credibility furthermore depend upon an open characterization and communication of uncertainties in both the structure of the tool and the results it generates.

In addition, to ensure user satisfaction and high usability of a decision-support system, many technical and design issues need to be considered (Klein et al., 2016). Technical components, e.g., server performance and browser compatibility, and design components, e.g., the graphical user interface and layout, can improve the accessibility and applicability of the actual information (Lauesen, 2005). A well-adjusted combination of these components enhances interactivity through smooth navigation and control of the provided information. A final challenge lies in the definition of criteria to evaluate the success of a decision-support system. Whilst success can be framed relatively easily in terms of interactions with end users, difficulties of measurability emerge in relation to the extent to which these systems achieve intended outcomes (e.g., generate transformation knowledge; McIntosh et al., 2011).
3. Methodology

The following sub-sections provide a short overview on challenges associated with the setup and application of coupled social-ecological models in general and the inter- and transdisciplinary development of the modeling system used in this thesis. The different methods which were linked to operationalize the theoretical framework (Figure 2.1) are described and their advantages and caveats are briefly discussed.

3.1. Coupled social-ecological models of ecosystem services provision

An appropriate addressing of the research questions in this thesis required a coupled social-ecological model that integrates both the supply and demand side of ES as well as related drivers at different scales. The development of social-ecological models, however, poses a number of challenges (Schaldach and Priess, 2008; Bennett et al., 2013; Brown et al., 2013; Giupponi et al., 2013; Kelly et al., 2013; Verburg et al., 2015): (1) A social-ecological model has to integrate knowledge of a variety of variables and their relationships and requires data on both social and ecological processes. This knowledge is scattered across many disciplines and data need to be collected with different methods, techniques and disciplinary epistemologies. (2) There is a trade-off between highly complex models that represent the dynamics in system components very well, but are often limited in their applicability to support policy processes, and models of reduced complexity which are tailored to support policy decisions, but often assume simple, hierarchical flow of information between model components. (3) The integrated social and ecological parts of the model may not employ a single spatial or temporal scale or resolution and cross-scale processes and feedbacks between these parts are highly difficult to represent. For example, ecological processes may happen at a time scale of several decades, while policy-making operates in cycles of a few years. Or, effects of climate change might be similar across ecosystems of the same type, but the response of affected communities is highly dependent on socio-cultural settings. (4) In addition, these dynamics involve major uncertainties from the global scale, e.g., related to the development of climate or global trade, to the local scale, e.g., related to how individual stakeholders behave given the effects of such global phenomena. (5) As a result, validation of social-ecological models is an extremely complex challenge.

As the concept of ES gained momentum in the last two decades (Section 2.1), various methods to model ES supply and to assess ES demand have been developed. The abundance of these methods enabled to focus the work in this thesis on a coherent coupling of existing methods from different disciplines rather than on the design of an entirely novel integral social-ecological model, and on its adaptation to a particular case study region (Voinov and Shugart, 2013; Hamilton et al., 2015). An embedding of several methods in a social-ecological model called for a proper conceptual and technical harmonization of the interface between different methods. Furthermore, the development of the modelling system had to deal with the above outlined challenges and thus required: (1) interdisciplinary research processes (Schlüter et al., 2014), (2) a choice of methods that are appropriate for the particular use and purpose of the integrative model (Brown et al., 2013; Kelly et al., 2013), (3) an integration of larger scale processes, e.g., climatic changes, and smaller scale factors, e.g., political boundary conditions or values of relevant actors (Giupponi et al., 2013; Verburg et al., 2015), (4) an evaluation and communication of the various involved uncertainties (Refsgaard et al., 2007; Scholes et al., 2013; Uusitalo et al., 2015), and, (5) a validation of the individual model components and an evaluation of the integrated model in light of the model objectives (Jakeman et al., 2006).

In the last decades, different coupled models have been developed for simulating ES provision into the future (for reviews see e.g., Nelson and Daily, 2010; Vigerstol and Aukema, 2011; Bagstad et al., 2013c). In these models, demand for ES is commonly estimated based on statistical regressions between land use and socio-economic factors as for example in InVEST (Nelson et al., 2009), exogenously by data on demographic and economic trends, as for example in IMAGE (Knight, 2000), or more sophisticatedly by identifying values of different ES beneficiaries with the help of consumption data as in ARIES (Villa et al., 2009). As a consequence, these models rely on data extrapolation to represent future demand for ES and are not tailored to integrate normative visions of stakeholders. Furthermore, they are often either suited to simulate the functioning of specific systems (system knowledge) or to address management and policy questions (target knowledge), but seldom allow for providing knowledge into all three knowledge domains (Kelly et al., 2013; Verburg et al., 2015). In this thesis, I provide a novel linking of methods and models, which is necessary to address the requirements of backcasting (see Section 2.3) and which enables generating knowledge of different types. To ensure a consistent integration of different methods I based my modelling system on a welfare economic foundation. Welfare economic theory
investigates the interaction between supply of and demand for goods and services to achieve an optimal allocation of resources that maximizes human well-being (Freeman III et al., 2014). It is increasingly used as an analytical framework for a systematic, concise and policy-relevant assessment of ES supply and demand and helpful for linking explorative and normative analysis of ES (Polasky and Segerson, 2009; Cavender-Bares et al., 2015).

Figure 3.1 illustrates how the theoretical framework (Figure 2.1) was operationalized and which methods were linked in the integrated modelling system BackES that has been developed during this thesis. The project started with a stakeholder workshop to define regionally relevant ES and to elicit concerns of local experts regarding their future provision (Section 3.2). Following the idea of backcasting, in a second step, future demand for these ES was assessed as a normative vision with a discrete choice experiment involving local residents (Section 3.3). An economic agent-based land-use model was then applied to simulate land-use changes and the corresponding changes in the supply of ES under different scenarios of global and regional change and implementing a variety of potential policy strategies (Section 3.4). These methods were linked in a forth step via a utility function to assess ES benefits (Section 3.5). Finally, in a second workshop, the suitability of the modelling system to support decision-making processes and to serve the aspired purposes was investigated (Section 3.6). Many aspects of the modelling system are described in detail in Section 5. The next paragraphs include supplementary information and outline advantages, caveats and underlying assumptions of the selected methods.

3.2. Stakeholder workshop 1

Both workshops were planned, organized and run by an interdisciplinary research team. The first workshop was held in Visp (see Figure 4.1) with fifteen representatives from forestry, agriculture, regional development, nature conservation and local policy in April 2013. The main goals of the workshop were to inform the participants on past and planned research activities, to discuss their concerns regarding the development of the case study region and to reflect on regionally relevant ES and their future provision.

In a first part, we explained and debated on results from a prior phase of the MOUNTLAND project (see Box 1.2). In a second phase, we organized a World Café, a conversational process that helps groups engage in a constructive dialogue around critical questions, to
build personal relationships, and to foster collaborative learning (e.g., Brown, 2002; Schieffer et al., 2004). In relation to other collaborative approaches, the World Café is powerful in the cross-pollination of ideas through evolving rounds of information exchange. Furthermore, the use of a café-style social context allows sharing of information in an equitable and non-threatening manner. Participants move between a series of tables where they discuss a set of questions in a café-like ambience. Our World Café was set up with three tables each corresponding to one of the three main land-use types in the region: agriculture, forest and settlement (Figure 3.2). At each table there was a poster with different characteristic attributes of the respective land use. Participants, split into three groups, moved between the tables where they were each time asked the same two questions: (1) Which maximum or minimum levels of an attribute would you still tolerate in 2030 (for settlement and agriculture) or 2050 (for forest, on a scale between 0% and 100% increase or decrease)? (2) How important is an attribute for the future development of the case study (on a scale between 0 and 10)? Each participant could pin a point on a poster to manifest his/her opinion while justifying the choice in a few words so that when people changed tables, they could see what previous members had expressed in their own words and images (Figure 3.3). The motivation and thoughts of the different people offered an insight into the most valued ES in the landscape and the link between landscape attributes and ES. In a final plenum discussion, the most critical land-use changes and threatened services were determined. The workshop thus helped select the final set of ES included
Background

experiments, are applicable to all kinds of ES and are typically the only option for estimating non-use values. These methods attempt to construct pseudo markets via surveys and derive the value for ES from people’s responses to hypothetical questions. The hypothetical nature of the market and their non-binding character is, however, a major drawback of these methods, which has raised many discussions regarding the validity of the estimates (Pascual et al., 2010; Atkinson et al., 2012; Turner et al., 2016).

Since the importance of (non-marketable) cultural ES and non-use values was highlighted by most of the stakeholders during the first workshop (Section 3.2), I chose a stated preference method to assess ES demand. Choice experiments have been applied in numerous studies to derive public preferences for alternative states of a set of ES (e.g., Adamowicz et al., 1994; Hasund et al., 2010; Huber et al., 2011; Bateman et al., 2013; Shoyama et al., 2013; Ryffel et al., 2014). In ES choice experiments, individuals are typically presented with several choice sets representing hypothetical scenarios of a number of ES (so called attributes) in a landscape. Each of these attributes has a number of varying levels, one of which typically represents the status quo. In each choice task, respondents are asked to indicate their preferred option in each set. The attribute levels in the choice sets are varied to allow the scientist to infer trade-off relations between ES and marginal willingness-to-pay for changes in attribute levels (Moran et al., 2007).

In the context of this study, choice experiments offer several advantages relative to other stated preference methods (Hanley et al., 1998; Fisher et al., 2008; Huber, 2011; Bateman et al., 2013; Shoyama et al., 2013; Ryffel et al., 2014). In ES choice experiments, individuals are typically presented with several choice sets representing hypothetical scenarios of a number of ES (so called attributes) in a landscape. Each of these attributes has a number of varying levels, one of which typically represents the status quo. In each choice task, respondents are asked to indicate their preferred option in each set. The attribute levels in the choice sets are varied to allow the scientist to infer trade-off relations between ES and marginal willingness-to-pay for changes in attribute levels (Moran et al., 2007).

3.3. Ecosystem services demand: choice experiment
To assess ES demand in terms of their economic value (Section 2.1.3), a range of valuation techniques have been developed and increasingly refined (comprehensive reviews are provided e.g. by Barbier et al., 2009; Pascual et al., 2010). These methods are commonly categorized into three main types: (1) direct market valuation, (2) revealed preference and (3) stated preference methods. Direct market valuation approaches use data from actual markets, e.g., commodity prices (as in market price-based approaches) or the costs incurred by replacing an ES with artificial technologies (as in the replacement cost method). The main advantages of these approaches are that data are relatively easy to obtain and reflect actual preferences of or costs to individuals. In the absence of such information, revealed preference methods infer price information based on proxies, either from parallel market transactions that are associated indirectly with the service to be valued (as in the case of the hedonic pricing method), or on observed consumed behavior of such proxies (as in the travel cost method). These approaches are expensive and time-consuming as they need large data sets and complex statistical analyses. In both direct market and revealed preferences methods, market imperfections and policy failures can distort the estimated value of ES. Furthermore, they do not include non-use values (see Section 2.1.3) and are not applicable to non-marketable ES. In contrast, stated preference methods, e.g., contingent valuation or discrete choice experiments, are applicable to all kinds of ES and are typically the only option for estimating non-use values. These methods attempt to construct pseudo markets via surveys and derive the value for ES from people’s responses to hypothetical questions. The hypothetical nature of the market and their non-binding character is, however, a major drawback of these methods, which has raised many discussions regarding the validity of the estimates (Pascual et al., 2010; Atkinson et al., 2012; Turner et al., 2016).

Since the importance of (non-marketable) cultural ES and non-use values was highlighted by most of the stakeholders during the first workshop (Section 3.2), I chose a stated preference method to assess ES demand. Choice experiments have been applied in numerous studies to derive public preferences for alternative states of a set of ES (e.g., Adamowicz et al., 1994; Hasund et al., 2010; Huber et al., 2011; Bateman et al., 2013; Shoyama et al., 2013; Ryffel et al., 2014). In ES choice experiments, individuals are typically presented with several choice sets representing hypothetical scenarios of a number of ES (so called attributes) in a landscape. Each of these attributes has a number of varying levels, one of which typically represents the status quo. In each choice task, respondents are asked to indicate their preferred option in each set. The attribute levels in the choice sets are varied to allow the scientist to infer trade-off relations between ES and marginal willingness-to-pay for changes in attribute levels (Moran et al., 2007).

In the context of this study, choice experiments offer several advantages relative to other stated preference methods (Hanley et al., 1998; Fisher et al., 2008; Huber,
2010; Bateman et al., 2011): They minimize many of the biases that can arise in open-end contingent valuation studies where respondents are presented with the unfamiliar and often unrealistic task of putting prices on non-market amenities. Instead, they can take into account ES of different types and allow the respondents to think in terms of trade-offs, which might be easier than directly expressing monetary values. Moreover, if the number of participants is sufficiently large, only a small sample from the whole range of alternatives must be valued by the individual respondent. Finally, even if the absolute value estimated in a choice experiment is not precise, the relative values or priorities elicited are likely to be valid and useful for policy decisions.

In addition to the caveats of economic valuation in general (Section 2.1.2), there are, however, also some disadvantages of using choice experiments (King et al., 2004; Moran et al., 2007; Huber, 2010): Respondents might be unfamiliar with the trade-offs in the experiment, they might apply simplified decision rules if choices are too complicated or the number of attributes or levels of attributes are too high, there can be a loss of interest with a large number of choice tasks or respondents may be forced to make choices that they would not voluntarily make which increases protest bids. While the latter can be filtered from the set of valid responses, the inclusion of visual information in the choice set has proven to be a useful approach to overcome the problem of insufficient understanding of attributes and levels by interviewees (Bateman et al., 2009).

In our case study region, the discrete choice experiment was conducted between February and September 2013. Details about the survey, the response rate and the statistical analysis are given in Section 5 and an exemplary questionnaire is presented in Appendix A. Within the modeling system BackES the choice experiment served two main purposes: First, four regionally relevant ES and corresponding indicators were specified in an iterative stakeholder process as part of the development and pre-testing of the experiment. Indicators were drafted based on quotations from semi-structured interviews using non-technical language and refined based on insights from the first stakeholder workshop (Section 3.2). The final indicators were then determined in a way that they were simple enough to effectively communicate with the local residents and policy-makers and at the same time relate to the functioning of the SES (Barbier et al., 2008; Seppelt et al., 2011). Second, the experiment allowed evaluating future demand for ES. Marginal utility coefficients were estimated for each ES that indicate how much a change in a service increases or decreases the utility of the landscape for the participants. These utility coefficients capture a suite of values behind expressed preferences for ES and were used in the last step of the analysis to evaluate ES benefits given alternative pathways of ES supply.

### 3.4. Ecosystem services supply: agent-based land-use model

To simulate ES supply, many studies have applied land-use change models, since they allow the link between indirect and direct drivers, the land system and the services it provides (e.g., Schröter et al., 2005; Metzger et al., 2006; Nelson et al., 2009; Huber et al., 2014; Kirchner et al., 2015). These studies acknowledge that the functionality of the land and its capacity to provide ES is inherently linked to land use (Verburg et al., 2009). Some authors derive information on ES supply directly from land use or land-use based proxies, which is appropriate in areas where the dominant services strongly relate to land use (Maes et al., 2012). More sophisticated approaches integrate dynamic process-based ecosystem modules in order to take into account the intricate mechanisms which underlie ES delivery (Nelson et al., 2009). A variety of land-use modeling techniques have been developed to serve different research purposes ranging from statistical approaches, to cellular automata or Bayesian belief networks (for reviews see e.g., Verburg et al., 2004; Koomen and Stillwell, 2007; van Schrojenstein Lantman et al., 2011). However, not all types of models are equally suitable to be used in a backcasting context. In order to explore pathways to desirable futures and to infer management and policy strategies, a model should be (1) process-based and physically feasible, representing cause-effect relationships in the system (Robinson, 1990), (2) dynamic, i.e., simulate intermediate time steps with the possibility to intervene in the system in appropriate intervals (Gomi et al., 2011), and (3) flexible enough to implement new management options and open the current political and socio-economic constraints (Grêt-Regamey and Brunner, 2011). Thus, the predictive orientation based on the continuation of historical data inherent in model types such as cellular automata or statistical techniques make them inappropriate for backcasting. In this thesis, I use a spatially explicit agent-based land-use model based on linear programming.

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2 While I was substantially involved in the design and setup of the questionnaire, the survey was conducted and analyzed under the lead of social scientists from the University in Göttingen.

3 Exemplary quotes: “Tradition is very connected with agriculture.” “The forest has of course a lot destroyed [from the landscape].” “I would make disappear some of the new houses, these horrible buildings.”
3.4.1. Advantages and caveats of agent-based models and linear programming

In the last decade, agent-based models (ABM) have emerged in the modeling of land-use changes as a way to better capture complex system characteristics of coupled SESs (for reviews see Parker et al., 2003; Matthews et al., 2007; Filatova et al., 2013). ABM simulate a number of decision-makers (agents) which interact through prescribed rules and which are embedded in and interact with a dynamic environment. As the environment changes, actors have the capacity to learn and adapt (Farmer and Foley, 2009). One of the main added values of ABM compared to other land-use modeling techniques is its ability to represent human behavior more realistically by considering individual preferences or motivations in land-use decisions (Valbuena et al., 2010; Schreinemachers and Berger, 2011). ABM are primarily applied to improve our understanding of the dynamic interactions between agents and their settings and to investigate consequences of land-use policies at landscape level (e.g., Le et al., 2008; Bakker and van Doorn, 2009; Schouten et al., 2013). They are very useful for developing a shared system understanding and building credibility when working with stakeholders (Kelly et al., 2013).

Most of the caveats of ABM result from the complexity of the system and the interactions they represent. Model development and parameterization are difficult and require detailed information on individual agents, their behavior, beliefs and adaption mechanisms. As the structures of ABM are generally highly complex, the models tend to have high numbers of parameters and significant computational resource requirements. Programming furthermore often needs skilled computer scientists in order to avoid errors and bugs. Model development issues aside, validating of ABM remains an ongoing challenge (Grimm et al., 2005; Heckbert et al., 2010; Kelly et al., 2013). Another unresolved problem in the use of ABM is that most models consider feedbacks on just one side of the SES. That is, most land-use ABM either consider the environment as fixed or changing according to simple rules (Matthews et al., 2007).

The ABM used in this thesis is implemented with linear programming, a simulation method to achieve the best outcome - usually maximum profit or lowest cost - in a mathematical model represented by linear relationships. That is, while taking into account agents’ individual characteristics, the model assumes that agents optimize their profit based on limited resources (Buysse et al., 2007). Linear programming has several advantages for social-ecological modeling in the context of a backcasting approach in mountain regions (Havlik, 2006; Buysse et al., 2007; Huber, 2010): The link between economic and ecological elements is straightforward and an explicit and efficient optimum seeking procedure is provided. Thus, the behavior of the system agents follows a traceable principle and cause-effect chains within the system can be explained and explored. The modular structure of normative linear programing models makes possible the introduction of new activities, such as new crops or irrigation systems. This is a necessary precondition if alternative pathways and management strategies that adapt to global change are to be explored in a backcasting approach. Many activities and restrictions can be considered at the same time, the latter being of importance in mountain regions where land use is constrained by many environmental and topographical factors. Furthermore, they allow the integration of different submodels into a larger framework which is necessary to couple forest and settlement dynamics to agricultural land-use decisions.

Important constraints in the use of linear programing is the assumption of linearity and (in our case) the lack of major feedbacks. Furthermore, the simple goal function limits the interpretation of the results to a prescriptive perspective – it assumes that agents will succeed in maximizing their profits if they behave as the model does, not because they behave like it (as in a descriptive analysis; Huber, 2010).

3.4.2. Specifications of ALUAM-AB

I simulated the supply of ES with the agent-based land-use model ALUAM-AB (Alpine Land Use Allocation Model – Agent Based; Briner et al., 2012; Brändle et al., 2015). The major reasons for choosing this model relate to the advantages of ABM and linear programming in general: (1) The recursive-dynamic model simulates intermediate yearly time steps, hence, allows system dynamics to be tracked over time. (2) The effect of larger scale socio-economic and political drivers and individual farmers’ behavior that lead to a spatially explicit land-use pattern can likewise be explored. (3) Individual preferences and motivations beyond pure income maximization, which play an important role in mountain farming, are included in the model (Schirpke et al., 2012; Flury et al., 2013; Celio et al., 2014). (3) The model has been developed over years and is specifically tailored to the case study (Section 4; Briner et al., 2012; Briner et al., 2013b; Huber et al., 2014; Brändle et al., 2015). As inherent characteristics of the region, such as land management types and physical resource constraints, are accounted for, causal structures are well represented. On the one hand, the empirical grounding increases the credibility of the model and its
value for operational decision support (Kelly et al., 2013). On the other hand, it improves the validity of the model. **ALUAB-AB** was validated against observed livestock and land-use data. Overall and unequal variation errors of model performance were small (on average 6.5%), thus, **ALUAM-AB** captures the mean and trends of the observed data satisfactorily (see Appendix B). (4) The concept of income maximization under various socio-economic constraints captures farmers’ situation in the case study region\(^4\). At the same time, it roots the model in economic theory and allows the conceptual link with the choice experiment.

**ALUAM-AB** has been developed and continuously refined by different scientists over several years. This thesis contributed in two ways to an improved model structure: On the one hand, a settlement module was developed in form of a selection algorithm that defines the most suitable parcels for urban growth allowing to account for population growth and migration when simulating land-use changes. On the other hand, the model was extended with equations to calculate those ES that have been identified as relevant in the choice experiment, both spatially-explicitly and regionally aggregated, as well as different sustainability indicators such as the diversity of land-use or farm types. An overview of model processes and of the linkages between the submodels and between models and data is given in Figure 3.4. A detailed description of **ALUAM-AB** is provided in Appendix C using the ODD protocol (Grimm et al., 2006) as well as in Section 5.

The main characteristics of **ALUAM-AB** are:

**Economic maximization:** The model follows an overall farm income optimization approach which governs the allocation of agents’ available resources to production, considering natural, farm-level and individual constraints as well as incentives and regulations from the market and policy scenarios. Thus, the fundamental concept of the model is rational economic behavior (land rent maximization), and no learning patterns exist. However, the consideration of individual constraints, such as opportunity costs, minimum income wage and limited time resources, includes non-economic and agent-specific goals in the decision-making process.

**Agent interaction:** Structural change is modeled using a land market module that identifies land units that are no longer cultivated under the existing farm structure. The land market randomly assigns such land units to one of the other agents and then checks whether the

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\(^4\) Personal talks with farmers revealed that they perceive themselves as proud entrepreneurs who run profitable businesses rather than being ‘landscape gardeners’ of urban people.
agent is able to expand its cultivated area. This procedure is repeated until all land units are assigned to a farm or none of the farms is willing to take the land units left on the market. Land units that are not transferred to other farms are defined as abandoned and natural vegetation dynamics get under way on these units (Figure C.1, Appendix C).

**Linear:** The modeling system, including the estimation of ES, is based on linear relationships.

**Spatially explicit:** The model allocates an optimal land use to each of the approximately 13'000 land units within the region. Accordingly, the provision of land-use related ES is calculated in each of these units. Land units are represented on a 100m x 100m grid and do not correspond exactly to the paddocks as used by the individual farmers.

**Recursive dynamic:** The model proceeds in annual time steps. The number of stables and the number of animals of the preceding year are considered in the optimization, since stables are assumed to cause fixed costs and since only a restricted number of animals is available to increase herd size. In addition, after each simulation year, the age structure of the different agents is updated in the model.

**Integration of submodels:** Spatially explicit climate change impacts on grasslands and forest are considered via the linkage with the forest landscape model LandClim, while population growth and migration scenarios can be explored through the settlement module (Appendix C).

### 3.5. Ecosystem services benefits: utility function

To evaluate changes in ES benefits, I calculated the change in utility along different pathways of ES supply based on the preferences for these ES as inferred in the choice experiment. Such an approach assumes that, although all outcomes of ALLIUM-AB maximize farmers’ income (given the respective boundary conditions), the different supply of ES might not be equally desirable to local residents. Each outcome offers stakeholders a certain level of satisfaction as described by the utility. The utility implicitly includes not only the direct benefits associated with ES, but also stakeholders’ connection with nature and other altruistic motivations that influence their preferences (see Section 2.1.2; King et al., 2015). Utility functions have been used for assessing the impact of scenarios on the quality of life (Labiosa et al., 2013; Murray-Rust et al., 2013); however, so far they have not been applied to consistently link an economic valuation of ES with an economic-based model simulating ES supply.

In BackES the utility function, $\Delta U$, is a weighted sum of predicted changes in the key ES relative to the reference year 2013, $\Delta ES_i$, in which the weight is given by the marginal utility coefficients from the choice experiment, $\beta_i$ (McFadden, 1973):

$$\Delta U = \sum \Delta ES_i \cdot \beta_i \tag{3.1}$$

Positive changes of $\Delta U$ indicate a gain in the benefits resulting from changes in ES, while negative changes denote a loss in the benefits as compared to 2013. Negatively perceived changes in single services can be compensated by positively weighted changes in others.

In my approach, I held the marginal benefits constant (a) for the whole range of assumed changes (i.e., the utility function is linear), (b) over time, (c) across space and (d) across stakeholder groups. The assumption of linearity makes the analysis valid only within a certain range of ES supply in which thresholds, beyond which ES are especially scarce or abundant and ES benefits accordingly change disproportionally, are not crossed (Fisher et al., 2008). I assumed a constant function in time, because both the form and rate of the discounting procedure are still subject to an intense controversy (Bateman et al., 2011). Therefore in my approach, the utility change is driven by quantitative changes in ES supply while people’s preferences are kept constant over time (Boyd and Banzhaf, 2007). Likewise, spatial variations related to ES demand are not included in my approach. While sophisticated spatial value functions have recently been suggested, these methodologies require comprehensive datasets of exploratory socio-economic variables across the entire study area which are very difficult to obtain or model for the future (Schägner et al., 2013). This limitation has to be kept in mind especially when looking at spatially explicit ES benefits. Finally, a generalized utility function representative for all local residents in the case study assumes that different groups of stakeholders share common preferences based on similarities in their livelihoods, cultural values, economic outlooks and historical background (King et al., 2015).

### 3.6. Stakeholder workshop 2

The second workshop was held in Mai 2015 in Visp with ten representatives from agriculture, regional development, nature conservation and local policy. While the represented stakeholder groups were similar in both workshops (Section 3.1), only two participants managed to attend both events. The main goal of the workshop was to test the acceptance of different policy strategies with a focus on spatial planning interventions. This focus was chosen since urban sprawl was an especially...
pronounced concern in the first workshop and because the national spatial planning law had been revised in 2014 (Section 4.2.3) which still requires implementation and regulations at regional scale. In addition, the workshop was set up to evaluate how an interactive visualization platform could support the generation of system, target and transformation knowledge.

The workshop consisted of three parts: In an introductory part, preliminary research results from MOUNTLAND were presented and quickly discussed with the participants. In an extended second phase, stakeholders could explore and discuss regional effects of different policy strategies in small groups of three with the help of a collaborative platform. Each group was guided through the platform by a scientist, who at the same time moderated and documented the discussions between the participants (Figure 3.5). The platform enabled stakeholders to switch between different policy strategies and immediately see the consequences on different regional characteristics with the help of several visualization types (Figure 3.6). Information shown on the platform was based on results from BackES and included the amount of settlement growth per municipality, the corresponding loss of different ES, a visualization of the consequences in Visp, the urban center of the region, as well as in Saas Fee.

The small number of participants did not allow a quantitative evaluation of preferred policy strategies. However, insights from the workshops regarding both the acceptance of different strategies and the validity of assumptions in the underlying model have been used to discuss the results presented in the single papers. The questionnaire revealed that participants gained system knowledge throughout the workshop, but did not allow a conclusion on whether the platform could potentially support the generation of target and transformation knowledge. A series of workshops integrated in an
Background

Figure 3.6. Collaborative platform including (i) barplots: settlement growth and loss of ecosystem services (ES) per municipality, (ii) text: description of policy strategy, (iii) visualizations: Visp (top) and Saas-Fee (bottom), and (iv) a regional land-use map. The icons on the top right corner allow switching between different policy strategies (different levels of collaboration and consideration/ignorance of ES).

An ongoing regional planning process would be required to investigate how interactive and collaborative information transfer can contribute to enhancing these types of knowledge.
4. Case study

4.1. Overview on the case study area

The case study region is located in the canton Valais in Switzerland (Figure 4.1), a continental inner-Alpine environment characterized by relatively low precipitation and moderate temperatures (Figure 4.2). It spans an area of 334 km², from the remote Baltschieder-valley and the economically growing industrial and urban center Visp to the touristic destinations in the Saas-valley (Saas Fee, Stalden). Unproductive land and high mountain peaks account for 62% of the area, while 20% is covered by forest and 16% is cultivated by agriculture (SFSO, 2009). The 11 municipalities are home to around 15'555 residents including 161 active farmers. The secondary sector is primarily located in the valley bottom around

![Figure 4.1. Case study area Visp and Saastal.](image-url)
Visp with more than 50% of the employees working in the century-old Lonza AG, a supplier of pharmaceutical, healthcare and life science industries. In rural areas, the primary sector and tourism, especially winter tourism, are the most important income sources (Brand et al., 2013). Agricultural activities are dominated by grassland farming, including the special case of summer pastures, a seasonal expansion into the subalpine altitudinal zone, while crop production plays a minor role (FOAG, 2008). On average, each farm cultivates only 8ha of agricultural land and keeps around seven livestock units, larger dairy and beef/suckling cattle and/or sheep. Agriculture is highly subsidized and more than 90% of the farms are run part-time in combination with other economic activities. Many farmers are members of breeding associations that organize regular exhibitions, which root farming firmly into village traditions (Brändle et al., 2015). Seasonal Alpine grazing and the long-established

Figure 4.1 (continued). Case study area Visp and Saastal.
small-scale farming practices substantially contribute to maintaining the typical character of the landscape and the provision of ES (Briner et al., 2012). Regionally important ES include provisioning services, e.g., food and timber production, regulation and maintenance services, e.g., protection from natural hazards or habitat maintenance, and cultural services, e.g., cultural heritage and scenic beauty (Huber et al., 2013b).

Land-use change is an important issue in the region: Between 1981 and 2005, rapid urbanization processes around the industrial and touristic centers led to the expansion of the settlement area by over 30%. In the same period, mountain agriculture became less and less competitive and rapid economic growth pulled labor off the land. In peripheral areas, 14% of the productive agricultural land was abandoned and forest grew by 7% (SFSO, 2009). Between 2000 and 2012, the number of farms annually decreased by 2.8%. If observed land-use change trends continue, they will significantly affect the sustainability of the ES provision in the region.

The narrow socio-economic, political and ecological boundary conditions as reflected, for example, by the marginalization of agriculture, the high dependence on direct payments or steep altitudinal gradients, make the region especially susceptible to regional and global changes, e.g., in agricultural markets and policies, consumption patterns or migration and tourism. In addition, as the region is among the driest of the Swiss Alps, changes in temperature and the precipitation pattern are supposed to have a substantial impact on vegetation and agricultural yields in future (Briner et al., 2012).

4.2. Relevant actor groups

The potential of the mountain system to provide ES and benefit humans does not only depend on the above outlined boundary conditions, but also on the interactions and power relations among regionally relevant actor groups (Felipe-Lucia et al., 2015). Figure 4.3 presents an overview on the key stakeholders and their interactions influencing the management and provision of ES in the case study region. Farmers, residents and regional policy-makers have been actively involved in the research activities described in this thesis and their relationships and impacts on ES are well captured in the modeling system BackES. By contrast, the industry and tourism sector and policy-makers at the national level did not participate in the transdisciplinary research process and their influences on other actors and regional ES were only indirectly considered as boundary conditions in the model. The following paragraphs briefly describe the main interests of and connections between the central stakeholders with regard to ES. A more detailed overview on additional actors, their importance and motivations is provided in Table D.1 (Appendix D).

Farmers are the primary managers of ES in the region responsible for the overall appearance of the landscape (together with forestry and spatial planning). The group of farmers in the region can broadly be divided into five types differing in their structural characteristics, farming objectives and attitudes (Table 4.1, Brändle et al., 2015). Farming is the primary source of income only for a small percentage of farmers. Their average farm size is significantly higher than of other types, both with respect to area farmed and livestock kept, and they cultivate most of the land in the best production zone in the valley bottom. These farmers attach great importance to generating an adequate income, high yields and innovative products. By contrast, leisure farmers place stronger emphasis on social, ecological and landscape aspects of their farming activities and on maintaining family traditions. Leisure-oriented breeders and traditional leisure farmers specifically aim at earning recognition within their farming community by
showing livestock at competitions and exhibitions, while landscape stewards and leisure-oriented farmers aspire to contribute to local village life and an ecologically and aesthetically valuable landscape.

The residents of Visp and the Saas valley are the primary beneficiaries of ES. Furthermore, they are important stakeholders for shaping the future development of the region by providing work force to the industry and tourism and through their power in political decision-making. Interviews conducted in the pre-studies of the choice experiment (Section 3.3) revealed that cultural ES are of particular importance to the citizens. Local farming traditions, regional identity, a sense of place and a diverse landscape were named as valuable characteristics of the mountain system. The sample of residents included in this study represents inhabitants from 8 of the 11 municipalities (thereof 45.2% from Visp and 17.3% from Saas-Fee). 51% of the participants were male and 49% female, and their average age was 49 years. The declared annual income tax payment was 6’000 CHF (+/- 4’000 CHF) and the majority of involved people had completed either a vocational training (44%) or a higher education program (38%).

Tourism is the dominant economic sector in the Saastal. Especially Saas-Fee providing diverse skiing and hiking opportunities and Visperterminen hosting the highest European vineyards are important destinations for winter and summer tourism. Maintaining a high quality and originality of the landscape and ES are very important goals of the sector due to both national and international competition (Aebi et al., 2015). Although tourists are important beneficiaries of ES, their demand has not been included in this study. The tourism sector also provides valuable additional income to most of the farmers, especially during the peak season, allowing them to run part-time businesses with small profits.

The industry is the most important economic sector in Visp providing around 3’000 of the 8’500 jobs in the municipality (Hirschi, 2009). The sector offers highly qualified jobs and promising career perspectives for residents, but at the same time also profitable job alternatives for farmers. As a consequence, the opportunity costs of farming rise and the willingness of the younger generation to take over the businesses from their parents decreases. In order to be a competitive location, the industry is primarily interested in solid transport infrastructure, while the provision of ES is of lower priority. The energy sector, although of growing regional importance, operates largely independently of other economic sectors (Aebi et al., 2015).

Policy-making at the federal level is highly relevant for the regulation of land-use activities and the related ES provision in the case study region (Section 4.3). Important national policy actors include the Federal Council, the

![Diagram showing the interactions between different stakeholders and ecosystem services.](image)

**Figure 4.3.** Overview on the most relevant actor groups and their interactions for the provision of regional ecosystem services. Blue stakeholders actively participated in the research and their (inter)actions are well represented in the modeling system, while (inter)actions of grey stakeholders were only indirectly considered. Solid black arrows denote relationships captured in the model, dotted grey influences were not included.
Federal Office for Agriculture and the Swiss Farmers’ Association. While all these parties are interested in strengthening mountain agriculture and ES, they partly disagree in how to best achieve this goal. The governmental agencies favor a greening of the agricultural sector and a deregulation of international agricultural markets, the Farmers’ Association insists on maintaining a more traditional production-oriented public support (Hirschi et al., 2013). At cantonal level, the administration of the Valais is organized in five departments, each headed by a member of the state council, the executive branch of the canton. Spatial planning is institutionalized within the department of economic affairs, environmental affairs are organizationally combined with transportation and construction. The grand council is the legislative branch of the canton. At the communal level, the municipalities of the study region are organized in an executive branch with a mayor and a municipal council with up to eight members. As widespread in Switzerland, assemblies at the municipal level constitute the legislative branches of the municipalities. Usually, all residents with Swiss citizenships are eligible to participate in these meetings. In general, policy-makers are interested in a flourishing tourism, high attractiveness of the region for industry, qualified jobs and a unique mountain landscape (Aebi et al., 2015). The goals of policy actors of different sectors are discussed in more detail in the next section.

4.3. Policy background in Switzerland

Land use in the case study region is regulated and constrained by a federalist and multi-sectoral policy system. Relevant policies of the agricultural, forestry and spatial planning sector operate at different governmental levels and are negotiated in different political arenas as outlined in the next paragraphs.

4.3.1. Agricultural policy program

The Swiss Agricultural Policy Program is enacted at a national level and has been revised periodically in the last decades shifting from a production orientation towards a stronger ecological and services orientation (Bardsley and Bardsley, 2014). In two major reform cycles during the 1990s, market support was reduced stepwise, and area- and livestock-based subsidies were introduced, divided into general and ecological direct payments with cross-compliance. Only recently, in 2014, this system was reformed again: The yearly budget of around 2.8 Billion CHF and the elements of cross-compliance were maintained, but the payments were restructured based on the Tinbergen rule. That is, each individual instrument was designed to address a single policy goal (Mann and Lanz, 2013). Five overarching agricultural goals were defined (Table 4.2): (1) ensuring food supply, (2) maintaining cultural landscapes, (3) conserving biodiversity, (4) improving landscape quality, (5) ensuring food supply, (2) maintaining cultural landscapes, (3) conserving biodiversity, (4) improving landscape quality.

### Table 4.1. Key characteristics of farmers in the region (median values) based on a survey among 119 farmers (Brändle et al., 2015). The last four lines describe farming motivations: Competition & recognition = farmers’ aspiration to earn recognition within their own farming community, specifically by showing their livestock and skills at competitions and exhibitions, profit & yield = degree to which farmers aim to achieve an adequate income, high profits and yields from their farming activities, local influence = contributing to local village life through farming, compliance & tradition = motivation to maintain family traditions and fulfill societal expectations, e.g., with respect to providing additional ecosystem services.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Unit</th>
<th>Production-oriented farmers</th>
<th>Ecological and landscape stewards</th>
<th>Leisure-oriented breeders</th>
<th>Traditionalist leisure farmers</th>
<th>Leisure-oriented farmers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of total farmers in the region</td>
<td>%</td>
<td>14.4</td>
<td>17.1</td>
<td>27.1</td>
<td>15.3</td>
<td>26.1</td>
</tr>
<tr>
<td>Managed agricultural land</td>
<td>ha</td>
<td>22.9</td>
<td>14.5</td>
<td>9.1</td>
<td>7.7</td>
<td>6.9</td>
</tr>
<tr>
<td>Total livestock</td>
<td>Livestock Units</td>
<td>25.7</td>
<td>16</td>
<td>8.5</td>
<td>6.4</td>
<td>6.4</td>
</tr>
<tr>
<td>Small livestock</td>
<td>%</td>
<td>20</td>
<td>22</td>
<td>58</td>
<td>64</td>
<td>65</td>
</tr>
<tr>
<td>Land in best production zone</td>
<td>%</td>
<td>29</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Steep land (&gt;18°)</td>
<td>%</td>
<td>51</td>
<td>74</td>
<td>86</td>
<td>78</td>
<td>82</td>
</tr>
<tr>
<td>Income</td>
<td>CHF/year</td>
<td>60'000</td>
<td>82'000</td>
<td>66'000</td>
<td>68'000</td>
<td>76'000</td>
</tr>
<tr>
<td>Income from agriculture</td>
<td>%</td>
<td>52</td>
<td>35</td>
<td>19</td>
<td>17</td>
<td>13</td>
</tr>
<tr>
<td>Competition &amp; recognition</td>
<td>Likert scale 1-5</td>
<td>2.2</td>
<td>2.7</td>
<td>4.5</td>
<td>3.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Profit &amp; yield</td>
<td>Likert scale 1-5</td>
<td>3.3</td>
<td>2.8</td>
<td>2.8</td>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td>Local influence</td>
<td>Likert scale 1-5</td>
<td>3</td>
<td>4</td>
<td>4.5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Compliance &amp; tradition</td>
<td>Likert scale 1-5</td>
<td>3.3</td>
<td>4</td>
<td>4.3</td>
<td>4.3</td>
<td>4</td>
</tr>
</tbody>
</table>
and (5) developing close-to-nature and animal-friendly production systems. For each of these goals one or several payment schemes were established (Mann and Lanz, 2013). Almost 40% of the direct payments in Switzerland aim at securing food supply, i.e., at maintaining the current level of production and reducing the loss in productive agricultural land. 16.5% of the budget are payments for cultural landscapes mainly focused on supporting difficult farming conditions and reducing the rate of forest encroachment in mountain areas. Contributions to biodiversity conservation make up 13% of the total direct payments and include area-based payments to increase the amount of extensively used grassland and performance-based payments to enhance the quality of ecological compensation areas. A smaller amount of support (2.5%) is spent on collaborative projects that contribute to an improved landscape quality by maintaining and developing regionally typical landscapes. Finally, the Swiss government supports environmental- and animal-friendly production practices with around 16% of the budget. These payments target an increase in N- and P-efficiency and a reduction of NH₃ emissions and stimulate the participation of farmers in animal welfare programs. Farmers receive all these direct payments only if they meet environmental and social requirements. With respect to the environment, they have to provide a proof of ecological performance (cross-compliance measures). Key elements include an

![Table 4.2. Payment scheme of the Swiss agricultural policy (table adapted from Huber et al., 2017). Payments marked by a * were considered in the modeling system BackES.](image-url)

<table>
<thead>
<tr>
<th>Policy goal</th>
<th>Subsidy scheme</th>
<th>Specification</th>
<th>Payments (CHF/ha)</th>
<th>Annual payments (Mio. CHF) (share of total in parentheses)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ensuring food supply</strong></td>
<td>Basic payment*</td>
<td>Per ha for food production</td>
<td>900</td>
<td>824 (30%)</td>
</tr>
<tr>
<td></td>
<td>Payments for production under difficult conditions*</td>
<td>Per ha for food production depending on production zone</td>
<td>240-360</td>
<td>160 (6%)</td>
</tr>
<tr>
<td></td>
<td>Payments for arable crops*</td>
<td>Per ha</td>
<td>400</td>
<td>112 (4%)</td>
</tr>
<tr>
<td><strong>Maintaining cultural landscapes</strong></td>
<td>Payments for cultural landscapes on hillsides and mountain regions*</td>
<td>Per ha depending on production zone</td>
<td>100-390</td>
<td>141 (5%)</td>
</tr>
<tr>
<td></td>
<td>Payment on steep slopes*</td>
<td>Per ha on slopes between 18-35%; 35-50% and &gt;50%</td>
<td>410-1000</td>
<td>121 (4.4%)</td>
</tr>
<tr>
<td></td>
<td>Payment for farms sending animals to summer pastures*</td>
<td>Per livestock unit sent to summering pastures</td>
<td>370</td>
<td>102 (3.5%)</td>
</tr>
<tr>
<td></td>
<td>Payments for keeping animals in the summering area*</td>
<td>Per livestock unit on summering farms depending on animal type</td>
<td>320-400</td>
<td>121 (4.4%)</td>
</tr>
<tr>
<td><strong>Conserving biodiversity</strong></td>
<td>Payments for extensively used grassland (ecological compensation areas)*</td>
<td>Basic subsidy per ha depending on production zone</td>
<td>1350-1650</td>
<td>284 (10%)</td>
</tr>
<tr>
<td></td>
<td>Payment for connected ecological compensation areas*</td>
<td>Project based (collaborative)</td>
<td>1000</td>
<td>80 (3%)</td>
</tr>
<tr>
<td><strong>Improving landscape quality</strong></td>
<td>Payment per ha or livestock unit</td>
<td>Project based (collaborative)</td>
<td>240 (livestock unit) / 360 (ha)</td>
<td>70 (2.5%)</td>
</tr>
<tr>
<td><strong>Developing environmental friendly production systems</strong></td>
<td>Payments for organic agriculture</td>
<td>Based on organic certification and type of land-use</td>
<td>200 - 1600</td>
<td>40 (1.5%)</td>
</tr>
<tr>
<td></td>
<td>Payments for extensive crop production*</td>
<td>Per ha with no fertilization and pesticides</td>
<td>400</td>
<td>32 (1%)</td>
</tr>
<tr>
<td></td>
<td>Payment for grassland-based milk and meat production*</td>
<td>Per livestock unit if less than 10% of concentrated feed in animal diet</td>
<td>200</td>
<td>105 (3.5%)</td>
</tr>
<tr>
<td></td>
<td>Payments for animal welfare*</td>
<td>Per livestock unit under free range and in animal friendly housing systems</td>
<td>90-360</td>
<td>262 (9.5%)</td>
</tr>
<tr>
<td></td>
<td>Payments for resource efficiency i.e., specific farm technologies</td>
<td>Per ha</td>
<td>30-250</td>
<td>6 (0.2%)</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td>Transition payments (phase out in 2021)*</td>
<td>Per farm</td>
<td>314</td>
<td>314 (11.5%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>2773</td>
<td></td>
</tr>
</tbody>
</table>
appropriate proportion of ecological compensation areas (minimum of 7% of total farm area), balanced use of fertilizers, crop rotation, soil protection, specific use of plant treatment products and animal welfare measures. Social requirements encompass a minimal farm size, appropriate education and the use of family labor on the farm (Huber et al., 2017). Overall, the Swiss agricultural policy provides a high level of domestic producer support: In 2015, 62% of total agricultural production value was based on direct payments, compared to only 19% in the EU (OECD, 2016).

4.3.2. Forest Law
The enactment of the National Forest Act in 1876 was one of the earliest environmental policy laws in Switzerland and a milestone in the sustainable use of natural resources. The law holds a unique position in the body of land-use regulations as it generally prohibits deforestation, thus protecting forests in terms of both their spread and their spatial distribution (Art. 5). Forest may be cleared only in the state’s interest given the condition that a particular project cannot be realized in a different location. Only projects that essentially contribute to a wider public benefit (e.g., a drinking water reservoir) and that are not motivated by financial interests, such as the potentially profitable use and low-cost acquisition of land for non-forestry purposes, are valid reasons for deforestation. If a special permit is issued, trees covering an identical area must be replanted as a substitute in the same region. The specific use and management of the forest is regulated by cantonal planning and management regulations and has to take into account biodiversity and a sustainable use of forest resources (FOEN, 2013). The imperative of forest conservation substantially constrains land use in mountain regions.

4.3.3. Spatial Planning Regulations
The spatial planning process in Switzerland is organized across three spatial scales. While framework legislation is in the responsibility of the Confederation, practical planning implementation remains essentially a matter of the cantons, which in turn often delegate a number of tasks to the communes. The Federal Law on Spatial Planning distributes the tasks as follows: At national scale, overarching planning principles and goals are outlined, instruments and related rules of procedures are defined, and sectoral plans for topics of national interest are set up. The primary principle of Swiss spatial planning is an “economical use of land”, as only 30% of the comparatively small area of the country is suitable for intensive human use. An economical use of land refers to both a restriction of land consumption and an optimal organization of different land uses. Another important element of the Swiss planning policy is the orientation towards “decentralized concentration”, that is, a controlled settlement development not only in the large agglomerations of the Swiss Plateau, but also in the agglomerations and regional centers in the Alpine valleys (Muggli, 2004).

The 26 cantons are responsible for the implementation of the spatial planning regulation including the design of a structural plan, which includes a comprehensive planning strategy of land uses within the cantonal area. The high autonomy of the cantons provides possibilities for locally adapted solutions while maintaining a harmonization and coordination with the national level. Structural plans need to be updated and revised every 10 years or earlier if necessary. All structural plans are made available to the public and need to be accepted by the cantonal government before they are finally approved by the national government (Grêt-Regamey et al., 2016a). The structural plan of the canton Valais outlining the spatial development strategy up to 2020 is currently pending at the federal government for approval. The most important goals of the strategy are listed in Box 4.1.

Box 4.1. Important goals of the spatial development strategy 2020 of the canton Valais.

1.1 Providing good conditions for diverse and competitive mountain farming.
1.3 Conserving diverse natural habitats and strengthening ecological connectivity.
1.4 Conserving natural and cultural landscapes.
3.1 Preserving the functionality and population in small and rural municipalities.
3.2 Strengthening economic and innovation locations in urban centers.
3.4 Constraining urban sprawl and promoting densification of existing settlement structures.

At municipality scale, land-use plans are developed that lay down the use in different zones, particularly the delimitation of the building area from the non-building area, in a binding manner for landowners. The designation of the building zones must respect the cantonal structural plan and the national planning principles. The federal law authorizes the responsible authorities to initiate building land rationalizations and reorganize and rearrange building plots without the agreement of the landowners. However, revisions of land-use plans have to be accepted in a public vote in the municipality or the municipal parliament and be approved by the canton (ARE, 2004).
In 2014, an updated version of the Federal Law on Spatial Planning was enacted. The novel regulations triggered many negative reactions in the canton of Valais, where many residents are owners of small land parcels. In the past, the canton Valais has designated a surplus of building zones, which must be reduced in the coming years to prevent further urban sprawl. Landowners fear a loss of both the value of their asset and potential building plots for their descendants. Despite this opposition, the canton and municipalities are now forced to adapt their structural and land-use plans.

4.4. Downscaled global change scenarios
Future ES provision was analyzed under different global change scenarios according to the Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC). In a first step, a formative scenario technique was applied to regionally downscale the four IPCC SRES storylines (Walz et al., 2014). In a second step, these storylines were translated into quantitative scenarios to feed the modeling system BackES (Section 5.2.3). The socio-economic and political boundary conditions in the case study region under each scenario are described in Figure 4.4.
Zwei Dinge sind zu unserer Arbeit nötig: 
Unermüdliche Ausdauer und die Bereitschaft, 
etwas, in das man viel Zeit und Arbeit gesteckt hat, 
wieder wegzuwerten.

Albert Einstein
5. A backcasting approach for matching regional ecosystem services supply and demand

Ecosystem services (ES) modeling studies typically use a forecasting approach to predict scenarios of future ES provision. Usually, these forecasts do not inform on how specific policy alternatives will influence future ES supply and whether this supply can match ES demand – important information for policy-makers in practice. Addressing these gaps, we present a multi-method backcasting approach that links normative visions with explorative land-use and ES modeling to infer land-use policy strategies for matching regional ES supply and demand. Applied to a case study, the approach develops and evaluates a variety of ES transition pathways and identifies types, combinations and timings of policy interventions that increase ES benefits. By making explicit ES sensitivity towards regional policy strategies and global boundary conditions over time, the approach allows to address key uncertainties involved in ES modeling studies.

Software availability

Name of tool: Integrated backcasting modeling system BackES
Developers: Sibyl H. Brunner, Adrienne Grêt-Regamey, Simon Peter, Simon Briner, Swiss Federal Institute of Technology; Robert Huber, Swiss Federal Institute for Forest, Snow and Landscape Research. The model version presented in this paper and example input data are offered free of charge from the corresponding author (sbrunner@ethz.ch)

Software required: Linear Programing Language (LPL), Virtual Optima; ILOG CPLEX Optimization Studio, IBM


5.1. Introduction

The future provision of ecosystem services (ES) will depend on forthcoming land-use changes which, in turn, are strongly influenced by environmental, socio-economic and political developments (Foley et al., 2005; Turner et al., 2007; Rounsevell et al., 2012; Verburg et al., 2013). In order to project future ES provision, modeling studies typically use a forecasting approach or explorative storylines. They thus organize complex information into coherent scenarios to help people conceptualize the future (Polasky et al., 2011a) and provide insight into the range and uncertainty of future ES changes (Rounsevell et al., 2012; Grêt-Regamey et al., 2013a). This information can provide guidance for policy development, land-use planning and land management (Metzger et al., 2010). Foresight scenario analyses are particularly helpful to illustrate emerging synergies and trade-offs among ES (e.g., Nelson et al., 2009; Schirpke et al., 2012; Reed et al., 2013) and between economic development and ES (e.g., Metzger et al., 2006; Goldstein et al., 2012). They, however, have two constraints: Firstly, the most plausible futures may not be the most feasible ones and exploring the desirability of alternative futures may be more important than their coherence (Robinson, 2003). Secondly, scenarios tend to be static representations and are of limited value for scrutinizing the dynamic response of a system to alternative policy options (Rounsevell and Metzger, 2010). In particular, the time horizon of scenarios seldom matches the short-term nature of policy cycles that affect actions of decision-makers (Bryson et al., 2010). Thus, forecasting scenarios often fail to provide clear information on how specific policy alternatives will influence future ES supply and how this supply relates to social preferences.

Backcasting has been proposed as a complementary approach to forecasting. Backcasting first creates a future normative vision, then looks back to identify how this desirable future could be achieved and proceeds to define follow-up activities, strategies and pathways leading to the desired future state (Robinson, 1982). Hence, the focus is shifted away from predicting the most plausible future developments to exploring possible solutions to current and future problems based on socio-economic, political and environmental desirability.
criteria and goals (Robinson, 1982; Robért, 2005; Höjer et al., 2011). Backcasting focuses on determining the freedom of policy action with respect to desirable futures rather than on evaluating policy implications along a certain path or trend (Wilson et al., 2006). The concept was originally developed in the energy field as a new kind of normative future studies in the late 1970s (e.g., Lovins, 1977; Robinson, 1982). Since then, backcasting methods have expanded to strategic planning for sustainability (e.g., Dreborg, 1996; Holmberg, 2000), to participative backcasting tools involving stakeholders in local sustainability (e.g., Carlsson-Kanyama et al., 2008; Höjer et al., 2011; Kok et al., 2011; Quist et al., 2011; Berkel and Verburg, 2012), as well as to transportation (e.g., Robért, 2005; Mattila, 2011), conservation (Gordon, 2015) or spatial planning (Haslauer, 2015). Recently, methodological frameworks have been suggested for participatory backcasting (Quist and Vergragt, 2006) and for backcasting to support sustainable and adaptive spatial planning (Grêt-Regamey and Brunner, 2011; Haslauer et al., 2012). Furthermore, qualitative roadmaps to a post Kyoto protocol have been described in several climate change mitigation studies (e.g., Kok et al., 2003; Strachan et al., 2008). However, integrated backcasting approaches linking normative visions with explorative modeling have not yet been developed for ES studies (Rounsevell et al., 2012; Brown et al., 2013).

Applying backcasting in an ES context for inferring optimal policy and management strategies requires an integration of the supply of and demand for these services (Grêt-Regamey et al., 2012; Cavender-Bares et al., 2015; Wolff et al., 2015). Studies analyzing both, the supply and demand side of ES, are rare (e.g., Bryan et al., 2010; Huber et al., 2011; Burkhard et al., 2012; Grêt-Regamey et al., 2013c; Bagstad et al., 2014; Castro et al., 2014; Schulp et al., 2014b; Stück et al., 2014; Bagstad et al., 2015). Usually, these studies do not approach the problem in a conceptually or methodologically consistent manner (Bagstad et al., 2014) and provide a snapshot of current or past average conditions (Geijzendorffer et al., 2015). A systematic integration of society’s demand into ES modeling studies with regard to future ES provision is still lacking (Seppelt et al., 2011; Hauck et al., 2015).

As ES assessments become more widely used, various methods to measure ES demand and to model ES supply have been developed. Non-market valuation methodologies, such as economic valuation and participatory valuation techniques (Farber et al., 2002; de Groot et al., 2010b; Voinov et al., 2014), or mixed approaches (Vollmer et al., 2015), are applied to assess ES demand. These approaches allow the value of all types of ES to be captured, including non-marketable services (Farber et al., 2002). Still, cultural ES are often neglected in ES assessments (Daniel et al., 2012; van Berkel and Verburg, 2014). On the supply side, many studies have used land-use change models to assess the impact of climatic, socio-economic and political scenarios on ES at the global, European and regional level (e.g., Schröter et al., 2005; Metzger et al., 2006; Nelson et al., 2009; Haines-Young et al., 2012; Huber et al., 2014; Kirchner et al., 2015). These studies acknowledge that the functionality of the land and its capacity to provide ES is inherently linked to land use (Verburg et al., 2009). Some authors derive information on ES supply directly from land use or land-use based proxies, which is appropriate in areas where the dominant services strongly relate to land use (Maes et al., 2012). More sophisticated approaches integrate dynamic process-based ecosystem modules in order to take into account the intricate mechanisms which underlie ES delivery (Nelson et al., 2009). Among the variety of land-use modeling techniques that have been developed to serve different research questions (Verburg et al., 2004; Koomen and Stillwell, 2007; van Schrojenstein Lantman et al., 2011), agent-based models are increasingly used for policy analysis, since they allow simulating the dynamic interactions between local agent behavior and their regional and global settings (Filatova et al., 2013).

The abundance of these methods obviates the need for designing a new integral model for a backcasting application and enables coupling of existing methods and models in a way that they exchange information (Voinov and Shugart, 2013). Thus, the emphasis has to come to integrate methods from different disciplines in a consistent manner and to adapt these integrated approaches to particular case study regions and data (Hewitt et al., 2014). Such an embedment of several methods in a broader approach requires a proper conceptual and technical harmonization of the interface between different components (Hamilton et al., 2015). In addition, a wide range of uncertainties are inherent to integrated approaches which need to be evaluated, especially when they are used as tools to support policy decisions (Refsgaard et al., 2007; Scholes et al., 2013; Uusitalo et al., 2015). While specific models have been suggested for different objectives in integrated environmental assessments (Kelly et al., 2013; Laniak et al., 2013), we provide a novel linking of methods and models which is necessary to address the requirements of backcasting. To ensure a consistent integration we build our approach from a welfare economic foundation. Welfare economic theory investigates the interaction between supply of and demand for goods and services to achieve an optimal allocation of resources that
maximizes human well-being (Freeman III et al., 2014). It is increasingly used as an analytical frame for a systematic and concise assessment of ES supply and demand (Cavender-Bares et al., 2015).

In this paper, we propose an interdisciplinary multi-method backcasting approach to infer land-use policy strategies for matching the regional supply of and demand for ES, including cultural ES, over a given time horizon. It is a first contribution towards a coherent integration of normative and explorative approaches in land-use and ES modeling. We apply the approach to a mountain case study, where we observe an increasing mismatch between ES supply and demand (Koellner, 2009; Bryan et al., 2010; Huber et al., 2013c) and where cultural ES are of great importance (Daniel et al., 2012). We first assess future demand for ES with a discrete choice experiment involving local residents to obtain their stated preferences for changes in four ES (cultural heritage, protection from natural hazards, habitat protection and landscape aesthetics). Secondly, we use formative scenario analysis to define socio-economic and political boundary conditions. An economic agent-based land-use model is then applied to simulate land-use changes and the corresponding changes in the supply of the four target ES under various land-use policy strategies. Finally, we evaluate for each model run, how well ES demand is satisfied at the planning horizon. The combination of a choice experiment and an economic land-use model allows the integration of production functions and utility functions from a welfare economics perspective (Fisher et al., 2008; Cavender-Bares et al., 2015).

The development of the backcasting approach was led by three objectives: (1) demonstrating its advantages compared to traditional forecasting methods for use in a policy context, (2) understanding modeling sensitivities in the multi-method approach that are relevant to the results, and (3) simulating plausible policy strategies to provide guidance for policy development in a case study region.

The remainder of the article is organized as follows: In the next paragraph, we describe the case study area with a focus on land-use change and related challenges that motivated the development of the backcasting approach. Section 2 starts with an overview on the backcasting approach, followed by a detailed description of the methods used. The study results are presented in Section 3. Finally, we discuss the potential and limits of our approach in Section 4.

5.1.1. Case study region
The case study region is located in the Central Valais, a continental mountain area in the Swiss Alps (Figure 5.1). It includes the economically growing urban center Visp, the touristic Saas valley and the remote Baltschieder valley, and has a total of 11 municipalities. It covers an area of 334km² and is home to 15,346 residents. Unproductive land accounts for 62% of the area, while 20% is covered by forest and 16% is cultivated by agriculture. The mountain forests and grasslands provide a variety of ES: provisioning services, e.g., food and timber production, regulation and maintenance services, e.g., protection from natural hazards or biodiversity, and cultural services, e.g., cultural heritage and scenic beauty. The provision of ES is strongly influenced by climate change and human activities framed by socio-economic and political developments (Briner et al., 2012). In particular, land-use change is an important issue in the region. While the importance of agriculture is declining, touristic activities and settlement development are increasing steadily. In fact, about 14% of the agricultural land was abandoned between 1981 and 2005, while settlement expanded by over 30% and forest grew by 7% (SFSO, 2009). Between 2000 and 2012, the number of farms fell annually by 2.8%. In 2012, there were 161 active farms in the region which, on average, cultivated 8ha of agricultural land and housed around seven livestock units. Only 7% of the farms cultivated more than 0.5ha of arable crops (FOAG, 2008). Agriculture is highly subsidized, farmers in the region receive annual direct payments of around 3200 CHF/ha (SFSO, 2015b). Less than 10% of the farmers work full-time. Their main farming activity is the grassland-based production of livestock, predominantly larger dairy and beef/suckling cattle. By contrast, almost 50% of the part-time farmers keep sheep only (Brändle et al., 2015). Their farming practices substantially contribute to maintaining regional traditions, the typical character of the landscape and the provision of ES.

If observed land-use change trends continue, they will significantly affect the sustainability of ES provision in the region. The narrow socio-economic, political and ecological boundary conditions as reflected, for example, by the marginalization of agriculture, the high dependence on direct payments or steep altitudinal gradients, make the region especially susceptible to regional and global changes, e.g., in agricultural markets and policies, consumption patterns or migration and tourism (Briner et al., 2012). Actual policy programs often struggle with the formulation and implementation of effective mid- and long-term strategies to attenuate or mitigate the negative impacts of global change for several reasons: Long-term oriented strategies contain
Results

high uncertainties complicating the design and timing of policy interventions and they exceed typical election cycles and budgetary planning horizons of public institutions. Furthermore land use in the case study region is regulated, facilitated and constrained by a multi-level and multi-sectoral policy system. Policies of involved sectors, such as agriculture, forestry or spatial planning operate at different governmental levels and are discussed in different political arenas. Securing the long-term provision of ES in the case study requires policy-makers to better understand how their actions might change the ES supply from the short to the longer term, to consider trade-offs among policy options and to choose those actions that sustain the appropriate mix of services (Ash, 2010).

5.2. Methods and Data

5.2.1. Backcasting approach

Backcasting, as suggested by Robinson (1990), implies first creating a normative vision followed by looking back at how this desirable future can be achieved. Figure 5.2 illustrates the approach in four linked generic steps and shows how the approach is operationalized for application in ES assessments. The four generic steps are: (1) envisioning a normative desirable future, (2) describing boundary conditions relevant to the system, (3) designing and generating alternative transition pathways, and (4) assessing how well the pursued targets are achieved under different pathways.

Figure 5.1. The case study region in the Central Valais, southwest of the Swiss Alps.
To operationalize this general approach in a theoretical consistent manner, we base our backcasting approach on welfare economic theory. Welfare economic theory links combinations of goods or services that can be produced out of limited resources, with utility that expresses people’s priorities for these goods or services (Cavender-Bares et al., 2015). In our approach, we use ES demand for evaluating which pathways of ES supply are preferred and for quantifying the ES benefits they generate. We define *ES demand* as the preferences people express for different ES under a budget constraint (Geijzendorffer et al., 2015). We model ES supply based on production functions that describe land use and related ES supply under optimal allocation of available resources. The availability of these resources depends on ecological, socio-economic and political conditions. *ES supply* is thus defined as the type and quantity of services that are provided by an ecosystem as a combination of its natural functioning and its management (Geijzendorffer et al., 2015). *ES benefits* describe how the supplied ES affect people’s well-being according to their stated preferences (Tallis et al., 2012).

To implement the four steps of backcasting within this conceptual frame, we linked different methods and models: We used (1) a choice experiment for eliciting future ES demand, (2) a formative scenario analysis to sketch global socio-economic and political settings that govern future land use and the provision of ES, (3) an economic agent-based land-use model to (a) derive a set of land-use policy strategies that impact future ES supply based on an assessment of ES-relevant parameters in a sensitivity analysis and to (b) simulate alternative pathways of ES supply driven by these policy strategies, and (4) a utility function to assess ES benefits along each pathway. The different methods and models are linked in a way that one module delivers its output to another in the form of data files (step 1 to 4, step 2 to 3, and step 3 to 4) or qualitative information (step 1 to 2).

In the next paragraphs, we specify the rationale behind our choice of methods in the backcasting approach and provide detailed descriptions of data sources, methods and their linkages.

### 5.2.2. Choice experiment

To elicit future ES demand, we conducted a discrete choice experiment with local residents (Figure 5.2, step 1). Choice experiments have been applied in numerous studies to derive public preferences for alternative states of a set of ES (e.g., Adamowicz et al., 1994; Hasund et al., 2010; Huber et al., 2011; Shoyama et al., 2013; Ryffel et al., 2014). They offer several advantages relative to other ES valuation methods (e.g., Champ et al., 2012) in the context of our study. Firstly, participants are offered a set of feasible alternatives, each including a cost attribute. Thus, choice experiments link to the economic concept of demand based on utility maximization under a budget constraint (Louviere et al., 2010). Secondly, the responses allow an estimation of the value of marginal changes in

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**Figure 5.2.** Outline of the integrated backcasting approach: Bold titles delineate four generic steps of a backcasting analysis, subtitles show operationalization based on land use (LU) and ecosystem services (ES) in a welfare economic context, methods used in this study are given in italic. Arrows show qualitative and quantitative information exchanged between modules.
ES (Hanley et al., 1998). This is important because policy and management decisions normally act at the margin, that is, they deal with changing levels of ES, rather than with a complete loss or gain of services (Fisher et al., 2008). Finally, they are also applicable to non-marketable ES, such as cultural ES (Bateman et al., 2011).

The discrete choice experiment was designed to elicit how residents envision ES provision in the year 2035 and conducted between February and September 2013. Four regionally relevant ES and corresponding indicators were specified in an iterative stakeholder process (first column, Table 5.1). The focus on cultural ES reflects the perceived importance of agriculture to sense of place and an aesthetically attractive landscape. Two to four potential future states of each indicator (attribute levels) were defined based on discussions with 15 experts, among them forest managers, farmers, regional planners and local politicians, to guarantee that the scale of the experiment was meaningful and appropriate for the marginal analysis of ES changes (Table 5A.1, Appendix 5A). These attribute levels were combined into a total of 32 future visions using an orthogonal main effects design (Hensher et al., 2005). That is, the impractically large set of all possible combinations of attribute levels was reduced into an empirically feasible choice design. In the survey, participants had to perform six choice tasks in which they could choose between the current provision of ES and two alternative future sets of ES which were randomly selected out of the 32 visions. Each vision was described by four verbal attributes, the number of farms, the number of natural hazard incidents and the area of dry meadows as indicators for the ES cultural heritage, mass flow regulation, and habitat protection, respectively, plus a cost attribute. Four additional aesthetic attributes, the area of settlement, intensive grassland and forest areas as well as forest die-off, were merged into visualizations as a representation of landscape aesthetics (see Figure 5A.1, Appendix 5A for an example of a choice task).

After a pre-test (n=117), the survey was distributed to a sample of randomly selected 600 households in the case study region. In total, 260 questionnaires were returned (response rate 43%) of which 8 were omitted from further analysis, as respondents skipped the choice tasks. Based on the remaining 252 responses, we used the NLOGIT 5 software package and nested logit models to describe the choice behavior of people and statistically relate the discrete alternatives available to the participants (Louviere et al., 2000). Marginal utility coefficients were estimated for each ES indicator assuming a linear utility function with respect to the ES levels (Table 5.1). The utility of each attribute refers to its weight in decision-making inferred from stated choices on ES (Farber et al., 2002). Positive utility coefficients indicate a gain in utility with increasing amount of the ES indicator as, for instance, related to the area of dry meadows. Negative coefficients represent a loss in utility, for example due to an expansion of settlement area. The coefficients for all ES indicators were significant with the exception of “tree die-off”. Coefficients of the visual attributes were related to qualitative, i.e., dimensionless levels in the choice experiment (e.g., “one level more”). To convert the qualitative into quantitative levels in the visualizations we performed a picture analysis. We analyzed the share of different land uses among the visualizations by pixel counting and assumed the vistas to be representative for the whole region. This procedure proved to be a good proxy for depicting the visual magnitude of land-use types in mountain regions (Grêt-Regamey et al., 2007). The utility coefficients were used in the last step of the analysis to evaluate ES benefits along different ES transition pathways (Figure 5.2).

### Table 5.1.
Ecosystem services (ES) and respective indicators considered in the choice experiment, related marginal utility coefficients showing how much the utility for participants increases or decreases due to changes in the ES, and corresponding indicators modeled in ALUAM-AB.

<table>
<thead>
<tr>
<th>Choice experiment</th>
<th>ES indicators</th>
<th>Indicator type</th>
<th>Marginal utility coefficient ($\beta$) for 1% increase in indicator</th>
<th>Transition pathway modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultural heritage</td>
<td>Number of farms</td>
<td>verbal</td>
<td>0.031**</td>
<td>Number of farms</td>
</tr>
<tr>
<td>Mass flow regulation</td>
<td>Number of natural hazard incidents</td>
<td>verbal</td>
<td>-0.016**</td>
<td>Forest protection index</td>
</tr>
<tr>
<td>Habitat protection</td>
<td>Area of dry meadows</td>
<td>verbal</td>
<td>0.011**</td>
<td>Area of extensive meadows</td>
</tr>
<tr>
<td>Aesthetics</td>
<td>Forest area</td>
<td>visual</td>
<td>-0.232*</td>
<td>Forest area</td>
</tr>
<tr>
<td></td>
<td>Settlement area</td>
<td>visual</td>
<td>-0.164**</td>
<td>Settlement area</td>
</tr>
<tr>
<td></td>
<td>Intensive grassland area</td>
<td>visual</td>
<td>-0.021**</td>
<td>Area of intensive grassland</td>
</tr>
<tr>
<td></td>
<td>Forest die-off</td>
<td>visual</td>
<td>Not significant</td>
<td>Not modeled</td>
</tr>
</tbody>
</table>

Significance levels: *p < 0.05, **p < 0.001
**5.2.3. Formative scenario analysis**

As a frame for the backcasting analysis, trends of global exogenous processes relevant to the target ES must be made explicit (Figure 5.2, step 2). In our case study, we defined global socio-economic and political boundary conditions on the basis of two regionally downscaled global IPCC SRES scenarios that reflect potential developments of important drivers of land-use change and ES provision. Qualitative scenarios were developed using formative scenario analysis, a technique that combines expert judgments with a mathematical evaluation and optimization of these judgments (Walz et al., 2014). As compared to alternative concepts for downscaling scenarios (Zurek and Henrichs, 2007) this analysis ensures high consistency between the deduced scenarios and the parent scenarios and is less susceptible to personal biases.

The main scenario used in this paper conforms to the A2 scenario of the IPCC SRES and foresees an increasing importance of regional centers for preserving local identity and economic activity. Domestic support for the agricultural sector is maintained at current levels and market access remains restricted, guaranteeing higher producer prices in Switzerland as compared to the EU. The increasing accessibility of mountain regions coupled with a somewhat loose spatial planning policy promotes further settlement development (Walz et al., 2014). This scenario conforms best to a “business as usual” (BAU) development in the case study region.

To investigate the effect of alternative boundary conditions on the backcasting results we included a “liberalization” scenario consistent with the A1 IPCC SRES scenario. This setting implies rapid economic growth and global production processes that lead to a decline in the prices of agricultural commodities in Switzerland. Increased accessibility of remote regions, loose spatial planning policy and population growth leads to exploitive settlement development (Walz et al., 2014). Considerable temperature and precipitation shifts are expected in the longer term. However, no climatic effects, e.g., on yields or forest growth, were assumed within the time frame of this study. The two regionally downscaled scenarios thus reflect only socio-economic and political developments sketched in the IPCC SRES scenarios. The qualitative scenarios were translated into quantitative parameters to feed the land-use and ES model (Table 5B.1, Appendix 5B) based on national development scenarios (SFSo, 2013) and previous quantitative predictions of socio-economic development in the case study region (Briner et al., 2012; Huber et al., 2014) and in Europe (Abildtrup et al., 2006). If the model is thus run under the two baseline settings, it simulates ES supply under respective global changes, but with no additional policy actions taken in future.

**5.2.4. ALUAM-AB**

In our case study, we simulated the supply of target ES (i.e., the same ES as considered in the choice experiment) with the economic agent-based land-use model ALUAM-AB (Alpine Land Use Allocation Model – Agent Based) using Linear Programming Language and a CPLEX solver (Briner et al., 2012; Brändle et al., 2015). Similar to other agent-based models (Filatova et al., 2013), the purpose of ALUAM-AB is to simulate future changes in land use and ES supply triggered by the combined effects of climate, market and policy changes while considering individual behavior of agents. ALUAM-AB is useful in a backcasting context for several reasons: The recursive-dynamic modeling simulates intermediate yearly time steps, hence, allows system dynamics to be tracked over time. Furthermore, the effect of larger scale socio-economic and political drivers and individual farmers’ behavior which lead to a spatially explicit land-use pattern can likewise be explored. The model has been developed over years and is specifically tailored to the case study (Briner et al., 2012; Briner et al., 2013b; Huber et al., 2014; Brändle et al., 2015). As inherent characteristics of the region, such as land management types and physical resource constraints are accounted for, causal structures are well represented. On the one hand, this empirical grounding increases the credibility of the model and its value for operational decision support and decreases the risk of misleading information on alternative policy actions (Kelly et al., 2013). On the other hand, it improves the validity of the model. ALUAB-AB was validated against observed livestock and land-use data. Overall and unequal variation errors of model performance were small (on average 6.5%), thus, ALUAM-AB captures the mean and trends of the observed data satisfactorily (Brändle et al., 2015). Finally, the concept of income maximization under various socio-economic constraints captures farmers’ situation in the case study region. At the same time, it roots the model in economic theory and allows the conceptual link with the choice experiment.

ALUAM-AB simulates land-use decisions in yearly time steps assuming that agents are profit maximizers who make the best out of limited resources. Decisions on different level – parcel level, farm level and regional level – are optimized in a way that aggregated land rent is maximized. Different constraints assure that restrictions on different levels are met: On the parcel level, locational factors influence the choice of the land-use activity, on
the farm level nutrient and fodder balances constrain livestock activities, and hirable workforce and number of animals available for grazing on summer pastures restrict decision-making on regional level. Agents in the model represent types of farms in the case study region. They have been derived from interviews with 15 local farmers and a farm survey (n=111) combined with an analysis of agricultural census data. Agents differ in their household composition, their available resources (land, capital, labor) and their specific type of decision-making reflected by differing opportunity costs of labor, minimal income levels or household composition. Interaction between agents is represented by an exchange of land units. The model identifies land units that are no longer cultivated and either assigns a corresponding parcel to another agent, who can generate profit from the parcel and is willing to expand, or defines the parcel as abandoned in which case it is subject to forest growth.

To simulate these processes, ALUAM-AB relies on four input data sets: (1) maps of potential yields of all agricultural activities generated by a crop yield model (Briner et al., 2012), and of forest activities generated by the forest-simulation model LandClim (Schumacher et al., 2004), (2) spatially explicit data assembled for each parcel (100m x 100m), e.g., slope, elevation, distance to the next farm or the soil suitability (Swisstopo, 2005; FOAG, 2008; SFSO, 2009), (3) specific farmer agent characteristics obtained from stakeholder surveys as described above (Brändle et al., 2015), and, (4) yearly data of parameters reflecting the global scenario, such as market prices for agricultural commodities or population development.

We extended ALUAM-AB with an additional selection algorithm that defines the most suitable parcels for settlement development to account for changes in the settlement area (for details see Appendix 5C). Prior to the optimization process each parcel is characterized by five location factors: elevation, slope, distance to road, distance to centers and view on mountains (Swisstopo, 2004, 2005). A suitability score for settlement development is then assessed for each parcel based on normalized scores for each location factor, an equal weighing of all factors and a neighborhood effect (Garcia et al., 2009; Abdullah, 2014). If population development, as defined in the two baseline settings, demands additional settlement parcels, the land units with the highest suitability score are assigned to the settlement area in each simulation year.

Results in ALUAM-AB can be represented by land-use and ES maps and by aggregated regional values of ES for each simulation year. Indicators for ES supply in ALUAM-AB were defined as equal as possible to those in the choice experiment (right column, Table 5.1). The number of farms served as a proxy for the cultural heritage service. The area of extensive meadows was used to approximate the habitat protection service. Aesthetics were assessed based on the share of different land-use types. Mass flow regulation was assessed with a forest protection index that describes the ability of a parcel to provide protection from all gravitational hazards (Briner et al., 2013b). The index was calculated in LandClim for each parcel in the case study region and transferred to ALUAM-AB, where, in the optimization process, the index was allocated only to those parcels used as forest or fallow land.

5.2.4.1 Sensitivity analysis to design policy strategies
We derived a set of effective policy interventions for the backcasting analysis based on a sensitivity analysis of ALUAM-AB (Figure 5.2, step 3a). We identified the most important exogenous factors affecting model outcomes using elementary effects (Morris, 1991). Elementary effects show the degree and nature of a change in a specific output variable induced by a relative change in a single input parameter, e.g., how much the number of animals increases or decreases if the milk price drops. We calculated the impact of changes in 13 input parameters related to prices and costs, to direct payments and to agent characteristics, on land rent and the number of animals, since this output is highly correlated to ES provision in our case study (Briner et al., 2013b). Furthermore, we analyzed how combinations of these parameters affect model outcomes to account for non-linearities and interactions between exogenous factors driving ALUAM-AB (Uusitalo et al., 2015). Opportunity costs, i.e., benefits foregone due to alternative uses of labor, and production and input prices, especially milk and lamb prices, emerged as the main single exogenous drivers of the model. In addition, an interaction of changes in several parameters had an essential impact on livestock and thus ES changes (Brändle et al., 2015).

Based on these findings, we designed an initial set of three agricultural policy interventions for subsequent modeling of ES supply. Each intervention was described by a combination of modifications in several exogenous ES-relevant parameters (Table 5.2). We assessed the effect of a continuous opening of protected Swiss agricultural markets by a decline in prices of all agricultural commodities. A change in the system of national direct payments was represented by an increase in green direct payments (payments for extensive grassland and for grassland-based milk and meat production), monetary incentives for animal husbandry on summer pastures and an abolition of general area-based payments.
Results

selected combinations of two or three interventions in different sequencing (40 model runs). Finally, we assessed the effect of structural interventions at four additional levels (16 model runs). To investigate how a change in boundary conditions impacts ES supply and the effectiveness of policy strategies, we repeated all model runs under the liberalization scenario (72 model runs). Table 5B.3 (Appendix 5B) provides an overview on the sequencing of interventions in all performed model runs.

5.2.5. Utility function

In the final step of the backcasting analysis, each modeled pathway must be evaluated with respect to the desirable future elaborated in the choice experiment. We used the marginal utility coefficients from the choice experiment (i.e., ES demand) to assess changes in the benefit people would obtain from ES changes under different policy strategies (i.e., ES supply; Figure 2, step 4). Similar to other studies modeling the impact of different land-use change scenarios on the quality of life (Labiosa et al., 2013; Murray-Rust et al., 2013), we derived an additive utility function to quantify the ES benefit change (McFadden, 1973).

\[
\Delta U_{\text{tot}} = \sum \beta_i \cdot \Delta I_i
\]  

(5.1)

The status quo alternative specific constant of 0.181 was subtracted from the utility to correct the systematic preference for the status quo in the choice experiment.

Table 5.2. Basic set of policy interventions implemented in ALLUM-AB, based on which the impact of land-use policy strategies on ecosystem services (ES) supply was modeled.

<table>
<thead>
<tr>
<th>Policy intervention</th>
<th>Impact on driver(s) of ES change</th>
<th>Policy sector</th>
<th>Level of implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market opening*</td>
<td>Decline in prices for agricultural commodities, i.e., milk, meat, crop and breeding</td>
<td>Agriculture</td>
<td>National</td>
</tr>
<tr>
<td>Targeted direct payments</td>
<td>Increase in payments for extensive grassland, for grassland-based milk and meat production and for summering; abolition of general area-based payments</td>
<td>Agriculture</td>
<td>National</td>
</tr>
<tr>
<td>Structural interventions</td>
<td>Decrease in opportunity costs of labor and minimum income to remain in sector, increase in household labor availability and probability of farm succession</td>
<td>Agriculture</td>
<td>Regional</td>
</tr>
<tr>
<td>Restrictive spatial planning</td>
<td>Restricted settlement area granted per additional resident, i.e., no additional land used for settlement</td>
<td>Spatial planning</td>
<td>Regional</td>
</tr>
</tbody>
</table>

*Under a liberalization scenario the market intervention is opposite, i.e., inland markets are being gradually protected resulting in an increase of agricultural commodity prices.

Structural interventions were implemented as financial aid for farmers. We included general monetary support to lower their opportunity costs for labor as well as the minimum income level below which they would exit the sector, and to increase their household labor availability. These payments were combined with special monetary support for young farmers to increase their willingness to succeed retiring farmers. A more restrictive spatial planning policy, i.e., a reduction of the settlement area for new residents, to prevent further urban sprawl, was added as a fourth intervention to include another policy sector relevant to the target ES. A detailed overview on the modification of the parameters related to each intervention is provided in Table 5B.2 (Appendix 5B).

5.2.4.2. Modeling ecosystem services transition pathways

Based on the elaborated set of policy interventions (Table 5.2), we modeled various pathways of ES supply (Figure 5.2, step 3b). The interventions were implemented in the model in different combinations and sequences at four different points in time to describe a wide range of alternative policy strategies. We started implementing policy strategies in 2018, since the current agricultural policy program was set up for the policy cycle until 2017 and any changes of the agricultural sector within this period are unlikely (Hirschi et al., 2013). Furthermore, the policy strategies were designed to be economically and politically plausible to increase the credibility of the backcasting analysis (Mahmoud et al., 2009).

Given the BAU scenario, we first analyzed the effect of policy strategies that were composed of single interventions, i.e., each of the four interventions was introduced in 2018, 2022, 2026 or 2030, corresponding to the policy cycle in which agricultural programs are updated in Switzerland (16 model runs). We then tested selected combinations of two or three interventions in different sequencing (40 model runs). Finally, we assessed the effect of structural interventions at four additional levels (16 model runs). To investigate how a change in boundary conditions impacts ES supply and the effectiveness of policy strategies, we repeated all model runs under the liberalization scenario (72 model runs). Table 5B.3 (Appendix 5B) provides an overview on the sequencing of interventions in all performed model runs.
Positive changes of $\Delta U_{\text{tot}}$ indicate a gain in the benefits resulting from changes in ES, while negative changes denote a loss in the benefits as compared to 2013. In this function, the utility change is driven by quantitative changes in the ES while people's preferences are kept constant over time (Boyd and Banzhaf, 2007).

We evaluated the effect of policy strategies on the utility in three steps: (1) We analyzed utility changes induced by alternative policy strategies over time comparing single interventions, combined interventions and different levels of structural interventions given two different boundary conditions as described above. (2) To unravel ES trade-offs caused by policy interventions, we analyzed separately the effect of interventions on the supply of individual ES and on the related contribution of the single ES to the total utility change. (3) To address the impact of the timing of interventions, we analyzed the average response of the utility to each intervention compared to the baseline run, regardless of the implementation year.

5.3. Results

Results of the backcasting analysis highlight three aspects important for the identification of land-use policy strategies for matching regional ES supply and demand in our mountain case study region: (1) They show which policy strategies increase the utility of ES over time, (2) they illustrate ES trade-offs caused by policy interventions and explain how policy interventions, ES supply and demand are linked, and (3) they inform on the best timing for implementing different interventions with regard to the planning horizon in 2035.

5.3.1. Changes in utility over time

Figure 5.3 and Figure 5.4 show how different types of policy interventions (Figure 5.3a and 5.4a), in different combinations (Figure 5.3b and 5.4b) and related to different levels of structural interventions (Figure 5.3c and 5.4c) change the utility of ES in the case study region assuming two global change scenarios. The utility decreases along all modeled pathways indicating a divergence between ES supply and preferences for future ES provision. In the baseline setting (black line), if no actions are taken but the demographic trend continues as observed, the utility as compared to the present drops by more than 3 given a BAU (Figure 5.3) and by nearly 8 given a liberalization scenario (Figure 5.4).

Assuming BAU boundary conditions, agricultural policy interventions are most effective in increasing the utility of ES at the planning horizon relative to the baseline (Figure 5.3a). A targeted scheme of direct payments (green lines) reduces the loss in utility in 2035 by more than a third and structural interventions that support local farmers (red lines) by at least one fifth. Upon implementation at the beginning of any policy period both interventions lead to a recovery of the gradually falling utility related with the inaction baseline. A restrictive spatial planning policy (purple lines) attenuates the utility loss from the moment of enforcement with slightly positive impact on the utility in 2035. In contrast, an opening of agricultural markets (blue lines) amplifies negative changes in the utility of mountain ES.

Figure 5.4a illustrates the effect of the same interventions on ES utility given a liberalization scenario. The most distinct difference as compared to Figure 5.3a is the massive drop of utility in case no policy actions are taken, as illustrated by the black line. In the liberalization scenario, the market intervention is opposite than in the BAU scenario, i.e., inland markets are being gradually protected resulting in an increase of agricultural commodity prices. The blue lines demonstrate that, contrary to an opening of markets (Figure 5.3a), such an action can mitigate the large utility loss, however only if implemented as early as 2018. This indicates that market protectionism as it exists currently in Switzerland contributes to securing the provision of demanded ES. While restricting the spatial planning activities has more impact on the utility as in the BAU scenario (purple lines), the relative efficiency of the other two interventions is similar in both scenarios.

Figure 5.3b shows utility changes caused by policy strategies that introduce structural support and at the same time or in a subsequent policy cycle another intervention, in a BAU setting. Such combined strategies are more likely to enhance the utility than isolated interventions (Figure 5.3a), especially if structural interventions are combined with a reform in agricultural direct payments or a restrictive spatial planning policy. The dashed green and purple lines indicate how the implementation of a second intervention improves the performance of a policy strategy. Dashed purple pathways do not merge at the time horizon in 2035, thus, combined spatial planning and structural interventions are more effective if implemented early in time. In contrast, alternative strategies combining adjusted direct payments and structural interventions result in a similar utility in 2035, as illustrated by the convergence of the dashed green lines over time. This implies a certain decision scope for policymakers regarding the sequencing of these interventions. The dashed blue lines show that the adverse effect of a market opening on the utility can be substantially attenuated if structural interventions are implemented prior to, or at the same time as market
Figure 5.3. Effect of different policy strategies on the utility of ecosystem services compared to 2013 in a business as usual scenario: (a) single interventions, (b) combined interventions, (c) increasing levels of structural interventions and faster structural change.
Figure 5.4. Effect of different policy strategies on the utility of ecosystem services compared to 2013 in a liberalization scenario: (a) single interventions, (b) combined interventions, (c) increasing levels of structural interventions and faster structural change. Note the different scaling of the axes than in Figure 5.3.
Changes. Thus, given the preferences for ES in our case study region, regional structural interventions can build resilience to provide desirable ES against national and international market developments. A coupling of all three interventions mitigates the utility decrease most effectively (dotted brown lines). This suggests that an integration of different sectoral policies operating at different levels is a promising strategy to match ES supply and demand in our case study region.

Figure 5.4b pictures that the relative efficiency of combined policy strategies in a liberalization scenario is similar as in the BAU scenario: Strategies that establish three interventions are most beneficial (dotted brown lines) and structural interventions combined with targeted direct payments (dashed green lines) result in a larger recovery of the utility loss than combined with restrictive spatial planning or market interventions (dashed purple and blue lines). This indicates that a similar set of policy strategies might be robust and enhance ES benefits independent of the development of global boundary conditions. While the increase in utility upon implementation of a specific policy strategy is higher relative to its effect in the BAU setting, the utility in 2035 remains lower in any of the modeled pathways. For example, starting with a combination of three interventions in 2018 enhances the utility over the planning period as compared to the baseline up to 1.7 given the BAU (Figure 5.3b), and up to 6.5 given the liberalization scenario (Figure 5.4b). Still, in 2035 the utility is 0.5 lower assuming a more globalized world. This comparison illustrates that both the effectiveness and the urgency of policy actions to secure mountain ES depend on the boundary conditions and that global change will contribute to how much ES supply and demand can be balanced, especially if no adaptive policy actions are taken.

Given a BAU scenario, an increase in the level of support for local farmers through structural interventions has only a minor impact on the utility as implied by the converging dashed lines in Figure 5.3c. This indicates that structural support is only useful up to a certain threshold level above which additional interventions do not pay off. By contrast, in a liberalization scenario, higher levels of structural support can attenuate the distinct utility loss, especially if implemented early in time. In both Figures 5.3c and 5.4c, the dotted lines indicate that structural change is an important determinant of the change in utility in the mountain region. An acceleration of structural change, i.e., a faster abandonment of farms, decreases the utility of ES substantially below the baseline. In a liberalization setting, the system approaches a state in which the utility gets highly sensitive to structural changes and directly reflects yearly abandonment of farms.

5.3.2. Ecosystem services trade-offs under different policy strategies

The changes observed in the utility can be explained by ES trade-offs driven by different policy interventions. Figure 5.5 shows how the supply of individual ES changes over time (left axis) and how strongly these changes translate into utility changes (right axis) in a BAU setting. The different scales of the utility axis among the plots indicate that people expressed differing preferences for individual ES. The colored bands span the range of changes that emerge from implementing one type of intervention at different points in time. They thus show the sensitivity of single ES towards different policy interventions. The distinct decrease of utility in the baseline setting (Figure 5.3a, black line) is caused by settlement development and forest expansion that reduce the aesthetics of the mountain region (Figure 5.5c and 5.5d), as well as by a decline in the number of farms that negatively impacts the cultural heritage service (Figure 5.5e). The simultaneous conversion of intensive to extensive grassland is beneficial in terms of aesthetics and habitat protection, but these benefits cannot outweigh the losses in utility. As the right axes of Figure 5.5a and 5.5b illustrate, the changes in agricultural land-use types contribute less to changes in the utility than changes in settlement and forest area. Hence, two factors determine how effectively an intervention enhances the utility relative to this baseline: (1) the sensitivity of ES supply towards the policy intervention and (2) the preferences people expressed for different ES, quantified by the marginal utility coefficients (Table 5.1).

Altering the system of direct payments influences the aesthetics of the mountain region and affects the habitat protection service. Payments for summer pastures encourage farmers to keep cattle on these upland pastures. This hinders the regrowth of forest and the utility is substantially enhanced when compared to the baseline (Figure 5.5d) as people expressed an aversion to forest expansion for aesthetic reasons (Table 5.1). Since more animals are kept for grazing, the conversion of intensive into extensive grassland is not as distinct as in the baseline scenario implying a relative loss in habitat protection (Figure 5.5a and 5.5b). However, residents expressed lower preferences for habitat protection and aesthetics of grassland. That is, ES trade-offs emerging from this policy intervention substantially enhance the utility. A similarly strong, but adverse effect on the utility is caused by an opening of agricultural markets. The decline of prices for agricultural commodities forces
farmers to give up many agricultural land-use activities, especially cattle farming. This leads to an expansion of the forest area (Figure 5.5d). The resulting loss of the utility disproportionally diminishes the positive impact of this intervention on the increased share of extensive grassland (Figure 5.5a and 5.5b). More restrictive spatial planning has only marginal effects on agricultural and forest land uses. The utility, however, increases compared to the baseline setting (Figure 5.3a), since settlement development is attenuated with a positive effect on the aesthetics of the mountain region (Figure 5.5c). Structural intervention to support young farmers and maintain the regional workforce is the only way to counteract the closure of farms and the related loss of utility (Figure 5.5e). As the right axes of Figure 5.5c and 5.5e illustrate, without appropriate interventions both settlement expansion and the decreased supply of cultural heritage are important drivers of the utility loss along all pathways. The modeled interventions only marginally affect mass flow regulation, since natural forest growth on former pastures does not occur in avalanche or rockfall release areas and climate change has no impact yet (Figure 5.5f).
5.3.3. Timing for implementing policy interventions

The backcasting approach allows not only assessing the impact of policy interventions on the utility of ES over a defined planning period, but also how fast or slow the utility changes occur once these interventions are implemented. Figure 5.6 visualizes the rate of change in the utility compared to the baseline setting when implementing different policy interventions in a BAU scenario. As we implemented interventions at different points in time in the model, we could compare the effect of each intervention with regard to its duration between four pathways. Rates given in Figure 5.6 show an average response of the utility to each intervention upon enforcement in 2018, 2022, 2026 and 2030. Relatively small standard deviations indicate similar temporal effects of policy interventions during the planning period considered. A change of direct payments provokes an immediate gain in the utility but the curve levels off after the implementation period of four years (green diamonds). This indicates that there is a limit to the scope of improvement that can be achieved by means of specific monetary incentives for mountain farmers. Thus, a reallocation of direct payments is a useful strategy if a rapid adaption to ES demand is required in the region. However, the timing of the intervention is less important with regard to a mid-term planning horizon in 2035 (cf. Figure 5.3). Similarly, we observe a distinct increase in the utility due to structural interventions within the first years but only marginal gains in the longer-term (red squares). By contrast, the rates of change in the utility induced by an opening of the markets and a restrictive spatial planning policy are more linear, indicated by the blue circles and the purple triangles. Regional spatial planners are thus well advised to restrict settlement development as early as possible since the positive impact on the utility grows continuously during the term of the intervention.

5.4. Discussion

In this paper, we propose a novel backcasting approach for application in ES modeling. The approach coherently links normative and explorative methods for assessing which policy strategies best match future ES supply and demand – an integration that is currently lacking in ES assessments (Rounsevell et al., 2012; Brown et al., 2013; Bagstad et al., 2014; Geijzendorffer et al., 2015). Analysis of ES in our backcasting approach complements knowledge gained in existing forecasting studies in three ways: Firstly, backcasting not only makes it possible to evaluate combinations of ES that are more beneficial at some point in future, but also to explore the processes that might produce such an ES supply (Brown et al., 2013). The results of our analysis explicitly show the dynamic relationships between policy interventions, land-use, ES and resulting benefits over time. In our study, we identified changes in forest and settlement area related to aesthetic services as especially critical for generating ES benefits. As a consequence, policy interventions that prevented from forest and settlement growth increased the overall benefits. Secondly, in contrast to many forecasting studies that rely on few scenarios only, the modeling of various policy strategies extends and refines the scope of potential outcomes and allows for the assessment of path dependency (Koomen et al., 2008; Rounsevell and Metzger, 2010; Cavender-Bares et al., 2015). Our results illustrate that ES benefits depend on the type and timing of policy interventions and on concomitant changes of other political actions. Thus, backcasting can inform on necessary policy actions in time scales that influence the work of institutions and individual decision-makers (Bryson et al., 2010). Thirdly, future ES supply depends on different sectoral policies, such as agricultural or forestry policy and cross-sectoral policies, such as spatial planning. The backcasting approach can evaluate how effectively interventions from different policy sectors change ES and unravel trade-offs behind these changes. This can facilitate the design of a well-founded package of interventions and support integrative policy-making processes.

Contrary to other approaches that have assessed ES demand and supply in decoupled steps (Geijzendorffer et al., 2015), in our approach, we link existing methods and models for the quantification of supply and demand based on a welfare economic framework. Such an integrated approach is especially suitable for representing complex and interlinked socio-economic, ecological and political processes operating at different scales (Hamilton et al.,
The repeated application of all involved components by researchers in their corresponding fields guarantees that mechanisms and concepts of all components have been thoroughly tested (Hewitt et al., 2014). On the other hand, the uncertainties inherent to each model and method remain, thus, addressing uncertainties in integrated approaches is challenging (Giupponi et al., 2013). In the following, we discuss the main uncertainties along with the advantages and limitations of each method linked in the backcasting approach.

In the first step of the backcasting approach, we used a choice experiment to assess demand for ES, since it allowed the inclusion of regionally relevant cultural ES (Bateman et al., 2011). However, in choice experiments only a narrow set of ES can be included (Louviere et al., 2000) and considering more ES in the analysis could refine and potentially broaden the set of suitable development options. On the one hand, the method allowed engaging a large number of stakeholders in developing a quantitative vision of future desirable ES provision, contrary to many participatory backcasting studies that draw a qualitative normative goal from workshops with a limited number of experts (Vergrat and Quist, 2011). On the other hand, the one-time assessment of preferences did not enable interactions between stakeholders and mutual learning processes (Quist and Vergragt, 2006). In addition, our approach assumes that people can envision ES at a distant planning horizon and that their demand for services does not change over time. In reality, societal values are not inert but change over time (Kumar et al., 2013; Voinov et al., 2014). In particular, people might adapt to ongoing land-use changes and perceive a future differing ES provision to be less negative than envisioned at the present moment (Hunziker et al., 2008). The preferences regarding the direction of changes in ES, however, are in line with other studies in mountain regions (Grêt-Regamey et al., 2007; Hunziker et al., 2008; Olschewski et al., 2012), thus, the relative performance of policy alternatives likely remains valid. Longitudinal studies of preferences and repeated participatory workshops could improve the backcasting approach through the engagement of stakeholders in a reflexive and iterative process that supports social learning (Robinson et al., 2011), and enable formulating adaptive policy recommendations (Murray-Rust et al., 2013). Given these uncertainties, the time horizon of the backcasting analysis should be chosen carefully and the normative vision be considered as a conservative lower boundary of acceptable ES changes (Baveye et al., 2013). The 2035 time frame of our approach spans approximately one generation which is reliable regarding both the normative vision and the ES modeling: Participants of the choice experiment still care for what happens to their children (Vergragt and Quist, 2011), and, the assumptions regarding agent-behavior and characteristics in the land-use and ES model are not violated.

To simulate ES supply we used an agent-based economic optimization model that allocates land-use activities by maximizing farmers’ income under socio-economic, ecological and political constraints. This model choice guarantees that ES supply follows an economic production function while considering specific decision-making processes in marginal areas (Schreinemachers and Berger, 2011; Pinter and Kirner, 2014; Brändle et al., 2015; Huber et al., 2015). Understanding how ES providers respond to changing boundary conditions and incentives is vital for the design of regionally relevant policy interventions that match ES supply and demand in future (Nelson and Daily, 2010). Results, however, do not consider the uncertainty inherent in farmers’ reaction to policy changes along a simulated pathway. Furthermore, changes in indicators for ES depend linearly on land-use changes which represents a simplification of interaction and feedback effects (Bennett et al., 2009; Cavender-Bares et al., 2015). More information on minimum levels of land-use types and structures needed for continued ES delivery specific to our case study could help setting constraints to our model (Grêt-Regamey et al., 2014).

To generate different ES transition pathways, we modeled the impact of various policy strategies on ES benefits given two predictions of socio-economic boundary conditions, a business as usual and a liberalization scenario. Key uncertainties in this step of the analysis relate to the choice of policy strategies, their quantitative parameterization in the model and uncertainties inherent to the boundary conditions. We followed a two-step procedure for reasonably well capturing the sensitivity of our model with regard to policy options. First, we used elementary effects (Morris, 1991) to identify single socio-economic and political input parameters to which ES supply is most sensitive. We then combined these parameters into a set of four policy interventions which we implemented in different combinations and sequencing and at different points in time. The resulting transition pathways represent a multifaceted set of variations in several components of the system and provide a dynamic view of possible future ES supply as well as of the sensitivity of ES towards policy interventions (Refsgaard et al., 2007; Mahmoud et al., 2009; Scholes et al., 2013). Uncertainties in the model parameterization were accounted for by testing several quantitative levels of policy options and by adopting numerical values that lie within a politically feasible range, that is, in the range...
of governmental investments that have been made in past policy reforms in Switzerland. Finally, assumptions regarding future socio-economic boundary conditions were addressed by providing information on how various policy strategies play out under two different scenarios. While results indicate that the magnitude of the effect of policy strategies on ES will differ depending on the boundary settings, our findings regarding the relative importance of the interventions are consistent across the two tested scenarios. Future research should continue to explore the effect of different boundary conditions on the backcasting results in order to identify policy strategies that are robust under multiple projections of global change and to compare the sensitivity of ES towards global change on the one hand and towards regional and national policy strategies on the other hand.

We used the change in utility determined on the basis of a linear combination of preferences for ES to evaluate changes in ES benefits along different pathways of ES supply. While utility functions have been used for assessing the impact of different land-use scenarios on the quality of life (Labiosa et al., 2013; Murray-Rust et al., 2013), no study so far has applied them to consistently link an economic valuation of ES with an economic-based model simulating ES supply. The utility function, however, depends on the utility coefficients which are (i) assumed to be linear with respect to the ES levels, (ii) averaged among all respondents, and (iii) not spatially explicit. The assumption of linearity in our model makes the analysis problematic when approaching a threshold where marginal benefits of ES suddenly change disproportionally (Fisher et al., 2008). The uncertainty related to where these thresholds lay and where in time they might be crossed makes it difficult to determine when marginal analysis ceases to be appropriate (Farley, 2012). In addition, while the modeled changes in ES at the planning horizon lie above the incremental changes people perceived as positive or negative in the choice experiment, the smooth temporal utility curves might not reflect that minor gradual changes in a landscape often occur unnoticed by residents until a certain threshold is reached (Bieling, 2013). Social groups may exhibit different preferences (Hunziker et al., 2008) which must be explored and addressed if results of the backcasting analysis are discussed in a stakeholder dialogue (Rounsevell et al., 2012). In this context, a quantitative indicator and its graphical representation may, on the one hand, help policy-makers understand the relative importance of various interventions or the time required for them to take effect (Gomi et al., 2011). On the other hand, in participatory processes the highly synthesized, condensed and reduced information should be supported by appropriate documentation, for example on trade-offs along different pathways between ES or between ES and other socio-economic criteria. Finally, people request specific services, especially cultural services to be provided at specific locations (Geijzendorffer et al., 2015), whereas the utility approach is restricted to inform on ES mismatches on a regional level. To map demand for cultural ES, preference analyses have been completed with use-data or other characteristics of cultural sites (Wolff et al., 2015). Coherent values-based spatially explicit methods for assessing ES, however, are lacking (Rounsevell et al., 2012). To account for spatially explicit ES demand, our backcasting approach could profit from strategic local and regional land management plans. Such documents could help prioritize among a set of policy options with similar impact on aggregated regional ES benefits, but different spatial ES supply. The aggregation of locally differing ES demand and supply was a major criticism when we tested the policy relevance of the approach in practice. We integrated the modeling results in a preliminary decision-support platform and presented the platform to a group of ten local stakeholders, including farmers, municipal and cantonal spatial planners and politicians. Based on six policy pathways stakeholders could interactively explore the effects of the alternative strategies on ES supply. General feedback was positive, especially regarding the possibility to compare different currently discussed and regionally relevant policy options and the integration and representation of different sectors. However, participants suggested improved spatially explicit representation of local preferences and ES supply to support joint regional policy-making processes that account for specific characteristics and needs of involved communities.

The following three additional aspects were not addressed and should receive further attention in the application of the backcasting approach: (i) Efficiency of policy strategies, i.e., costs, also including transaction costs and public spending in relation to the benefit they generate (Fisher et al., 2008). While the costs for some interventions, e.g., changes in direct payment schemes are easy to appraise, an estimation of costs and benefits related to others, e.g., an opening of agricultural markets, remains a big challenge due to off-site effects (Seppelt et al., 2011; Liu et al., 2013). (ii) Equity, i.e., the distribution of costs and benefits related to different policy strategies among society, government and ES managers. Such analyses are important for designing policy strategies that minimize the divergence between net private and social benefits (Polasky et al., 2011b). (iii) Sustainability and long-term provision of ES. Navigating the trade-offs between different ES in a way that does not compromise
the natural capital needed to provide services in the future is essential for achieving sustainability (Cavender-Bares et al., 2015). It is critical whether regional preferences for ES can generate visions that do not come at the cost of negative impacts on critical natural capital in the longer term and sufficiently consider the sustainability perspective (Iwaniec et al., 2014). Employing more rigorous visioning methodologies that strictly adhere to a set of reference criteria can help face the critical task of creating both a shared desirable and sustainable vision (Wiek and Iwaniec, 2014). In addition, the agent-based modeling approach is critical for analyzing the impact of long-term effects such as climate change on ES trade-offs. To complement our short-term study and account for possible differential impacts on longer time scales, we suggest applying the same model, but with more attention given to the global level interactions and consequences on ES provision (Rounsevell et al., 2012; Brändle et al., 2015).

5.5. Conclusion
We present a backcasting approach to infer land-use policy strategies for matching regional ES supply and demand. The approach is a first step towards an integration of explorative modeling and normative visions in ES assessments in a consistent framework. Applied to a case study, the approach unraveled the consequences of different policy strategies on ES over time by making explicit the linkages between policy interventions, land-use, ES and the societal benefits they generate. Backcasting, as compared to a forecasting approach, can integrate societal values as lower boundaries for future ES provision and generate temporal information of added value for policy-making processes. Especially, backcasting can pinpoint crucial land-use decisions in time and show the sensitivity of ES towards regional policy interventions given global boundary conditions. Including further global scenarios in the analysis could improve the identification of robust policy pathways that mitigate uncertain negative effects of global change on ES benefits at the regional scale.

Acknowledgements
This work was supported by the CCES (Competence Centre Environment and Sustainability of the ETH Domain, Switzerland) as part of the inter- and transdisciplinary research project MOUNTLAND, by the European Union Seventh Framework Programme as part of the project OPERAs and by the Swiss National Research Programme NRP68 as part of the project OPSOL. We thank the anonymous reviewers for their constructive and helpful comments on earlier versions of the manuscript.
Appendix 5A: Choice experiment

Table 5A.1. Choice experiment attributes and levels defined based on an iterative stakeholder process.

<table>
<thead>
<tr>
<th>ES indicator</th>
<th>Levels</th>
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</thead>
<tbody>
<tr>
<td>Number of farms</td>
<td>50 farms less, 25 less, 10 less, status quo</td>
</tr>
<tr>
<td>Number of natural hazard incidents within 10 years</td>
<td>8 incidents less, 4 less, status quo, 4 more</td>
</tr>
<tr>
<td>Area of dry meadows and pastures</td>
<td>40 ha less, status quo, 40 ha more, 60 ha more</td>
</tr>
<tr>
<td>Forest area</td>
<td>Status quo, tree die-off (lower elevations)</td>
</tr>
<tr>
<td>Settlement area</td>
<td>Status quo, expansion (higher elevations)</td>
</tr>
<tr>
<td>Intensive grassland area</td>
<td>Status quo, expansion (lower elevations)</td>
</tr>
<tr>
<td>Income change per year and person by changes in tax statement</td>
<td>6% less, 3% less, status quo, 3% more, 6% more</td>
</tr>
</tbody>
</table>

Figure 5A.1. Exemplary choice set (translated from German): Participants had to choose between the current provision of ecosystem services (ES) and two alternative future sets of ES.
Appendix 5B: ALUAM-AB model specifications

Table 5B.1. Qualitative levels of important exogenous factors (Walz et al., 2014) and related parameter values in the business as usual and the liberalization scenario.

<table>
<thead>
<tr>
<th>Factor</th>
<th>“Business as usual” scenario</th>
<th>“Liberalization” scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qualitative level</td>
<td>Parameter values</td>
<td>Qualitative level</td>
</tr>
<tr>
<td>Parameter values</td>
<td></td>
<td>Parameter values</td>
</tr>
<tr>
<td>Climate</td>
<td>A2: Crop yield and timber harvest according to Briner et al. (2012)</td>
<td>A1: Crop yield and timber harvest according to Briner et al. (2012)</td>
</tr>
<tr>
<td>Population CH</td>
<td>75 Mio.: Regionally-downscaled medium growth population development scenario for Switzerland (SFSO, 2013)</td>
<td>9.5 Mio.: Migration to agglomeration</td>
</tr>
<tr>
<td>Migration within CH</td>
<td>Regional centers</td>
<td></td>
</tr>
<tr>
<td>Accessibility of mountain regions</td>
<td>High increase</td>
<td>High increase</td>
</tr>
<tr>
<td>Agricultural markets</td>
<td>Stable prices (border protection)</td>
<td>Large decline in prices (open markets)</td>
</tr>
<tr>
<td>Agricultural policy</td>
<td>Reduced domestic support Direct payment scheme according to the recently enacted federal agricultural policy directive (DZV, 2013)</td>
<td>Liberalization Abolishment of general area-based direct payments and payments for grassland-based milk and meat production, otherwise direct payment scheme according to the recently enacted federal agricultural policy directive (DZV, 2013)</td>
</tr>
<tr>
<td>Spatial planning policy</td>
<td>Laisser-faire Constant average settlement area granted per additional resident (SFSO, 2009, 2013)</td>
<td>Laisser-faire Constant average settlement area granted per additional resident (SFSO, 2009, 2013)</td>
</tr>
<tr>
<td>Consumption patterns</td>
<td>Regional products Constant opportunity costs and labor force according to Huber et al. (2014)</td>
<td>Global products 50% increase in opportunity costs and 50% decrease of labor force according to Huber et al. (2014)</td>
</tr>
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</table>

Table 5B.2. Parameter modifications in ALUAM-AB related to different interventions.

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<th>Affected parameters</th>
<th>Change in parameter</th>
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<tr>
<td>Market opening*</td>
<td>Milk price</td>
<td>For all prices: Linear decrease towards an alignment with EU prices in 2050 as estimated by Abildtrup et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Meat price</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wheat price</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Livestock price</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Costs of fodder</td>
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</tr>
<tr>
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<td>Costs of concentrated feed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Costs for livestock</td>
<td></td>
</tr>
<tr>
<td>Targeted direct payments</td>
<td>General area-based direct payments</td>
<td>Linear decrease to 0 within 4 years</td>
</tr>
<tr>
<td></td>
<td>Payments for cultural landscape</td>
<td>Doubling of payments within 4 years</td>
</tr>
<tr>
<td></td>
<td>Payments for extensive grassland</td>
<td>Doubling of payments within 4 years</td>
</tr>
<tr>
<td></td>
<td>Payments for grassland-based milk/meat production</td>
<td>Doubling of payments within 4 years</td>
</tr>
<tr>
<td></td>
<td>Payments for summer pastures</td>
<td>Doubling of payments within 4 years</td>
</tr>
<tr>
<td>Restrictive spatial planning</td>
<td>Average settlement area granted per additional resident</td>
<td>Linear decrease to 0 within 4 years</td>
</tr>
<tr>
<td>Structural interventions</td>
<td>Probability of a successor</td>
<td>Increase of 20% within 4 years</td>
</tr>
<tr>
<td></td>
<td>Opportunity costs</td>
<td>(Increase of 25%, 30%, 35% / decrease of 20%)**</td>
</tr>
<tr>
<td></td>
<td>Labor force</td>
<td>Decrease of 50% within 4 years</td>
</tr>
<tr>
<td></td>
<td>Minimum income</td>
<td>(Decrease of 55%, 60%, 65% / increase of 50%)**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increase of 25% within 4 years</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Increase of 30%, 35%, 40% / decrease of 25%)**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decrease to 0 for part-time farmers within 4 years, decrease of 10’000 CHF for full-time farmers within 4 years (Decrease of 12’000 CHF, 14’000 CHF, 16’000 CHF for full-time farmers / increase of 10’000 for all farmers)**</td>
</tr>
</tbody>
</table>

* In a liberalization scenario: Market closing and corresponding increase in prices
**Values in brackets indicate additional levels of structural interventions modeled
Table S8.3. Model runs performed with ALLUM-AB under different policy strategies based on 4 policy interventions: M = market opening (BAU)/closing (LIB), T = targeted direct payments, R = restrictive spatial planning, S = structural interventions. O = intervention not implemented, 1 = intervention implemented, 2/3/4/5= different levels of intervention. Each code group represents a four year period, starting with the period between 2018 and 2022. The last period is longer (2030-2035).

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Results
### Results

**Table 5B.3. Continued.**

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<td>MoToRoSi1 - MoToRoSi1 - MoToRiSi1 - MoToRiSi1</td>
<td>134</td>
<td>MoToRoSi1 - MoToRoSi1 - MoToRiSi1</td>
</tr>
<tr>
<td>62</td>
<td>MoToRoSi1 - MoToRoSi1 - MoToRiSi1 - MoToRiSi1</td>
<td>135</td>
<td>MoToRoSi1 - MoToRoSi1 - MoToRiSi1</td>
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<tr>
<td>63</td>
<td>MoToRoSi1 - MoToRoSi1 - MoToRiSi1 - MoToRiSi1</td>
<td>136</td>
<td>MoToRoSi1 - MoToRoSi1 - MoToRiSi1</td>
</tr>
</tbody>
</table>

**Combinations of three interventions, BAU**

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Timing and sequencing of interventions</th>
<th>Run No.</th>
<th>Timing and sequencing of interventions</th>
</tr>
</thead>
<tbody>
<tr>
<td>64</td>
<td>MoToRoSo - MoToRoSo - MoToRoSo - MoToRiSi1</td>
<td>137</td>
<td>MoToRoSo - MoToRoSo - MoToRiSi1</td>
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<td>MoToRoSo - MoToRoSo - MoToRiSi1</td>
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<tr>
<td>66</td>
<td>MoToRoSo - MoToRoSo - MoToRiSi1 - MoToRiSi1</td>
<td>139</td>
<td>MoToRoSo - MoToRoSo - MoToRiSi1</td>
</tr>
<tr>
<td>67</td>
<td>MoToRoSo - MoToRiSi1 - MoToRiSi1 - MoToRiSi1</td>
<td>140</td>
<td>MoToRoSo - MoToRiSi1 - MoToRiSi1</td>
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<td>MoToRoSo - MoToRiSi1 - MoToRiSi1</td>
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<td>142</td>
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<td>MoToRiSi1 - MoToRiSi1 - MoToRiSi1</td>
<td>146</td>
<td>MoToRiSi1 - MoToRiSi1 - MoToRiSi1</td>
</tr>
</tbody>
</table>
Appendix 5C: Settlement module

The choice experiment revealed that settlement expansion was a significant factor negatively affecting landscape aesthetics (Table 5.1). We thus extended ALLAM-AB with a settlement module taking into account the suitability of parcels for urban growth on the one hand, and socio-economic demand for further housing on the other hand.

The model selects parcels suitable for settlement growth based on five location factors essential for settlement development in rural areas with small towns (Garcia et al., 2009; Abdullah, 2014). These include elevation, slope, view on mountains and distance to roads and centers, respectively. Firstly, for each parcel, we calculated elevation, slope and, using a viewshed analysis, the view on mountains based on a digital elevation model (Swisstopo, 2005). Distance to roads and centers were determined with the vector25 dataset (Swisstopo, 2004) which provides information on locations of buildings and streets in Switzerland. We assumed post offices to be the local city centers. Secondly, the values of each factor were normalized in order to scale the value range precisely between 0 and 1, the latter indicating highest suitability for settlement development among the parcels in the case study landscape. Elevation, slope and view on mountains were normalized with linear scale transformation according to the score range procedure and applying the benefit criteria (Malczewski, 1999). As non-linearity of utility functions for distances is widely accepted (Koppelman, 1981; Malczewski, 1999), we applied a value function approach to scale the distance to roads and centers. A negative exponential function was used to account for a disproportionally high decrease of suitability for settlement expansion with increasing distance to the streets and villages (Koppelman, 1981). Thirdly, we estimated the overall suitability of a parcel weighing all factors equally. We included neighborhood effects by calculating the average suitability for settlement development within a circular distance of 300m around each parcel (Garcia et al., 2009). We then recalculated the overall suitability including this value as an additional criterion.

To assess future needs for settlement area, we estimated population development in the 11 municipalities of the case study region based on regionally-downscaled population development scenarios in Switzerland (SFSO, 2013). We selected a medium growth scenario in line with the business as usual scenario and a large growth scenario in line with the liberalization settings (Section 5.2.3) and calculated annual demand for settlement parcels, assuming a constant average need of space for housing per person (SFSO, 2009).
6. Mapping uncertainties in the future provision of ecosystem services in a mountain region in Switzerland

Original article:
URL: http://link.springer.com/article/10.1007/s10113-017-1118-4/fulltext.html
Dates: Received 28 June 2016, accepted 25 January 25, available online 15 February 2017.

Ecosystem services (ES) management has to cope with a high degree of uncertainty related to changes in socio-economic and climatic conditions as well as in societal values. Information regarding the quantity and location of these uncertainties can facilitate identifying which areas require management attention and policy support. In this context, science for mapping ES is evolving rapidly, but there remains a lack of quantitative methods to integrate and visualize uncertainties related to regional and global changes that affect both ES supply and demand. Using a mountain case study in Switzerland, this paper quantifies and maps the uncertainty of future ES provision related to changes in regional and global socio-economic and climatic drivers as well as in ES preferences. We model and map patterns of (dis-)agreements regarding ES in a multitude of scenarios and evaluate the magnitude and sources of uncertainty in these patterns. The results illuminate which drivers cause the highest levels of uncertainty in future ES provision and highlight areas where changes in ES are similar across scenarios or where changes are dependent on regional or global contexts. In this case study, changes in ES occur more consistently in remote areas, while in the main valley such changes are highly uncertain and particularly sensitive to national socio-economic drivers and climate change. The uncertainty maps can serve as a basis for discussing regional development plans and national policy strategies. The suggested approach could serve as a straightforward means to quantify and communicate spatial uncertainties in future ES studies.

6.1. Introduction

Globalization and climatic changes have accelerated fundamental land-cover and land-use changes across the globe, with potentially widespread consequences for the provision of ecosystem services (ES) (Verburg et al., 2013; Magliocca et al., 2015a). Effective and efficient management of ES under these pressures requires integration of the supply of and demand for these services (Cavender-Bares et al., 2015; Wolff et al., 2015), which allows a spatial targeting of actions to maximize the societal benefits of ES (Crossman et al., 2013; Grêt-Regamey et al., 2013a). At the same time, ES management has to cope with a high degree of uncertainty related to the uncertain dynamics of regional and global changes that impact ES provision (Hou et al., 2013). Therefore, to explicitly account for ES in management and policy strategies, accurate ES maps that convey the future spatial distribution of ES supply, demand and benefits are required (Maes et al., 2012; Geijzendorffer et al., 2015; Vorstius and Spray, 2015). In addition, to provide reliable guidance for decision-makers, such maps should also offer information on the inherent uncertainties of future predictions (Schägner et al., 2013; Schulp et al., 2014a; Prestele et al., 2016). The transparent communication of uncertainties resulting from a wide range of possible futures advises decision-makers on robust decisions that perform well in a variety of circumstances (Polasky et al., 2011a; Uusitalo et al., 2015). Particularly, an explicit consideration of spatial uncertainties can support a spatial tailoring of policies, as uniform measures are unlikely to secure demanded ES in the future (Bateman et al., 2013; Briner et al., 2013b; Stürck et al., 2015).

Research on ES has grown rapidly in recent years (Kareiva et al., 2011; Schägner et al., 2013; Grêt-Regamey et al., 2015). Only a small fraction of studies, however, have combined ES supply and demand to assess ES benefits and have concurrently addressed or quantified the uncertainty of the results (Seppelt et al., 2011; Schulp et al., 2014a). ES assessments include modeling (e.g., Bagstad et al., 2013a; Brunner et al., 2016) as well as mapping approaches (e.g., Burkhard et al., 2012; Castro et al., 2014) and provide important insights into the spatially explicit (mis)match of ES supply and demand. Uncertainty in ES assessments can occur because (1) the relationships between land use, ecological processes and the generation of ES (and consequently model structures) are uncertain, (2) preferences for ES are uncertain or (3) driving forces of ES supply and demand (and consequently model parameters) are uncertain (Grêt-Regamey et al., 2013a; Hou et al., 2013). These aspects of uncertainty have been addressed by Monte Carlo simulations (e.g., Boithias et al., 2016), Bayesian network approaches (e.g., Grêt-Regamey et al., 2013a; Landuyt et al., 2015), model comparison (e.g., Dennedy-Frank et al., 2016) and by assessing ES provision under alternative scenarios (e.g., Metzger et al., 2006; Schulp et al., 2014a). Scenario analyses are especially helpful for supporting decision-making processes, since such analyses provide insights into drivers of change, the
space of potential implications of different trajectories into the future and options for action (Metzger and Schröter, 2006; Palacios-Agundez et al., 2015). Scenario analyses ensure that assumptions about future developments are made transparent and are often the only way to deal with the unknown future (Refsgaard et al., 2007).

Though scenario analyses are useful tools, existing scenario approaches in ES assessments often lack integration of uncertainties in different drivers of ES provision (Hou et al., 2013) and in quantification of spatial uncertainties (Seppelt et al., 2011; Pagella and Sinclair, 2014; Schulp et al., 2014a). Most studies focus on uncertainties related to the development of climate and global markets and much less on how local socio-economic factors or preferences for ES may change in future (Valkering et al., 2011; Johnson et al., 2012; Geijzendorffer et al., 2015; Hauck et al., 2015). In addition, analysis of the magnitude of uncertainty usually takes priority over the quantification and visualization of the uncertainty pattern (Uusitalo et al., 2015). The few scenario-based ES studies that visualize uncertainty combine maps of the most frequent value with maps of an uncertainty score based on the frequency of this value in multiple simulations (e.g., Sample et al., 2016). Important drawbacks of such maps include the loss of information for those areas where uncertainty is high and the dependence of the results on the number of simulations. In addition, the visualization of magnitude and uncertainty of ES changes on two separate maps makes their interpretation more demanding for decision-makers (Grêt-Regamey et al., 2013b). Therefore, to support policy processes, the incorporation of both dimensions in one map becomes indispensable (Schägner et al., 2013).

In this contribution, we quantify and map uncertainties in the future provision of ES resulting from uncertainties in climatic and socio-economic driving forces and societal values. We map patterns of agreements and disagreements of ES provision in multiple scenarios using the integrated modeling system BackES (Brunner et al., 2016) and evaluate the magnitude and sources of uncertainty in these patterns. Specifically, we (1) quantify the uncertainty in spatial ES supply caused by different climatic as well as regional and global socio-economic drivers with two indices for both quantity and allocation disagreement, (2) map the uncertainty of ES benefits across scenarios accounting for uncertainty in ES demand, and (3) analyze whether the uncertainty in the future ES provision is subject to path dependency, that is, dependent on the current land management. The maps pinpoint areas where changes in ES are prone to low and high levels of uncertainty. In other words, the maps indicate where changes in ES occur in a majority of scenarios and identify areas where ES management has to deal with several uncertainties to secure a desired provision of demanded ES. As such, the maps are well suited to discuss spatially explicit management and policy actions at the landscape scale that can secure ES benefits under continuous regional and global change.

We apply the scenario analysis approach to a case study in the Swiss Alps. In mountain regions, regional and global socio-economic developments such as population growth and globalization of markets, or outmigration and changing labor opportunities, increasingly threaten the delivery of essential ES, e.g., the preservation of cultural landscapes and biodiversity or the protection against natural hazards (Huber et al., 2013c). In addition, climate change is predicted to have greater effects on mountain ecosystems and their services than on most other landscapes (Beniston, 2003). But, while the pronounced vulnerability of mountain regions to these pressures has been frequently demonstrated (Grêt-Regamey et al., 2012; Haida et al., 2015), substantial uncertainty exists regarding how these trends will evolve across space and time and affect land-use patterns and the related provision of ES in particular regions in the future (Gurung et al., 2012; Stürck et al., 2015). Furthermore, as extreme biophysical gradients within mountain landscapes create unique vulnerabilities to disturbance and provision of ES, assessing the spatial uncertainty of future land-use and ES changes is especially crucial for the definition of sustainable policy and management strategies (Grêt-Regamey et al., 2013a; Houet et al., 2014; Kirchner et al., 2015).

6.2. Materials and Methods

6.2.1. Case study

The case study region is located in the Southern Alps of Switzerland and covers an area of 334 km². It includes the growing urban center of Visp in the main valley, the touristic Saas valley and the remote Baltschieder valley. Unproductive land accounts for 62% of the region, while 20% is covered by forest, 16% by agriculture and 2% by settlement, respectively. Unproductive land includes rocks, debris or firn and was not considered in the modeling. The extremely difficult topographic conditions and the trend of farm abandonments make future management of these lands very unlikely. Analyses were therefore run for an area of 127 km² in total.

The mountain forests and grassland provide a variety of ES, such as protection from natural hazards, biodiversity, cultural heritage and scenic beauty. Over the past decades, the region has experienced significant urban
growth with the settlement area increasing by over 30% between 1981 and 2005. In the same period, agriculture has become less and less competitive, and 14% of the productive agricultural land has been abandoned while forest grew by 7% (SFSO, 2009). The currently 161 active farms are highly dependent on direct payments, and over 90% of the farms are run part-time (Brändle et al., 2015). The traditional farming practices are dominated by grassland farming, including the special case of summer pastures, a seasonal expansion into the subalpine zone. As the region is among the driest of the Swiss Alps, changes in temperature and the precipitation pattern are supposed to have a substantial impact on vegetation and agricultural yields in the future (Briner et al., 2012). These socio-economic, political and ecological boundary conditions make the region especially susceptible to current and projected regional and global changes, e.g., in agricultural markets and policies, migration and population growth. Securing the long-term provision of the regions’ ES and determining management actions and policy measures thus requires reliable and robust information on how and where regional and global pressures will impact ES in the future.

6.2.2. Methodological approach

Figure 6.1 describes the model-based scenario approach for assessing the uncertainty in the future provision of ES. The approach builds on the well-established “cascade” framework for structured and comprehensive ES assessments (Haines-Young and Potschin, 2010). The framework includes, on the one hand, supply of ES, which is influenced by direct and indirect driving forces and farmers’ land management (de Groot et al., 2010a). On the other hand, the framework includes ES demand by stakeholders, which depends on preferences for different services (Geijzendorffer et al., 2015). Finally, ES benefits describe how the supplied ES affect the socio-cultural and economical welfare or utility gain according to the preferences people express for the services (Cavender-Bares et al., 2015). We operationalize this framework with the integrated modeling system BackES (Brunner et al., 2016). BackES links simulations of ES supply with an assessment of ES demand to map future ES benefits (Section 6.2.3). In our simulations, we consider four different types of scenarios (Section 6.2.4). First, we use scenarios of national socio-economic driving forces such as population growth, market and policy developments. Second, we implement regional socio-economic scenarios that locally constrain and affect farmers’ land management decisions. Third, we include climate scenarios to represent direct driving forces of land management and ES supply. The combination of these scenarios depicts the variability of regional and global pressures on spatially explicit ES supply. Fourth, in addition to these supply side scenarios, we include preference scenarios reflecting the uncertainty related to the future regional demand for ES. Based on this multitude of scenarios, we simulate maps of both ES supply and ES benefits and infer the magnitude and pattern of uncertainty in the ES provision (Section 6.2.5).

6.2.3. Modeling system BackES

The integrated modeling system BackES was developed to simulate regionally aggregated and spatially explicit (100m x 100m) changes in ES benefits, accounting for both changes in ES supply triggered by socio-economic and climate changes and local residents’ preferences for ES. The modeling system was set up, validated and tested in the case study region for three regionally relevant ES: mass flow regulation, habitat maintenance and aesthetics of the landscape. The ES were chosen and operationalized with indicators together with local stakeholders and were linked to one specific or a share of land-use types (Table 6.1). Furthermore, stakeholders agreed on 2035 as a reasonable time horizon for an ES assessment, which is still relevant to current management and policy decisions. The following sections provide a brief overview of the main components of BackES, i.e., the identification of ES demand in a choice experiment, the simulation of ES provision in an agent-based modeling framework and the integration of these data in a spatially explicit utility index. For details of BackES, including an in-depth discussion of assumptions, advantages and caveats of the different techniques and their integration, we refer to Brunner et al. (2016).

6.2.3.1. Ecosystem services demand: choice experiment

Future demand for ES was elicited in a discrete choice experiment among a random sample of 600 households in the case study region. In the survey, participants could choose between the current provision of the three target ES and alternative future sets of these services based on verbal descriptions and visualizations of the landscape. In total, 252 responses were valid and used for statistical analysis. Marginal utility coefficients ($\beta$) were estimated for each ES indicator ($I$) with nested logit models. Table 6.1 shows how much an increase of one hectare in a specific land use and its related ES enhances or lowers the utility for residents. We fully acknowledge the complex aspects of spatial variations in preferences for ES (Schägner et al., 2013). The underlying design of the choice experiment, however, did not allow inferring variations of the coefficients in space. Thus, we assume that preferences for particular ES are uniform in space across the case study region.
6.2.3.2. Ecosystem services supply: agent-based economic land-use modeling

Land-use and land-management changes and related changes in ES supply between the years 2013 and 2035 were simulated in BackES with a suite of modules that capture the key processes relevant to the supply of mountain ES: (i) the economic agent-based land-use model ALUAM-AB simulates farmers’ decision-making processes, (ii) the forest-simulation model LandClim examines forest dynamics and simulates grassland and forest yields, and (iii) a settlement module accounts for urbanization processes (Brunner et al., 2016). All components rely on region-specific spatial and non-spatial data and are fed with projected time series of parameters reflecting regional and global socio-economic pressures and grassland yields in changing climate conditions (Section 6.2.4). ALUAM-AB simulates land-use decisions of farmers in yearly time steps assuming that agents are profit maximizers. Decisions are restricted by different constraints reflecting production conditions and technology as well as farmers’ (i.e., agent) characteristics in the case study region. These agent characteristics were derived from interviews with and a survey among local farmers (Brändle et al., 2015).
Table 6.1. Marginal utility coefficients reflecting residents’ future preferences for ecosystem services changes.

<table>
<thead>
<tr>
<th>Ecosystem service (I)</th>
<th>Indicator (I)</th>
<th>Marginal utility coefficient per ha increase in indicator (β)</th>
<th>Standard deviation of utility coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow regulation</td>
<td>Protective forest area</td>
<td>0.0059**</td>
<td>0.0017</td>
</tr>
<tr>
<td>Habitat maintenance</td>
<td>Extensive grassland area</td>
<td>0.0069**</td>
<td>0.0013</td>
</tr>
<tr>
<td>Aesthetics</td>
<td>Forest area</td>
<td>-0.0035*</td>
<td>0.0015</td>
</tr>
<tr>
<td></td>
<td>Settlement area</td>
<td>-0.0198**</td>
<td>0.0032</td>
</tr>
<tr>
<td></td>
<td>Intensive grassland area</td>
<td>-0.0019**</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

Significance levels: *p < 0.05, **p < 0.001

The settlement module defines most suitable parcels for urban growth. Depending on the population growth scenario, a varying number of parcels is no longer available for agricultural production. Forest processes at landscape level are simulated on a decadal time step and fed into the modeling system (Schumacher and Bugmann, 2006). Integrating these different processes, BackES simulates changes in land use and ES supply at hectare resolution. The model was calibrated and validated over the period 2001-2012, and a series of sensitivity analyses showed high accuracy with respect to observed land-use changes (Brändle et al., 2015).

6.2.3.3. Ecosystem services benefits: utility function

In a final step, BackES calculates spatially explicit changes in ES benefits based on an additive utility index (McFadden, 1973). The index is a weighted sum of changes in the indicators I of the target ES i, in which the weight is given by the marginal utility coefficients β (Table 6.1):

$$\Delta U = \sum \beta_i \cdot \Delta I_i$$ (6.1)

The change in the utility ΔU in each grid cell is driven by the change in land use and associated ES supply as well as by the weight local people give to these changes.

6.2.4. Scenario analysis

Scenarios were implemented in BackES as variations in input parameters related to direct and indirect driving forces and preferences (Figure 6.1). We accounted for population development, agricultural market prices and agricultural direct payments as global/national socio-economic drivers, which are subsequently referred to as “global”. Available workforce, opportunity costs, i.e., the measure of benefits forgone due to alternative uses of labor, and the probability of a successor are regional/local socio-economic factors that influence land management and ES supply and are termed “regional”. Each of these factors was described with three potential development trajectories into the future, and their effect on ES supply was examined separately and in all possible combinations within a category, resulting in 27 scenarios for regional and global socio-economic drivers. We did not include combined scenarios of regional and global drivers, since we aimed at evaluating drivers’ relative impact on ES supply and uncertainty and because the considered factors are not obviously tied to each other in our case study area. For example, population development does not imply an increase in available workforce in the agricultural sector, but rather a growth in the regional industry. Details on the modification of the parameter time series related with each factor are provided in Appendix 6A. Each of the 54 socio-economic scenarios was combined with a set of 10 climate scenarios. In the first step, we implemented predicted temperature and precipitation changes under the climate scenarios RCP4.5 and RCP8.5 to simulate spatially explicit grassland yields using the LandClim model. Forest yields were not significantly affected by climate change within the time scale of the study and were therefore similar across all scenarios. Based on 100 LandClim model runs for each climate scenario, we then randomly selected five replicates from the RCP4.5 and RCP8.5 for implementation in BackES as time series of grassland yields.

Preference scenarios were implemented as varying utility coefficients in the utility function in BackES. The three levels were assumed based on the mean value and the standard deviations of each coefficient as estimated in the choice experiment (Table 6.1). The standard deviations reflect the uncertainties related to the diversity of preferences among different stakeholders. ES benefits were then estimated with BackES under all given combinations of ES supply and demand scenarios (1620 scenarios). A business-as-usual (BAU) scenario assuming constant values of socio-economic parameters and the mean value of ES preferences was chosen as a reference scenario for further quantitative analysis (Figure 6.1).

6.2.5. Quantitative analysis of uncertainty

The multitude of output maps of ES supply and benefits enabled a quantitative analysis of the uncertainty in ES provision related to the uncertainties in the future development of socio-economic and climatic pressures and of preferences for ES. That is, the maps allowed for the differentiation of regions that experience changes.
Results

in ES provision under all scenarios, regions that are impacted under certain scenarios, i.e., in which changes in ES provision are more uncertain, and regions that are not impacted under any scenario. To explore and visualize the uncertainty in detail, we used different quantitative techniques, which are described in the following paragraphs. All analyses were conducted based on maps of ES supply and benefits in the year 2035.

6.2.5.1. Quantity and allocation disagreement
To infer the importance of variations in regional and global socio-economic and climatic drivers on variations in ES supply, we overlaid maps of ES supply in 2035 generated under each scenario with a corresponding reference map of ES supply in 2035 and assessed their quantity and allocation disagreement (Pontius and Millones, 2011). Quantity and allocation disagreement are two indices developed for accuracy assessments and map comparison, which are usually applied in the calibration and validation of land-use models (van Vliet et al., 2016a). Quantity disagreement \(Q\) is the difference between a reference map and a comparison map that stems from the mismatch in the proportion of categories (Equations 6.2 and 6.3). Allocation disagreement \(A\) is the amount of difference between a reference map and a comparison map, which is due to the mismatch in the spatial allocation of the categories (Equations 6.4 and 6.5). Both indices are calculated based on an error matrix computed for a comparison and a reference map:

\[
q_g = \left(\frac{\sum_{j=1}^{J} p_{ig}}{\sum_{j=1}^{J} p_{ij}}\right) - \left(\frac{\sum_{j=1}^{J} p_{ij}}{\sum_{j=1}^{J} p_{ig}}\right)
\]

(6.2)

\[
Q = \frac{\sum_{g=1}^{J} q_g}{2}
\]

(6.3)

\[
a_g = 2\min\left[\left(\frac{\sum_{j=1}^{J} p_{ig}}{\sum_{j=1}^{J} p_{ij}}\right) - \frac{\sum_{j=1}^{J} p_{ig}}{\sum_{j=1}^{J} p_{ig}}, \left(\frac{\sum_{j=1}^{J} p_{ij}}{\sum_{j=1}^{J} p_{ij}}\right) - \frac{\sum_{j=1}^{J} p_{ij}}{\sum_{j=1}^{J} p_{ij}}\right]
\]

(6.4)

\[
A = \frac{\sum_{g=1}^{J} a_g}{2}
\]

(6.5)

where \(p\) is the portion of a map with a particular value of ES supply, \(J\) is the total number of ES supply values, and \(g\) is one category of ES supply values. Equations 6.2 and 6.4 compute the quantity and allocation disagreement between a comparison and a reference map for an arbitrary category \(g\), and equations 6.3 and 6.5 compute the overall quantity and allocation disagreement incorporating all \(J\) categories. Detailed explanations of all arguments in the equations are given in Pontius and Millones (2011).

Comparison and reference maps were chosen as follows: To assess the effect of variations in single socio-economic driving forces on ES supply, two levels of variation in each driver were compared to the BAU reference under each of the ten climate scenarios, thus yielding a set of 20 pair-wise comparisons for each driving force. Additionally, of the 27 combined scenarios in both socio-economic driver categories, the BAU was chosen as a reference and compared to the remaining 26 under each climate scenario. The resulting 260 pair-wise comparisons allowed an assessment of the combined effect of variations in regional or global drivers on quantity and allocation disagreement. Finally, the effect of each of the 10 climate scenarios on ES supply was compared to a scenario with a constant climate in each of the 54 socio-economic settings, resulting in 540 pair-wise comparisons, 270 comparisons for both the RCP4.5 and the RCP8.5 scenarios. Based on the results of the pair-wise comparisons, we estimated the average, maximum and minimum disagreements for different categories of drivers.

6.2.5.2. Uncertainty mapping
We quantified and mapped the magnitude and uncertainty of changes in ES benefits based on the mean and the coefficient of variation (CV), i.e., the standard deviation divided by the mean, of utility values in each grid cell given a range of scenarios (Schulp et al., 2014a). To identify the origin of the uncertainties in the spatial ES benefits, we included different number and types of scenarios in the calculation of these values. For a straightforward visualization of both magnitude and uncertainty in one map we assumed two categories of mean values: (1) a gain in future ES benefits and (2) a loss in future ES benefits; and four uncertainty categories: (1) very certain: \(CV = 0\), i.e., predicted changes in the utility are the same under all considered scenarios, (2) certain: \(0 < CV < 50\%\), (3) uncertain: \(50\% \leq CV < 100\%\), (4) very uncertain: \(CV \geq 100\%\).

6.2.5.3. Analysis of path dependency
To assess whether the uncertainty in future ES benefits is influenced by past land-use and management decisions, we analyzed the link between current land use and the uncertainty in future ES benefits. In the first step, we related the land use in 2013 in each grid cell to the uncertainty in the ES benefits in 2035 in the grid cell. This analysis was based on the uncertainty map that included all 1620 scenarios, and the uncertainty in each grid cell was normalized with the maximum uncertainty estimated across the region. We then statistically aggregated the future uncertainty in benefits for the four main land-use categories: extensive meadows, intensive
meadows, summer pastures and forests. To explain the results, in the second step, we analyzed the occurrence and consistency of land-use change trajectories among the scenarios and quantified their overall frequency and the frequency of their occurrence in each grid cell.

6.3. Results

6.3.1. Uncertainty in ecosystem services supply

Table 6.2 shows the quantity and allocation disagreement among maps of ES supply in 2035 summarized over particular sets of scenarios. Overall, differences among the maps are rather small, which reflects the boundary conditions of the mountain region, where only around 30% of the area is currently managed or accessible for future management actions and where the options for changes in land use and ES are limited. On average, variations in regional and global socio-economic driving forces cause around 3% disagreement in the magnitude of ES changes, more than twice as much as compared to climatic variations. This means that the number of grid cells that change their ES supply to a certain magnitude is in many climate change scenarios similar as in the reference. Despite the relatively small average quantity disagreement across all climate scenarios, variations are considerable with a maximum disagreement of almost 8% in one of the RCP8.5 scenarios. With regard to regional socio-economic conditions, the available workforce causes more uncertainty in ES supply compared to opportunity costs or successor probabilities. With regard to global socio-economic pressures, the capping of agricultural direct payments results in the largest variability in the amount of grid cells that change in their ES supply. In contrast, population development and changes in market prices result in small variations of ES supply as compared to the reference. If uncertainties in all three regional or global socio-economic driving factors are considered simultaneously, the maximum quantity disagreement is higher as compared to scenarios with variations in one single pressure only. These maximum disagreements result from scenarios in which all three factors change to an extent that farmers are forced to abandon pastures since income generated from these areas is too low. This happens, for example, in a scenario in which available workforce and successor probability is low, and opportunity costs are high.

While the quantity of changes in ES supply across different climate scenarios is rather similar, the spatial variation of grassland yields across the scenarios has a distinct influence on the spatial uncertainty of future ES supply, even in moderate RCP4.5 scenarios. Maps simulated under climate change differ on average more than 3% from the reference map in their pattern of ES supply.

Spatial uncertainty in services is less sensitive to socio-economic drivers. However, factors with little impact on the quantity disagreement, i.e., the development of market prices and population or the probability of successors for retiring farmers, add more uncertainty to the pattern of ES changes.
Results

In areas around Visp in the north of the valley, changes in ES benefits are similar across scenarios, even if regional socio-economic conditions are uncertain (Figure 6.2a). In contrast, variations in global socio-economic drivers add more uncertainty to future benefits (Figure 6.2d). This higher level of uncertainty has two origins: on the one hand, the uncertainty in population growth enhances the uncertainty related to changes in ES benefits in grid cells with a potential for settlement development and thus a loss in ES benefits. On the other hand, uncertainties in market prices or direct payments affect the uncertainty of benefits on extensive and intensive grasslands. In remote regions, as exemplarily shown for the section in the eastern part of the valley, the loss of ES is fairly consistent across all global socio-economic scenarios, but prone to higher levels of uncertainty across all regional socio-economic scenarios. The availability of workforce and opportunity costs determine how many summer pastures can still be managed and thus how much agricultural land is abandoned. Variations in these parameters increase the uncertainty in the amount and

6.3.2. Uncertainty maps of ecosystem services benefits

Figure 6.2 shows the spatially explicit uncertainty of ES benefits estimated based on a varying number of scenarios. The distribution of gains and losses in ES benefits across the region is similar in all maps. Until 2035, positive changes in ES benefits occur primarily near the urban center of Visp and along the main valley and are related to gains in landscape aesthetics and habitat maintenance. Losses in ES benefits are observed in remote regions above the treeline or next to existing settlements in the main valley as a consequence of forest expansion and urban growth. Each of the land-use changes impairs the aesthetics of the region. Depending on the types and number of scenarios considered in each map, 670ha - 900ha gain in ES benefits while 1640ha - 2130ha are subject to losses. A quantitative summary of the magnitude and uncertainty of changes in ES benefits in each map as well as an animated image sequence of all maps in full extent are provided in Appendix 6B and online5, respectively.

5 https://static-content.springer.com/esm/art%3A10.1007%2Fs10113-017-1118-4/MediaObjects/10113_2017_1118_MOESM3_ESM.gif
locating of pasture-forest transitions and related losses in ES benefits.

Adding preference uncertainty in the mapping of ES benefits (Figure 6.2b and 6.2e) generally increases the uncertainty of ES benefits, especially in grid cells with highly consistent results in Figure 6.2a and 6.2d (cf. Table 6B.1, Appendix 6B). Furthermore, the inclusion of preference uncertainty changes the uncertainty pattern. As the uncertainty related to the demand for some ES is higher than for others (Table 6.1), the expected benefits of changes in these ES are likewise prone to more uncertainty. Preferences among residents varied more for the ES mass flow regulation and aesthetics than for habitat maintenance; thus, benefits are more uncertain in grid cells where the supply of these ES changes.

Adding the effect of climate variations in the maps enhances the number of grid cells with potential changes in ES benefits (Figure 6.2c and 6.2f). While the uncertainty of the predictions stays more or less similar in remote regions, it increases in the area around Visp. This reflects the variation in grassland yields in each parcel across different climate scenarios, which influences the management intensity of grasslands and related ES. The integration of the spatially explicit ES benefits simulated in all scenarios in one single map is shown in Figure 6.2g. The consideration of uncertainties in all drivers of ES supply and demand enhances the uncertainty of ES benefits in several grid cells, especially along the main valley. At other places in the case study region, however, the simulated ES benefits are quite consistent across a large number of scenarios. In summary, ES benefit changes are generally more uncertain in areas at lower elevations, near the settlement or near farms, and more consistent in remote areas where a similar loss of services is observed across all scenarios (see also Figure 6B.1, Appendix 6B).

6.3.3. Path dependency of the uncertainty in future ecosystem services benefits

The uncertainty regarding how ES benefits evolve in each grid cell of the case study area is highly dependent on how the grid cell is currently used or managed. Almost all pastures in the region, 98% of the extensively and 94% of the intensively managed grasslands, are subject to future land-use changes in at least one of the simulated scenarios. By contrast, 58% of the summer pastures and only 2% of the whole forest area are affected by the assumed changes in socio-economic or climatic driving forces. Across all scenarios, summer pastures are only prone to one development trajectory: they get abandoned and are then subject to forest growth. Thus, the only uncertainty in each grid cell is related to whether and how frequently it will be abandoned in the future given the range of scenarios. Inversely, conversions of current grasslands strongly depend on the strength and type of drivers. Averaged over all scenarios, 76% of the grasslands experience a change in the intensity of the management, 10% become encroached by forest, and 14% are converted to settlement area. However, the amount of particular land-use changes as well as the locations where they occur vary considerably across the scenarios. Accordingly, the changes in ES benefits are more manifold and less certain on agricultural lands. The few forest cells that are subject to changes are converted to intensively used, extensively used or summer pastures. Compared to grasslands, the fate of one particular forest grid cell is more consistent across the scenarios.

6.4. Discussion

6.4.1. Quantification and mapping of uncertainty

Modeling and mapping approaches in ES research currently lack an integration and spatial quantification of uncertainties associated with changes in both drivers of ES supply and in demand for ES. While existing quantitative methods in environmental modeling usually do not provide information regarding the pattern of uncertainties (Refsgaard et al., 2007; Uusitalo et al., 2015), current ES mapping practice either neglects uncertainties or simply discusses them qualitatively (Schägner et al., 2013; Pagella and Sinclair, 2014). In our study, we suggest a novel approach to quantify the extent and spatial variation of uncertainty in ES provision related to different drivers based on two indices usually applied in the validation and comparison of land-use maps (Prestele et al., 2016; van Vliet et al., 2016a): quantity and allocation disagreement. Using quantity and allocation disagreement could serve as a straightforward means to quantify and communicate uncertainties in future ES studies. The approach offers two main advantages: the two indices can be computed and interpreted easily, and, at the same time, they explain the reason for the disagreement of two maps (Pontius and Millones, 2011). Combined with an extensive scenario analysis, as in this study, analysis of the indices can provide insights into which drivers cause the highest level of uncertainty in future ES provision.

In this study, we mapped changes and related uncertainties in ES based on the mean and the CV across a multitude of scenarios, a technique previously applied to compare ES maps from different studies (Schulp et al., 2014a). Relative to other uncertainty mapping techniques, this simple approach is less sensitive to the number of simulations, especially if many scenarios
are considered, and enables the communication of the direction and uncertainty of ES changes in one map (Schägner et al., 2013; Sample et al., 2016). Resulting maps allow exploring the consistency of severe changes across space and scenarios and can thus enhance users’ degree of confidence (Vorstius and Spray, 2015). We include not only scenarios of different drivers (i.e., regional and global socio-economic and climatic changes), but also scenarios of ES demand that reflect the uncertainty in the preferences for ES among stakeholders. Accounting for demand uncertainty in the mapping of ES benefits has been identified as a key criterion for generating maps suitable for decision-support (Vorstius and Spray, 2015).

While our approach includes uncertainties in ES supply and demand, uncertainties in the data used, the model structure and the selection of ES indicators were not assessed. However, model and data uncertainty was explored and documented during the development and testing of BackES (Brändle et al., 2015; Brunner et al., 2016). The validation of the model against real data and the choice of ES in an iterative stakeholder process could reduce uncertainty in the process understanding and structure of the modeling system (Stürck et al., 2015). In our study, agent types in the model were developed based on interviews with and a survey among local farmers. The link to on-the-ground practices and actors could lower the uncertainty related to individual land management decisions represented in the model (Johnson et al., 2012). This data-intensive and case study-specific modeling process, however, did not allow for alternative methods to evaluate model uncertainties such as multi-model ensemble approaches or model emulation, as reviewed in detail by Uusitalo et al. (2015).

Additionally, spatial uncertainty related to ES demand is not included in our approach. Sophisticated ES mapping studies use value functions that map benefits across space based on a function that relates preferences for ES to multiple spatial variables or patterns, e.g., population density, income levels or distance to housing (Schägner et al., 2013). However, these methodologies require comprehensive datasets of exploratory variables across the entire study area, which are difficult to obtain for the future. Consequently, these techniques have so far only been applied for mapping current ES values. Further research should explore their application in combination with scenario studies.

6.4.2. Implications for policy-making and land management
In our case study region, the changes in ES benefits and related uncertainties emerge in a relatively clear pattern, which is indicative for mountain regions in Europe in general (Bender et al., 2011; van Vliet et al., 2015). Gains in future ES benefits are associated with high levels of uncertainty and occur primarily on current agricultural land in the main valley, while in remote areas, losses in ES benefits occur more consistently across the modeled scenarios. The detailed insights into the origin and extent of these uncertainties gained in this study allow informing decision-making processes at different scales (Uusitalo et al., 2015).

On grasslands in the main valley, the magnitude of changes in ES benefits differ most with variations in agricultural direct payments, while changes in demographics or agricultural markets play a smaller role. These results support current agricultural policy-making at the national scale, providing argumentation and legitimation for a continued financial support of farmers to secure ES benefits in mountain regions (Bender et al., 2011; Bardsley and Bardsley, 2014). The locations where ES benefits change in the future vary most across the climate scenarios. Depending on the predicted yield, farmers intensify different patches, resulting in alternative spatial patterns of intensive and extensive grasslands. Uncertainties in how people perceive and value these changes additionally increase the uncertainties in ES benefits. At the regional scale, the distinction among patches, which will likely deliver demanded ES in future from others where management is needed to prevent ES losses or secure an uncertain gain helps pinpoint areas that require attention in development plans. Furthermore, the maps provide information for spatial planners and farmers regarding where future conflicts between settlement development and agriculture are most likely.

The loss of ES benefits in remote areas is mainly caused by the abandonment of summer pastures. The magnitude of changes varies with the availability of workforce, opportunity costs and the number of young farmers, indicating that regional socio-economic structures are important factors for the maintenance of these pastures. Climate change not only increases the uncertainty in the spatial pattern of the losses (as in the lowlands), but also expands the areas potentially affected by abandonment. As the corresponding losses in ES benefits occur relatively consistent across all scenarios, policy interventions that support the agricultural sector in these regions are unlikely to counteract the projected changes. This information can prevent policy-makers from investing their limited resources in areas that are subject to a relatively predetermined pathway. At the same time, it may capture the attention of regional authorities and
trigger the development of alternative action plans for preventing an increasing forest encroachment and the loss of cultural landscapes.

To evaluate whether our results have potential to ultimately initiate uncertainty-reducing policy and management strategies, in a next step, the results should be transferred to and discussed with practitioners. Only then can decision-makers’ abilities and ways of including uncertainty into policy judgments and management processes be transferred and improved (Hou et al., 2013). Further research should thus address the question of whether decision outcomes change in the face of an explicit depiction of uncertainty and which ways of uncertainty communication and visualization most effectively support decision-making processes (Grêt-Regamey et al., 2013b).

In conclusion, evaluating and mapping the uncertainty of ES provision across a multitude of scenarios of regional and global drivers and societal values helped identify vulnerable areas where policy and management actions could secure ES benefits in the future. While such maps can support short- and medium-term decision-making, over the longer term, mountain regions may face unexpected shocks that can only be tackled by transformation of whole management systems. Novel modeling structures in land-use and ES assessments that capture emergent and evolutionary changes through time and space and that are able to integrate thresholds and shifts in both land and ES management practices and societal value systems are needed (Verburg et al., 2015). Applying our approach with such models could help quantify and visualize uncertainty in ES provision in a more dynamic manner and open the way for future innovative options of land management and planning.

Acknowledgments
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### Appendix 6A: Parameter variations in scenarios

Table 6A.1. Three levels of driving factors and translation into BackES parameter values under global/national and regional/local socio-economic scenarios. Parameter values were fed as time series into the modeling system. Italic levels denote the business-as-usual reference scenario.

<table>
<thead>
<tr>
<th>Global/national socio-economic scenarios</th>
<th>Regional/local socio-economic scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving factor</td>
<td>Level</td>
</tr>
<tr>
<td>Population development</td>
<td>(1) Low</td>
</tr>
<tr>
<td></td>
<td>(2) Medium</td>
</tr>
<tr>
<td></td>
<td>(3) High</td>
</tr>
<tr>
<td>Agricultural market prices</td>
<td>(1) Constant</td>
</tr>
<tr>
<td></td>
<td>(2) Small decrease</td>
</tr>
<tr>
<td></td>
<td>(3) Large decrease</td>
</tr>
<tr>
<td>Agricultural direct payments</td>
<td>(1) Constant</td>
</tr>
<tr>
<td></td>
<td>(2) 10% Reduction</td>
</tr>
<tr>
<td></td>
<td>(3) 30% Reduction</td>
</tr>
</tbody>
</table>
Appendix 6B: Supplementary results

Table 6B.1. Area with gains and losses in ecosystem services (ES) benefits under different scenarios classified according to their uncertainty. The coefficient of variation (CV) is the standard deviation divided by the mean.

<table>
<thead>
<tr>
<th>Uncertainty map and considered scenarios</th>
<th>Number of ha</th>
<th>No change</th>
<th>Gain in ES benefits</th>
<th>Loss in ES benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Very robust</td>
<td>Robust</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CV = 0</td>
<td>CV &lt; 50%</td>
</tr>
<tr>
<td>Regional socio-economic &amp; preferences &amp; climate change (n = 810)</td>
<td>9020</td>
<td>0</td>
<td>201</td>
<td>163</td>
</tr>
<tr>
<td>Global socio-economic &amp; preferences &amp; climate change (n = 810)</td>
<td>8885</td>
<td>0</td>
<td>120</td>
<td>148</td>
</tr>
<tr>
<td>All (n = 1620)</td>
<td>8782</td>
<td>0</td>
<td>125</td>
<td>150</td>
</tr>
</tbody>
</table>

Figure 6B.1. Uncertainty in relation to different location characteristics. The uncertainty in each grid cell is normalized with the maximum uncertainty estimated across the region.
5. Policy strategies to foster the resilience of mountain social-ecological systems under uncertain global change

Globalization and climate change threaten the sustained provision of essential ecosystem services (ES) for people living in and downstream of mountain regions. The increasing evidence of the many vulnerabilities of mountain social-ecological systems has highlighted the urgent need for policy-relevant research into ways of coping with these trends. In this context, resilience has been emerging as a concept for both understanding and managing the complex social-ecological systems in which ES are provided and consumed. Yet, literature on resilience of social-ecological systems is mainly theoretical with limited application in real-world mountain case studies. In this paper, we present a comprehensive quantitative assessment of the social-ecological resilience of a case study in the Swiss Alps under global change. We model and evaluate an indicator for resilience that shows the capacity of the mountain social-ecological system to provide a set of demanded ES. In a first step, we model the development of this indicator in different scenarios of global change. In a second step, we test the effect of a rich set of policy strategies under all these scenarios to identify types and timing of interventions that are robust under multiple global change settings. Results indicate that the resilience of the mountain social-ecological system is endangered in all scenarios, especially if strong globalization is assumed. Robust strategies that buffer the system against these pressures require early spatial planning action in combination with more targeted direct payments to support the current regional structure and traditional mountain farming practices. Such information is crucial to guide decision-making processes in the era of highly uncertain future global change.

5.1. Introduction
Mountains cover 24% of the Earth’s land surface and as repositories of biological and cultural diversity they provide essential ecosystem services (ES) to mountain dwellers and people living in their vicinity (Bernués et al., 2014). In addition, they are of global significance due to their key role in regulating processes such as carbon sequestration or water storage and purification (Grêt-Regamey et al., 2012). The provision of these services depends largely on land use which itself is shaped by long-established interactions of humans with nature in social-ecological systems (Rounsevell et al., 2012; Verburg et al., 2013). Mountain social-ecological systems are ecologically and economically sensitive to rapid global change and an increasing number of studies has investigated the large consequences of global drivers for local mountain environments and human well-being (e.g., Mottet et al., 2006; Huber et al., 2013c; Munteanu et al., 2014). But, while our understanding of these trends advances, there are rising concerns among scholars and policy-makers about the declining capacity of mountain social-ecological systems to cope with these trends and unexpected shocks accompanying them in future (Gurung et al., 2012). Accordingly, mountains have recently been taken up in many contemporary debates on rural development and policy-making from the national to the global level (Balsiger and Debarbieux, 2015).

Resilience is emerging as a frame for understanding the stability and trajectory of complex social-ecological systems in which ES are provided and consumed (Morehouse et al., 2008; Ifejika Speranza et al., 2014). Resilience was originally introduced by Holling (1973) as an ecological concept to help understand the capacity of ecosystems to persist in the original state when subject to perturbations. With the increasing extension of the concept to social, economic and coupled social-ecological systems since the late 1980s many alternative definitions have been proposed (Janssen and Ostrom, 2006). Social-ecological resilience is referred to as “the capacity of a system to absorb disturbances so as to still retain essentially the same function, structure, feedbacks and identity” (Walker et al., 2004). In the context of this study, we will equate resilience with the capacity of mountain social-ecological systems to maintain flows of target ES given by ES demand during a specific period of time (Janssen et al., 2007; Biggs et al., 2012; Bürgi et al., 2012). The more resilient a system, the better it can cope with external disturbances and continue to provide demanded ES.

Managing for resilience is becoming a central objective for policy-making, since it is expected to foster desirable development pathways in an environment of ongoing and partly unpredictable global change (Morehouse et al., 2008; Schwarz et al., 2011; Plieninger and Bieling,
In the last decade, many conceptual frameworks of resilience have been developed (e.g., Carpenter et al., 2001; Walker et al., 2004; Folke, 2006; Nelson et al., 2007), but only few authors have analyzed empirical problems in social-ecological systems through a resilience lens (Plieninger and Bieling, 2012). Studies in mountain regions tend to focus either on the ecological (e.g., Rescia et al., 2010; Oteros-Rozas et al., 2012; Tomczyk et al., 2016) or the social part (e.g., Luthe et al., 2012; Bardsley and Bardsley, 2014; Schermer et al., 2016) of the system. Integrative operationalization and modeling efforts, however, are lacking, complicated by the inherent complexity of social-ecological systems, such as non-linearity, feedback loops or multiple spatial and temporal scales (Cumming et al., 2005; Filatova et al., 2015). Existing modeling studies mostly build upon generic models to understand resilience of social-ecological systems at a very aggregate level with limited potential to address real world problems in which context-specific interactions determine system behavior (Schlüter et al., 2013). But, only if the analysis comes down to empirical case studies, it can be used by policy-makers to identify their actions as being (non) resilient as system disturbances occur (Schouten et al., 2009; Ifejika Speranza et al., 2014). Consequently, calls for decision-oriented research that facilitates choices between a range of alternative policy and management options to sustain resilience have become more frequent in recent years (Wise et al., 2014), especially in vulnerable mountain social-ecological systems (Gurung et al., 2012; Rueff et al., 2015).

This study is an important contribution to quantitative and policy-relevant applications of the resilience concept in social-ecological systems in the context of global climatic, socio-economic and political changes. The objectives of the paper are to advance techniques for simulating resilience in social-ecological systems and to fuel the scientific and policy debate on whether and which interventions are needed to guarantee a demanded level of ES in mountain regions given the uncertainty of future global change. Taking a valley in the Swiss Alps as a case study, we specifically aim at: (1) identifying critical global pressures that threaten the resilience of the mountain region, (2) comparing sectoral policy actions for attenuating negative regional effects of these disturbances, and (3) developing robust integral policy strategies that foster the resilience of the mountain system across a range of future disturbances.

7.2. Methods

7.2.1. Case study region

The case study region is located in the Central Valais in Switzerland, a continental inner-Alpine environment characterized by relatively low precipitation and moderate temperatures. It spans an area of 334km², from the remote Baltschieder-valley and the economically growing industrial and urban center Visp to the touristic destinations in the Saas-valley (Saas Fee, Stalden) and is home to 15'500 residents (Figure 7.1). Dominated by unproductive land and high mountain peaks, 20% of the area is covered by forest and 16% is cultivated by agriculture. Between 1981 and 2005, rapid urbanization processes around the industrial and touristic centers have led to the expansion of the settlement area by over 30%, and tourism and the leisure industry have become major economic factors. In the same period, mountain agriculture has become less and less competitive and rapid economic growth has pulled labor off the land. In peripheral areas, 14% of the productive agricultural land has been abandoned and forest grew by 7% (SFSO, 2009). Between 2000 and 2012, the number of farms annually decreased by 2.8%. The remaining 161 active farms in the region are highly dependent on subsidies and there is no 90% of the farms are run part-time in combination with other economic activities, predominantly in tourism (Brändle et al., 2015). Agricultural activities are dominated by grassland farming, including the special case of summer pastures, a seasonal expansion into the subalpine altitudinal zone. On average, individual farmers cultivate only 8ha of agricultural land and keep around seven livestock units. Many farmers are members of breeding associations that organize regular exhibitions which are very popular among locals and tourists and root farming firmly into village traditions (Brändle et al.,
Seasonal Alpine grazing and the long-established small-scale farming practices substantially contribute to maintaining the typical character of the landscape and the provision of ES (Brunner et al., 2016). In fact, the local cultural identity, including agriculture, its products and traditions has not only been safeguarded by the regional population throughout past crisis, but was also ranked the most important factor for the future development of the region in a series of stakeholder workshops (Brand et al., 2013).

Land use and the provision of ES in the case study region are regulated by a multi-sectoral and multi-level policy system which complicates the development of an explicit agenda for adaptive strategies to the observed and forthcoming global socio-economic and climatic changes (Brunner et al., 2016). The agricultural policy program is mainly enacted at a national level and has been revised periodically in the last decades shifting from a production orientation towards a stronger ecological and services orientation (Bardsley and Bardsley, 2014). In two major reform cycles during the 1990s, market support was reduced and area- and livestock-based subsidies were introduced, divided into general and ecological direct payments with cross-compliance. Only recently, in 2014, this system has been reformed again, maintaining the yearly budget of around 2.8 Billion CHF and the elements of cross-compliance, but differentiating payments according to the services farmers provide (Figure 7.1) (Mann and Lanz, 2013). Around 5.8 Million CHF of this budget is spent for supporting agriculture in the case study perimeter (based on SFSO, 2015a). Making up more than half of farmers’ incomes, the federal reimbursements substantially shape land use and ES provision in the case study area. In addition, the federal forest law and spatial planning directives constrain land use in the mountain region through the imperative of forest conservation and the designation of building zones, respectively. In 2012, Swiss voters accepted an initiative to restrict the percentage of secondary houses in each municipality to 20% or lower, an important milestone in the prevention of ongoing urban sprawl, particularly in touristic mountain regions.

![Figure 7.1. Historical land-use changes in the case study region in the Swiss Alps (based on SFSO, 2009) and development of the federal agricultural direct payments (DP) (based on SFSO, 2015a).](image)
7.2.2. Conceptual approach

Figure 7.2 shows our approach to analyze the resilience of the mountain social-ecological system. The resilience of the system was evaluated with a utility index that identifies the match between regional ES supply and demand (Section 7.2.3). Demand for ES was elicited in a choice experiment among local residents (Section 7.2.3.1). ES supply and corresponding utility pathways were then modeled using the integrated backcasting modeling system BackES (Section 7.2.3.2) following a hierarchical study design: in a first step, the utility was assessed under four global press scenarios according to the IPCC SRES scenario framework in combination with four accompanying pulse assumptions, describing the effect of global change on the resilience of the mountain system without additional policy actions taken (Section 7.2.4). In a second step, the impact of policy strategies implemented both early in time prior to pulses as well as later in time after pulses, and their robustness under different global change scenarios was investigated (Section 7.2.5).

Figure 7.2. Conceptual approach and related hierarchical study design: The match between ecosystem services (ES) supply and demand as an indicator for resilience was modeled under alternative presses and pulses. 4 press scenarios were combined with 4 pulse scenarios. For each of these 16 settings, 47 policy strategies were tested.
7.2.3. Operationalization and modeling of resilience

7.2.3.1. Operationalization of resilience and ecosystem services demand

Guided by the question "resilience of what?", we equated resilience with the capacity of the mountain social-ecological system to deliver a set of demanded ES during a specific time period (Janssen et al., 2007; Biggs et al., 2012; Bürgi et al., 2012). Thus, we first identified which ES local residents particularly value and wish to maintain in the case study region. In an iterative stakeholder process with local residents and 15 resource managers, planners and politicians, we specified four regionally relevant ES and elaborated corresponding indicators (Table 7.1): Cultural heritage was approximated with the number of farms, as residents linked the small-scale structure and abundance of farms very tightly to local traditions and regional identity. Mass flow regulation was operationalized with the number of natural hazard incidents per year (Olschewski, 2013) and habitat protection with the area of extensive dry meadows. These grasslands are amongst the most species-rich Alpine habitats harboring a high diversity of characteristic plants, and they are priority ecosystems for biodiversity conservation in Switzerland (Grêt-Regamey et al., 2014). Landscape aesthetics were described by the share of three land-use types which were perceived most dominant by the locals. The time frame of 2013 to 2035 was negotiated with the experts as reasonable for a policy-relevant resilience assessment. Based on this pre-work, we assessed future preferences for the focal services with a discrete choice experiment (Brunner et al., 2016). In the survey, participants of 600 randomly selected households had to choose between alternative future sets of ES, which were verbally and visually described. In total, 252 questionnaires were returned and valid for the subsequent statistical analysis. Marginal utility coefficients were estimated for each ES that indicate how much a change in a service increases or decreases the utility of the landscape for residents (Table 7.1).

These utility coefficients were fed into the ES modeling system to calculate an additive utility index for each simulation of ES supply (McFadden, 1973). The index is a weighted sum of predicted changes in the indicators $i$ of the focal ES $i$ relative to the reference year 2013, in which the weight is given by the marginal utility coefficients $\beta$:

$$\Delta U = \sum \beta_i \cdot \Delta I_i$$

(7.1)

The change in the utility $\Delta U$ shows whether future alterations in the supply of ES can satisfy ES demand. Negatively perceived changes in single services can be compensated by positively weighted changes in others, as inferred from the stated preferences of local people. Overall, a negative change in the utility denotes a loss in the ability of the system to provide demanded ES and thus a loss in resilience. We fully acknowledge the complex aspects of decision-making processes and the fact that the desired mix of ES may evolve with changing societal values over time (Voinov et al., 2014), but we do not address this here. Instead, we assume that the set of key ES has been collectively agreed upon and focus on how disturbances and policy strategies affect the resilience of the social-ecological system to provide these ES, accounting for trade-offs people are willing to make between the single services (Biggs et al., 2012).

7.2.3.2. Modeling of resilience and ecosystem services supply

Changes in ES supply and related utility changes were simulated with the integrated modeling system BackES that has been validated and tested for the case study region (for details see Brunner et al., 2016). BackES is composed of three modules that guarantee that the key components of the mountain social-ecological system relevant to the delivery of ES are captured: The economic agent-based land-use model ALLAM-AB, parameterized with data from interviews with and a survey among local farmers, simulates farmers decision-making processes assuming agents maximize their agricultural income under various local, regional and agent-specific constraints (e.g., locational factors, nutrient balances or opportunity costs) (Brändle et al., 2015). A settlement module defines most suitable parcels for urban growth which are not available for agriculture (Brunner et al., 2016). Finally, the forest-simulation model LandClim examines

<table>
<thead>
<tr>
<th>Ecosystem service ($)</th>
<th>Indicator ($)</th>
<th>Marginal utility coefficient for 1% increase in indicator ($\beta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultural heritage</td>
<td>Number of farms</td>
<td>0.031**</td>
</tr>
<tr>
<td>Mass flow regulation</td>
<td>Number of natural hazard incidents</td>
<td>-0.016**</td>
</tr>
<tr>
<td>Habitat protection</td>
<td>Area of dry meadows</td>
<td>0.011**</td>
</tr>
<tr>
<td>Aesthetics</td>
<td>Forest area</td>
<td>-0.232*</td>
</tr>
<tr>
<td></td>
<td>Settlement area</td>
<td>-0.164**</td>
</tr>
<tr>
<td></td>
<td>Intensive grassland area</td>
<td>-0.021**</td>
</tr>
</tbody>
</table>

Significance levels: *$p < 0.05$, **$p < 0.001$
forest dynamics at landscape scale (Schumacher et al., 2004). All components rely on region-specific spatial and non-spatial data, as well as on projected time series of parameters reflecting global pressures (Section 7.2.4). Integrating these different modules, BackES simulates land-use changes and calculates regionally aggregated ES supply ($I$, Table 7.1) and changes in the utility index $\Delta U$ (Equation 7.1) in each year.

7.2.4. Press and pulse scenarios
Addressing the question “resilience to what?”, we defined 16 disturbance settings against which the resilience of the mountain social-ecological system should be evaluated. We combined presses, i.e., more gradual or cumulative pressures on the system, and pulses, which represent disturbances that occur abruptly.

Press scenarios were developed by applying a formative scenario technique to regionally downscale four global IPCC SRES storylines (Walz et al., 2014). The storylines represent a distinction between (A) more economically and (B) more environmentally and equity-oriented futures, and between (1) a more globalization and (2) a more regionally-oriented development (Acosta et al., 2013). Accordingly, the four storylines are named “Growth and Convergence” (GC, A1), “Regional Centers” (RC, A2), “Green Growth” (GG, B1) and “Local Sustainability” (LS, B2). For each storyline, qualitative levels of social, economic, ecological and policy factors that influence the provision of ES were elaborated for the case study region (for details see Huber et al., 2014; Walz et al., 2014). The qualitative storylines were then translated into quantitative scenarios to feed the modeling system BackES by adjusting time series of input parameters related to the different influence factors (Appendix 7A, Table 7A.1). The recently enacted federal agricultural policy directions (Figure 7.1) were implemented in the model as the basic future agricultural policy setting, with small adjustments depending on the global scenario.

Overlaying these press scenarios, we defined three pulse scenarios with an abrupt increase in major disturbances currently affecting the system: (1) We assumed a shock in agricultural markets associated with a sharp fall of commodity prices. (2) We modeled the effect of a structural shock with an accelerated abandonment of farms due to a lower probability of a successor, increased opportunity costs and minimum incomes, and a decrease in the available labor force. In both of these socio-economic pulse scenarios, we assumed the shock to happen in 2024 with no subsequent regeneration of markets or resumption of the agricultural activities on abandoned farms. (3) We tested the effect of an increased frequency and intensity of climate extremes, which are expected to gain in importance as drivers of changes in mountain regions (Beniston, 2003). The climatic shock was implemented as a sequence of three dry and hot summers associated with a reduction in yields of grassland and forests in the respective years (Bender et al., 2011). Alike the presses, the pulses were implemented in BackES by changing time series of specific input parameters (Appendix 7A, Table 7A.2).

7.2.5. Policy strategies
To infer policy strategies that foster the resilience of the system against the assumed pressures, we first identified single interventions that specifically address the most prevalent land-use change trends in the case study region (Section 7.2.1). We derived four interventions as politically feasible modifications of the current agricultural and spatial planning regulations: (1) a reduced versus a sustained protection of Swiss agricultural markets to assess the effect of increasingly globalized commodity price levels on the system, (2) a reallocation of agricultural direct payments for food supply to direct payments for landscape quality, biodiversity and animal husbandry on summer pastures, that is, an adapted subvention scheme especially targeted to mountain farming activities, (3) structural interventions as monetary aid granted unconditional on specific farming activities to strengthen the regional agricultural sector and prevent from an accelerating farm abandonment, and (4) a stronger regulation of spatial planning activities to counteract the rapid urbanization. Related parameter modifications in BackES are given in Appendix 7A (Table 7A.3).

In an iterative process, we developed a set of 46 policy strategies which involved one to four of these interventions in different combination and timing and included as a reference an inaction strategy (Appendix 7B, Table 7B.1). To account for the recent agricultural policy reform, we run BackES with the novel payment scheme between 2014 and 2017 and started implementing policy strategies in 2018. Subsequently, we continued in four years intervals corresponding to the cycle in which policy programs are updated in Switzerland. The impact of the 47 strategies on the resilience of the mountain system was modeled in all 16 press-pulse scenarios describing in total 752 utility pathways.

7.3. Results
7.3.1. Resilience of the social-ecological system under global change
Figure 7.3 illustrates that the mountain social-ecological system is not resilient to global change. The decreasing utility over time demonstrates that demanded ES will
no longer be sufficiently supplied if no policy actions are taken. The loss of utility is particularly pronounced in the GC and GG scenarios with more open markets and migration policies. On the one hand, further farm abandonment decreases the cultural heritage service, as agricultural market prices drop. On the other hand, the aesthetic service of the region is impaired by forest growth on abandoned summer pastures and urban sprawl as a consequence of population growth and higher accessibility of the region. Pulses have similar effects on the utility in all scenarios, but in the most liberalized GC setting. Market and structural shocks persistently reinforce the decline in utility, while three consecutive years of drought only temporarily lower the utility. During these hot years farmers are forced to intensify many of their grasslands due to reduced yields on grasslands with a negative impact on the aesthetic service. The intensification however is reversible and with less extreme temperatures farmer return to a more extensive cultivation of their fields. Structural shocks erode the utility of the social-ecological system most. Especially in the GC scenario, in which the utility is impaired in parallel by heavy presses, the system reacts very sensitively with huge year to year fluctuations upon the shock. Negative utility peaks denote years in which many farmers retire or leave the sector, because opportunity costs are too high and labor force is too low. The loss of farms directly impairs the cultural heritage service of the region. Furthermore, as a consequence, many grasslands are temporarily not managed with negative effects on the aesthetic service. Slight recoveries illustrate that part of these grasslands can be taken over by the remaining farmers if the abandonment rate slows down. In other scenarios, the utility after a structural shock falls more gradually, since abandoned agricultural land can be better distributed among other farms.

Policy strategies can moderate these projected utility losses to a varying degree as the pathways in Figure 7.3 illustrate. Unless a structural shock occurs, utility can

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Figure 7.3. Bold lines show the utility over time in 16 global change scenarios without policy actions taken. Thin lines describe the impact of 47 policy strategies in each of the 16 scenarios. The bars on the right hand side of each plot illustrate the utility range at the mid-term horizon spanned by the set of policy strategies in the respective press-pulse setting.
nearly be sustained by at least one appropriate policy strategy in all global change scenarios as the bars at the right hand side of each plot demonstrate. While in an LS scenario many strategies maintain or restore the utility to a high degree up to 2035, most of the policy strategies can only partly buffer the strong pressures of the GC scenario. For example, even without a pulse, more than half of the pathways continue to gradually fall over time and result in considerable utility losses at the planning horizon. Clearly, the differences between the single pathways indicate that both the choice of the strategy and the global scenario, influence how well the system can buffer disturbances and how the provision of ES evolves over time.

7.3.2. Characterization of policy interventions

Figure 7.4 shows the isolated effect of single interventions on the utility in the four press scenarios. The interventions vary in terms of their context-dependency, i.e., how much their impact differs between the scenarios, as well as in terms of their time-dependency, i.e., how much their effectiveness depends on the time of implementation. Spatial planning restrictions are beneficial in a GC scenario but have no influence on the utility in a LS scenario, because migration to mountain regions and population growth is small (Figure 7.4a). At the same time spatial planning restrictions are highly time-dependent. If implemented early, they can build resilience and prevent a utility loss, but they lose effectiveness over time. Clearly, urban sprawl once advanced cannot be reversed and landscape aesthetics are impaired permanently. In general, targeting direct payments to increase support for traditional mountain farming practices is the most effective intervention to build resilience in all scenarios (Figure 7.4b). While the effect of this intervention on the utility is similar and independent on the timing in the RC, GG and LS settings, it is more pronounced and more time-dependent in the GC setting. Structural interventions influence the utility almost independently of the global context and weakly dependent on their

Figure 7.4. Impact of policy interventions on the utility in 2035 under alternative press scenarios depending on the time of implementation, relative to the baseline with no policy actions taken. Figure d: RC/LS: opening of markets (as in baseline closed markets), GC/GG: closing of markets (as in baseline open markets).
Both these instruments, direct payments and structural interventions, directly support farmers with monetary or human resources and help make their agricultural activities less susceptible to global socio-economic changes. An opening of markets is an adverse intervention in the GG and LS scenario, while a closing of markets slightly enhances the utility in the other two settings (Figure 7.4d). As observed for the other interventions, in the GC setting, early action pays off substantially, illustrating the urgent need for timely intervention if massive pressures threaten the system.

7.3.3. Robust policy strategies

Single interventions only partly restore the massive utility drop projected under global change. Optimal policy strategies for fostering resilience combine several interventions in appropriate sequencing drawing upon their effectiveness and their different time-dependence (Figure 7.5). Most robust strategies that result in minor utility losses of less than -2 are similar in all assumed global change scenarios and implement three or four interventions, at least two of them early in time. While the effect of a market closing as a fourth intervention is only minor (cf. Figure 7.4), agricultural direct payments as a third measure substantially attenuates utility loss as compared to strategies combining spatial planning and structural interventions only. The timing of these payments on the other hand is not paramount, as the similar outcomes e.g. of strategies 34 to 37 or of strategies 31 to 33 indicate. The effects of strategies based on one or two interventions are distributed among the whole utility range and are thus more uncertain. Implementing one single intervention early in time as in strategies 14 to 17 is nearly as effective as a late decision on two interventions as in strategy 18, which is an important information for policy-makers if resources are limited.

While pathways that result in high utilities in 2035 relate to the same policy actions in all global scenarios, the monetary revenues of farmers as ES providers along these pathways substantially depend on the global boundary conditions (Figure 7.6a). In a liberalized GC setting, farmers’ average income from agriculture between 2014 and 2035 is relatively low, even if the utility up to 2035 is restored. In contrast, in an RC scenario, farmers’ income over the same period is high, although the utility is not maximally sustained. Figure 7.6b clearly demonstrates that a continuous flow of direct payments is necessary to guarantee these higher returns to farmers.

7.4. Discussion

7.4.1. Resilience of mountain social-ecological systems

Historically, mountain regions have often been regarded as resilient systems, isolated from the lowlands, self-sufficient, rich in ES and being able to adapt to the natural variability or changing societal demands over time (Messerli, 1983; Körner et al., 2005). However, in recent decades, globalization trends, e.g., rising connectedness, farm abandonment or urbanization, have accelerated and caused major changes in these systems with potentially far reaching consequences for their ecological and socio-cultural integrity (Bender et al., 2011). Indeed, our modeling results indicate that these global drivers heavily impact the resilience of mountain regions to provide demanded ES in the future, if no policy actions are taken. In our case study, socio-economic pressures, especially liberalized markets and unrestricted migration, were most severely affecting the ability of the system to provide demanded ES in the medium timeframe considered. Globalization often acts as a top-down regulation process that ignores place-based conditions and local knowledge (Janssen et al., 2007), and creates direct constraints to farmers’ management practices and
Results which combine early spatial planning restrictions with direct and services-based financial support for farmers are particularly robust to changing levels of pressures and pulses. In the current era of accelerated global change, policy-making urgently requires the ability to make such robust decisions that do well under a wide variety of circumstances (Polasky et al., 2011a). In practice, however, cross-sectoral initiatives are often hampered, as they require complex negotiation processes to solve competing interests, close inter-agency collaboration and thus high transaction costs, and an awareness of the complexity of mountain social-ecological systems (Rueff et al., 2015).

Scientific approaches to assess the impact of policy actions often lack the necessary temporal resolution to adequately capture the different time frames of short-term policy and management decisions and longer-term environmental and socio-economic trends (Cash et al., 2006; Brunner et al., 2016). We evaluated the effectiveness of different policy strategies by adapting the national policy system under a range of global change scenarios. Assessing the context- and time-dependency of several interventions separately was a valuable approach for identifying the need to develop cross-sectoral strategies. Our approach could be further developed by the incorporation of probabilistic information into scenarios. Assessing the likelihood of global change scenarios could help improve the robustness analysis of policy strategies and reduce the uncertainty inherent in the policy recommendations (Rounsevell et al., 2012).

7.4.2. Policy implications
The lack of policy-relevant information on how national policy programs operate at local level is particularly pronounced for mountain regions (Gurung et al., 2012). Policy development can rarely spend sufficient resources thus ES supply (Briner et al., 2013a). Our results show, that these constraints substantially affected the resilience of the system to climate, market and structural shocks.

Climate shock scenarios with several consecutive years of drought only temporarily lowered the capacity of the system to provide demanded ES. The impact of temperature extremes and related fluctuations in yields could be buffered, since farmers have a rapid adaptive dynamic at their disposal: the yearly change in production decisions in husbandry and grassland management. However, in the longer term, an increased frequency and severity of climatic pulses in combination with the concomitant presses might induce changes in the forest structure or a permanent shift in agricultural management practices with negative impact on the resilience of the system. Market pulses had less effect on the resilience, as in our case study region both direct payments and off-farm employment provide important income streams for farmers. Alike in other European mountain regions, resilience is therefore relying on the current structure with mostly part-time farmers and a highly subsidized agricultural sector (Oteros-Rozas et al., 2012; Schermer et al., 2016). Consequently, an abrupt change in this structure, assumed in a third shock scenario, heavily threatened the resilience of the system. As in other rural regions, in our case study, the implementation of individual policy instruments could not sufficiently buffer the system against global change, but cross-sectoral strategies were necessary to sustain resilience (Bryan, 2013). These strategies tackled three important stressors of mountain systems simultaneously: targeted agricultural direct payments stabilized income flows of mountain farmers, structural interventions slowed down farm abandonment and spatial planning restrictions counteracted the increasing urbanization. Thus, our results highlight that strategies which combine early spatial planning restrictions with direct and services-based financial support for farmers are particularly robust to changing levels of presses and pulses. In the current era of accelerated global change, policy-making urgently requires the ability to make such robust decisions that do well under a wide variety of circumstances (Polasky et al., 2011a). In practice, however, cross-sectoral initiatives are often hampered, as they require complex negotiation processes to solve competing interests, close inter-agency collaboration and thus high transaction costs, and an awareness of the complexity of mountain social-ecological systems (Rueff et al., 2015).

Scientific approaches to assess the impact of policy actions often lack the necessary temporal resolution to adequately capture the different time frames of short-term policy and management decisions and longer-term environmental and socio-economic trends (Cash et al., 2006; Brunner et al., 2016). We evaluated the effectiveness of different policy strategies by adapting the national policy system under a range of global change scenarios. Assessing the context- and time-dependency of several interventions separately was a valuable approach for identifying the need to develop cross-sectoral strategies. Our approach could be further developed by the incorporation of probabilistic information into scenarios. Assessing the likelihood of global change scenarios could help improve the robustness analysis of policy strategies and reduce the uncertainty inherent in the policy recommendations (Rounsevell et al., 2012).

7.4.2. Policy implications
The lack of policy-relevant information on how national policy programs operate at local level is particularly pronounced for mountain regions (Gurung et al., 2012). Policy development can rarely spend sufficient resources

Figure 7.6. (a) Average annual income of farmers from agriculture generated over the course of a pathway (2014-2035) in relation to the final utility of a pathway; (b) Average annual income of farmers in dependence of the average annual direct payments.
to understand the complexity of these systems and policies are often devised with limited understanding and evaluation of their effects on remote conditions (Maru et al., 2014; Rueff et al., 2015). To test the acceptance of the suggested cross-sectoral policy strategies in the case study region, we integrated the study outcomes into a preliminary decision-support platform. In a workshop, we enabled ten local stakeholders, including policy-makers, planners and farmers, to interactively explore the impact of alternative policy strategies on regional ES provision. In general, participants supported more ES-oriented and integrative policies to maintain the landscape and identity of the region. However, two main concerns were raised: First, farmers were critical to increasing direct payments for cultural services at the cost of payments for food supply, as they would object their core business i.e., the production of agricultural commodities. In this context, a policy network analysis assessing the opinions of additional regionally-relevant policy actors confirmed that novel interventions to support non-marketable ES have to guarantee a continuing level of agricultural production (Hirschi et al., 2013). A second criticism was the limited consideration of specific characteristics and traditions of involved municipalities in the policy strategies. Participants suggested that community-based programs could substantially contribute to maintain the resilience in the case study region. A cooperation between municipalities when designating their building zones could for example help mitigate the loss of the most valuable areas for ES provision in the case study region (Drobnik et al., 2016). Or, regional marketing programs could help farmers diversify their income through mechanisms that respond to consumer perceptions of their unique, local and high-quality products (Bardsley and Bardsley, 2014). Thus, alternative governance mechanisms and bottom-up initiatives should be further evaluated with our approach.

Developing effective and efficient policy interventions requires a detailed knowledge not only of benefits, but also of costs related to alternative options (Polasky et al., 2011b). In our case study, the distribution of costs related to resilience-building policy strategies varied between the global scenarios. In a strong liberalization scenario, returns to farmers from agricultural activities were lowest, that is, farmers as ES managers bear more costs of ES provision as compared to a scenario with focus on regional centers and products. In such a setting, high federal direct payments warranted monetary compensation for farmers and consequently society as a whole bears more of the financial burden. Clearly, across all scenarios the ES provided by the mountain socio-ecological system can only be maintained at high societal costs. In Switzerland, farmed mountain landscapes are highly valued across the whole population, thus, there is both a perceived need and legitimation for governmental support (Bardsley and Bardsley, 2014). However, the cross-scale dependency that underpins the resilience of the system might increase its vulnerability in the longer term, as societal values and accordingly larger scale policy directives could change (Schouten et al., 2009). The assessment of additional cost factors related to the inferred policy strategies requires further attention in our approach. On the one hand, costs related to other than fiscal instruments, especially to spatial planning interventions, and transaction costs should be appraised for a more comprehensive cost estimation of the integrative strategies (Westhoek et al., 2013). On the other hand, changes in national policies, e.g., an adapted subvention scheme in support of mountain farming activities, will impact ES provision in other parts of Switzerland. Such cross-scale dynamics and distant effects and costs need to be evaluated for efficient and equitable policy designs (Liu et al., 2013).

While mountain social-ecological systems need to be able to buffer global pressures, especially shocks, in a short to medium timeframe, over the long term, they also need to be able to transform (Folke, 2006). Accordingly, policy strategies that continually cycle between incremental and transformative actions are required (Wise et al., 2014). Transformation as a long-term process has not been considered within the time horizon of this study, as it often conflicts with the values of stakeholders and requires high levels of collective action and learning which are not included in our modeling system. Adjusting BackES for developing longer term trajectories would require, on the one hand, a non-linear and dynamic utility index as an indicator for resilience to capture ecological and social thresholds of the system (Farley and Voinov, 2016). Including landscape metrics in the simulation of ES supply could help detect thresholds, beyond which certain land-use configurations cease to provide single ES (Grêt-Regamey et al., 2014). Choice tasks that sample preferences for entirely alternate states of the system and longitudinal studies of ES preferences could then be used to identify social thresholds and adaptation and learning processes (Verburg et al., 2015; Hein et al., 2016). On the other hand, longer-term decision-making mechanisms of farmers and novel management practices, e.g., with the help of agent functional types, could refine the modeling system to capture transformative processes in land management (Murray-Rust et al., 2014).

7.5. Conclusion
Theoretical literature on resilience is rich and rapidly
expanding, but only few empirical applications of the concept to mountain social-ecological systems exist. In this article, we have assessed the resilience of a mountain case study in the Swiss Alps under global change with an integrated social-ecological modeling system. The analysis generated insights into the most critical stressors eroding the capacity of the mountain region to provide demanded ES and unraveled policy strategies that are robust and sustain resilience under multiple global change settings. The systematic development and evaluation of a variety of transition pathways, as presented here, could serve as a powerful tool for supporting decision-makers explore and sequence a set of specific and robust actions in a highly uncertain future.

There is an urgent need for more empirical research into the resilience of vulnerable mountain social-ecological systems in order to support the timely formulation of robust policies for securing the valuable ES these regions provide.

Acknowledgments

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## Appendix 7A: Parameter values in BackES

*Table 7A.1.* Qualitative levels of drivers (Walz et al., 2014) and related parameter values in BackES under the four press scenarios. Parameter values were fed as time series into the modeling system.

<table>
<thead>
<tr>
<th>Type of driving factor</th>
<th>Driving factor</th>
<th>Qualitative level</th>
<th>Parameter values</th>
<th>Qualitative level</th>
<th>Parameter values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td>Climate</td>
<td>A1</td>
<td>Spatially explicit crop yield and timber harvest according to an A climate scenario (Briner et al., 2012)</td>
<td>A2</td>
<td>Spatially explicit crop yield and timber harvest according to an A climate scenario (Briner et al., 2012)</td>
</tr>
<tr>
<td>Social</td>
<td>Population CH</td>
<td>9.5 Mio.</td>
<td>Annual population growth according to a regionally-downscaled large population growth scenario for Switzerland (SFSO, 2013)</td>
<td>75 Mio. Regional centers</td>
<td>Annual population growth according to a regionally-downscaled medium population growth scenario for Switzerland (SFSO, 2013)</td>
</tr>
<tr>
<td></td>
<td>Migration within CH</td>
<td>Migration to agglomeration</td>
<td>High increase</td>
<td>Regional centers</td>
<td>High increase</td>
</tr>
<tr>
<td></td>
<td>Accessibility of mountain regions</td>
<td>Global production</td>
<td>Increase in agent-specific opportunity costs of 50% and decrease in agent-specific labor force of 50% as compared to 2013 (Huber et al., 2014)</td>
<td>Regional products</td>
<td>Constant opportunity costs and labor force (Huber et al., 2014)</td>
</tr>
<tr>
<td>Economic</td>
<td>Agricultural markets</td>
<td>Large decline in prices (open markets)</td>
<td>Fast linear decline to a factor of 1.3 of EU prices within 4 years, afterwards linear alignment to EU price in 2050 of all agricultural commodities according to Huber et al. (2014) and Abildtrup et al. (2006)</td>
<td>Stable prices (border protection)</td>
<td>Stable prices of all agricultural commodities according to Huber et al. (2014) and Abildtrup et al. (2006)</td>
</tr>
<tr>
<td>Policy</td>
<td>Agricultural policy</td>
<td>Liberalization</td>
<td>Decrease to 0 of general area-based direct payments and payments for grassland-based milk and meat production; otherwise direct payment scheme according to the recently enacted federal agricultural policy directions (DZV, 2013)</td>
<td>Reduced domestic support</td>
<td>Direct payment scheme according to the recently enacted federal agricultural policy directions (DZV, 2013)</td>
</tr>
<tr>
<td></td>
<td>Spatial planning policy</td>
<td>Laisser-faire</td>
<td>Constant average settlement area granted per additional resident (SFSO, 2009, 2013)</td>
<td>Laisser-faire</td>
<td>Constant average settlement area granted per additional resident (SFSO, 2009, 2013)</td>
</tr>
</tbody>
</table>
### Table 7A.1. Continued.

<table>
<thead>
<tr>
<th>Type of driving factor</th>
<th>Driving factor</th>
<th>Qualitative level</th>
<th>Parameter values</th>
<th>Qualitative level</th>
<th>Parameter values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td>Climate</td>
<td>B1</td>
<td>Spatially explicit crop yield and timber harvest according to a B climate scenario (Briner et al., 2012)</td>
<td>B2</td>
<td>Spatially explicit crop yield and timber harvest according to a B climate scenario (Briner et al., 2012)</td>
</tr>
<tr>
<td>Social</td>
<td>Population CH</td>
<td>9.5 Mio.</td>
<td>Annual population growth according to a regionally-downscaled large population growth scenario for Switzerland (SFSO, 2013)</td>
<td>7.5 Mio.</td>
<td>Annual population growth according to a regionally-downscaled small population growth scenario for Switzerland (SFSO, 2013)</td>
</tr>
<tr>
<td></td>
<td>Migration within CH</td>
<td>Amenity migration Sustainable</td>
<td>Increase in agent-specific opportunity costs of 25% and decrease in agent-specific labor force of 25% as compared to 2013 (Huber et al., 2014)</td>
<td>Certified products</td>
<td>Increase in agent-specific opportunity costs of 25% and decrease in agent-specific labor force of 25% as compared to 2013 (Huber et al., 2014)</td>
</tr>
<tr>
<td></td>
<td>Accessibility of mountain regions</td>
<td>Sustainable</td>
<td>Increase in agent-specific opportunity costs of 25% and decrease in agent-specific labor force of 25% as compared to 2013 (Huber et al., 2014)</td>
<td>Certified products</td>
<td>Increase in agent-specific opportunity costs of 25% and decrease in agent-specific labor force of 25% as compared to 2013 (Huber et al., 2014)</td>
</tr>
<tr>
<td>Economic</td>
<td>Agricultural markets</td>
<td>Decline in prices (more open markets)</td>
<td>Linear alignment to EU prices in 2050 of all agricultural commodities according to Huber et al. (2014) and Abildtrup et al. (2006)</td>
<td>Stable prices (more open markets, but increase in EU prices)</td>
<td>Stable prices of all agricultural commodities according to Huber et al. (2014) and Abildtrup et al. (2006)</td>
</tr>
<tr>
<td>Policy</td>
<td>Agricultural policy</td>
<td>Greening</td>
<td>Decrease to 0 of general area-based direct payments and doubling of payments for cultural landscape and extensive grassland; otherwise direct payment scheme according to the recently enacted federal agricultural policy directions (DZV, 2013)</td>
<td>Greening</td>
<td>Decrease to 0 of general area-based direct payments and doubling of payments for cultural landscape and extensive grassland; otherwise direct payment scheme according to the recently enacted federal agricultural policy directions (DZV, 2013)</td>
</tr>
<tr>
<td></td>
<td>Spatial planning policy</td>
<td>Restrictive</td>
<td>Decrease of 50% of average settlement area granted per additional resident (SFSO, 2009, 2013)</td>
<td>Restrictive</td>
<td>Decrease of 50% of average settlement area granted per additional resident (SFSO, 2009, 2013)</td>
</tr>
</tbody>
</table>
### Table 7A.2. Parameter changes in BackES associated with different pulses. Shocks were implemented as changes in time series of specific drivers.

<table>
<thead>
<tr>
<th>Shock in 2024</th>
<th>Affected parameters</th>
<th>Change in parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market shock</td>
<td>Milk price</td>
<td>Fall of prices to a factor of 1.3 of EU prices in 2050 as estimated by Abildtrup et al. (2006) in RC/GG/LS and to the level of EU prices in 2050 in GC, no recovery of prices was assumed</td>
</tr>
<tr>
<td></td>
<td>Meat price</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wheat price</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Livestock price</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Costs of fodder</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Costs of concentrated feed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Costs for livestock</td>
<td></td>
</tr>
<tr>
<td>Climate shock</td>
<td>Crop and forest yields</td>
<td>Spatially explicit yields were corrected by modeled lower standard deviations of the yields of Briner et al. (2012), based on a grassland module in LandClim (Schumacher et al., 2004), on average the corrected yields were 11% lower than in years without a shock, shock was implemented in three consecutive years</td>
</tr>
<tr>
<td>Structural shock</td>
<td>Probability of a successor</td>
<td>Decrease of 30% without recovery in consecutive years</td>
</tr>
<tr>
<td></td>
<td>Opportunity costs</td>
<td>Increase of 50% without recovery in consecutive years</td>
</tr>
<tr>
<td></td>
<td>Labor force</td>
<td>Decrease of 50% without recovery in consecutive years</td>
</tr>
<tr>
<td></td>
<td>Minimum income</td>
<td>Increase of 10’000 CHF without recovery in consecutive years</td>
</tr>
</tbody>
</table>

### Table 7A.3. Policy interventions and related parameter changes implemented in BackES.

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Affected parameters</th>
<th>Change in parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market opening/recovery</td>
<td>Milk price</td>
<td>Linear decrease towards an alignment with EU prices in 2050 as estimated by Abildtrup et al. (2006) (RC/LS)</td>
</tr>
<tr>
<td></td>
<td>Meat price</td>
<td>Linear increase towards an alignment with former CH prices up to 2050 (GC/GG)</td>
</tr>
<tr>
<td></td>
<td>Wheat price</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Livestock price</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Costs of fodder</td>
<td></td>
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<tr>
<td></td>
<td>Costs of concentrated feed</td>
<td></td>
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<tr>
<td></td>
<td>Costs for livestock</td>
<td></td>
</tr>
<tr>
<td>Targeted direct payments</td>
<td>General area-based direct payments</td>
<td>Linear decrease to 0 within 4 years</td>
</tr>
<tr>
<td></td>
<td>Payments for cultural landscape</td>
<td>Doubling of payments within 4 years</td>
</tr>
<tr>
<td></td>
<td>Payments for extensive grassland</td>
<td>Doubling of payments within 4 years</td>
</tr>
<tr>
<td></td>
<td>Payments for grassland-based milk/meat production</td>
<td>Doubling of payments within 4 years</td>
</tr>
<tr>
<td></td>
<td>Payments for summer pastures</td>
<td></td>
</tr>
<tr>
<td>Restrictive spatial planning</td>
<td>Average settlement area granted per additional resident</td>
<td>Linear decrease to 0 within 4 years</td>
</tr>
<tr>
<td>Structural interventions</td>
<td>Probability of a successor</td>
<td>Increase of 20% within 4 years</td>
</tr>
<tr>
<td></td>
<td>Opportunity costs</td>
<td>Decrease of 50% within 4 years</td>
</tr>
<tr>
<td></td>
<td>Labor force</td>
<td>Increase of 25% within 4 years</td>
</tr>
<tr>
<td></td>
<td>Minimum income</td>
<td>Decrease to 0 for part-time farmers within 4 years, decrease of 10’000 CHF for full-time farmers within 4 years</td>
</tr>
</tbody>
</table>
### Appendix 7B: Policy strategies

Table 7B.1. Combination and sequencing of interventions in all 47 policy strategies modeled. SP = spatial planning, SI = structural interventions, AP = agricultural direct payments, AM = agricultural market intervention

<table>
<thead>
<tr>
<th>Nr. of strategy</th>
<th>SP</th>
<th>SI</th>
<th>AP</th>
<th>AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>No intervention</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1 intervention</td>
<td>2</td>
<td>2030</td>
<td>-</td>
<td>-</td>
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<tr>
<td>3</td>
<td>-</td>
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<td>4</td>
<td>-</td>
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<td>17</td>
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<td>-</td>
<td>-</td>
<td>2018</td>
</tr>
<tr>
<td>2 interventions</td>
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<td>2030</td>
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<tr>
<td>27</td>
<td>2018</td>
<td>2018</td>
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<tr>
<td>3 interventions</td>
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<tr>
<td>37</td>
<td>2018</td>
<td>2018</td>
<td>2018</td>
<td>-</td>
</tr>
<tr>
<td>4 interventions</td>
<td>38</td>
<td>2030</td>
<td>2030</td>
<td>2030</td>
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<td>39</td>
<td>2026</td>
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<td>2022</td>
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<td>42</td>
<td>2022</td>
<td>2022</td>
<td>2022</td>
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<td>43</td>
<td>2022</td>
<td>2022</td>
<td>2022</td>
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<td>44</td>
<td>2018</td>
<td>2018</td>
<td>2018</td>
<td>2030</td>
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<tr>
<td>45</td>
<td>2018</td>
<td>2018</td>
<td>2018</td>
<td>2026</td>
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<tr>
<td>46</td>
<td>2018</td>
<td>2018</td>
<td>2018</td>
<td>2022</td>
</tr>
<tr>
<td>47</td>
<td>2018</td>
<td>2018</td>
<td>2018</td>
<td>2018</td>
</tr>
</tbody>
</table>
To be uncertain is to be uncomfortable, but to be certain is to be ridiculous.

*Chinese Proverb*
8. Synthesis

The synthesis section is structured into four subsections: In Section 8.1, the main results of the three papers are summarized with respect to the research questions. Section 8.2 discusses cross-cutting issues and problems that emerged throughout all analyses. Section 8.3 presents policy implications and evaluates the relevance of the thesis for society and research. Finally, in Section 8.4, further research directions are formulated.

8.1. Summary of key findings

This subsection addresses the research questions raised in Section 1.3. It provides an overview of the main findings of this thesis.

1. How can the integration of normative and explorative methods support our understanding of the future dynamics of mountain SESs?

The integrated social-ecological modeling framework BackES developed in this thesis combines explorative methods with normative methods. Section 5 illustrates how such an integration can profit from the complementarities of both perspectives and support our understanding of mountain SESs. The application of conventional (forecasting) scenario analyses showed the effects of global change assumptions and policy strategies on different indicators of the SES (e.g., land use or ES supply). From a sustainability perspective, it accounted for larger-scale environmental and economic aspects in the modeling of system dynamics. The integration of a normative vision unraveled how much changes in these indicators benefit people, whether there is a need for action, and which strategies perform best. Thus, it allowed the exploration of the desirability of different strategies within a coherent set of scenarios from a more local-scale, social perspective.

The results of my analysis explain how boundary conditions, policy interventions, and ES supply and demand are linked within the mountain SES. In particular, the integration of a normative vision into ES modeling could reveal how strongly changes in the supply of individual ES translate into ES benefits, accounting for trade-offs people are willing to do in the region. Furthermore, it was possible not only to evaluate combinations of ES that will be more beneficial in the future, but also to explore the processes that will allow for the provision of these services. Table 8.1 summarizes how the provision of ES evolves in a policy inaction, business-as-usual scenario and how strongly different system components affect future ES benefits as inferred from the analyses in this thesis (Sections 5, 6, and 7). Each investigated ES exhibits a different sensitivity to global changes and policy interventions and contributes to a varying degree to the total ES benefits, depending on the residents’ preferences. For example, the future development of the habitat protection service will be substantially influenced by larger-scale boundary conditions and policy actions taken. At the same time, changes in this service will not result in large changes in regional ES benefits. By contrast, although a little less sensitive to socio-economic and political drivers, changes in the forest area will considerably impact future ES benefits. Overall, my results illustrate that the integration of explorative and normative methods can provide sound information on how, where, and when ES are co-produced by the social and ecological parts of the system.

The inclusion of a target in the social-ecological modeling allowed the comparison of the effectiveness and efficiency of alternative single policy interventions and combined strategies given different global boundary conditions. In the mountain case study, the effect of interventions is comparable in different global change scenarios, whereas their efficiency is always higher given more liberalized boundary settings. That is, in liberalized conditions, a policy action will always result in higher relative gains in ES benefits. At the same time, total ES benefits remain lower than in other scenarios (Sections 5 and 7). These considerations, however, do not include a sound estimation of costs related to the implementation of interventions in different settings, which might substantially impact their efficiency (see also research question 3). In addition, my analysis can inform on the best timing for implementing different interventions with regard to a target, unravel the urgency of action dependent on the boundary conditions (Sections 5 and 7), and highlight areas where policy actions are most needed to secure desired benefits (Section 6). Overall, the integrated approach can improve our understanding of the relevance and impact of policy-making within the SES and of how, when, and where to best intervene in the system to reach a desired target. That is, it can inform on necessary policy actions in time scales that influence the work of institutions and individual decision-makers (see research question 3).

The integration of explorative and normative methods in a holistic approach required many simplifications. Several elements of and links within the SES have been excluded in the analysis of system dynamics. Relevant factors that should be considered in a more sophisticated
Synthesis

The transfer of the suggested backcasting approach to investigate the dynamics of other SESs is feasible, but a transfer of BackES to other regions would necessitate intense work. Other methods to elicit a normative vision and alternative ES models, which have already been applied in the specific setting of a case study, could serve as useful alternatives (Hewitt et al., 2014). However, their integration in a conceptually and methodologically consistent manner is essential (Bagstad et al., 2014; Hamilton et al., 2015). In addition, proper validation of the model is important to be able to reproduce observed patterns of relevant system elements and predict future trends credibly.

(2) Which global and regional drivers are key sources of uncertainty in the future provision of demanded ES across the case study region?

The spatially explicit analysis of data generated in an extensive scenario analysis using BackES revealed interesting insights into the future pattern of ES provision and associated uncertainties resulting from major drivers (Section 6). Given the preferences of local residents, changes in ES benefits in the case study region emerge with a relatively clear spatial pattern as summarized in Table 8.2. Gains in ES benefits occur predominantly in the valley bottom as a result of positive changes in landscape aesthetics of grasslands and habitat protection due to less intense management practices. However, the uncertainty related to the magnitude and location of these gains is high. The maintenance or conversion of valuable grasslands and related ES in the plain strongly depends on the strength and type of drivers, and we observe

Table 8.1. Projected development and sensitivities of ecosystem services (ES) provision in the mountain social-ecological system.

<table>
<thead>
<tr>
<th>ES (indicator)</th>
<th>Direction of future development (in a business-as-usual (BAU) scenario)</th>
<th>Sensitivity to global change</th>
<th>Sensitivity to policy interventions</th>
<th>Effect of change on regional human well-being/ strength of preferences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultural heritage (number of farms)</td>
<td>Decreasing</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium (negative)</td>
</tr>
<tr>
<td>Mass flow regulation (protection index)</td>
<td>Stable</td>
<td>Low</td>
<td>Low</td>
<td>Low (marginally negative)</td>
</tr>
<tr>
<td>Habitat protection (extensive grassland area)</td>
<td>Increasing</td>
<td>High</td>
<td>High</td>
<td>Low (positive)</td>
</tr>
<tr>
<td>Aesthetics (forest area)</td>
<td>Increasing</td>
<td>Medium</td>
<td>Medium</td>
<td>High (negative)</td>
</tr>
<tr>
<td>Aesthetics (settlement area)</td>
<td>Increasing</td>
<td>High</td>
<td>High</td>
<td>High (negative)</td>
</tr>
<tr>
<td>Aesthetics (intensive grassland area)</td>
<td>Decreasing</td>
<td>Medium</td>
<td>Low</td>
<td>Medium (positive)</td>
</tr>
</tbody>
</table>

1 Variations in indicators among global change scenarios: low = variation <6%, medium = variation between 6% and 12%, high = variation >12%
2 Maximum variations in indicators between best intervention and baseline scenario: low = variation <6%, medium = variation between 6% and 12%, high = variation >12%
3 Change in utility per 1% change in indicator: low = utility change <0.02, medium = utility change between 0.02 and 0.1, high = utility change >0.1

approach include the regional wine production, collaboration of farmers, links between tourism and agriculture, the budget of the canton, or cooperation among municipalities, among others (Brand et al., 2013; Drobnik et al., 2016). In addition, some crucial feedback mechanisms should be simulated in further analysis (e.g., whether outcomes can trigger learning mechanisms of farmers or change societal values and whether such changes in norms influence land-use management in the longer term; see Section 8.2).

Furthermore, the setup of the integrated modeling system was complicated and resource intensive. The time needed for validation, which is absolutely necessary for both scientific and societal credibility, exceeded my time schedule. Computational resources required for the social-ecological model were high, and the collection and preparation of data of different types and from different sources time intense. Similarly, the integration of methods from different disciplines asked for a conceptual and technical harmonization and clarification of terminology that was not straightforward from the beginning and had to be reviewed several times in the process. In particular, the integration of ES demand and supply based on a sound theory was subject to repeated discussions and the technical harmonization of visual information from the choice experiment with quantitative model results proved to be challenging. Thus, although clearly offering many advantages, the integration of explorative and normative perspectives in a social-ecological model needs an interdisciplinary approach and a considerable amount of resources.
little legacy effects. National socio-economic drivers, especially the agricultural policy budget, will determine the magnitude of gains in these benefits, whereas climate change will impact where farmers change their land management. Uncertainty in the preferences for ES increases the magnitude of uncertainties in future ES benefits, although, given my assumptions, to a lesser degree than uncertainties related to drivers of ES supply. The importance of the uncertainty in ES demand was underestimated in this study because only variations in the preferences of local residents were considered. The inclusion of preferences of other relevant stakeholder groups (e.g., tourism or industry) could substantially increase the variability in ES preferences and enhance uncertainties in future ES benefits, especially in the valley bottom where land is highly contested (see Section 8.2.4).

Future losses in ES benefits are mainly observed in remote regions above the tree line. They occur quite consistently across various assumed global and regional change scenarios and are related to an abandonment of summer pastures, which all face the same fate—they get encroached by forest. The loss of these currently highly valued pastures can only be slightly mitigated if regional workforce is maintained at a high level. Here, climate change not only increases the uncertainty in the spatial pattern of the losses, but also expands the areas potentially affected by abandonment and thus the magnitude of losses. However, substantial uncertainty exists in how aesthetic preferences evolve over generations, and this should be accounted for in an improved evaluation of these findings. Overall, my results indicate that readily accessible and remote areas are to a different degree sensitive to larger-scale changes. The development of the regional center Visp will depend on larger-scale population and migration dynamics. Furthermore, the full-time farmers in the main valley have more diverse land-use and livestock activities at hand than part-time businesses in remoter region, which can be better adapted to (inter)national market prices or changes in the direct payments. By contrast, remote areas are very likely to be abandoned regardless of how strongly global and national socio-economic drivers impact the mountain region. The regional farming structure, including the availability of work, opportunity costs, or successor probability, will determine how many of the valuable summer pastures can be managed in the future. Consequently, as more and more remote land is given up, the magnitude and pattern of changes in ES will depend less on the social environment and existing farm structures and more on public support for mountain agriculture, the influence of urban areas, and the extent of globalization.

The identification of major drivers and their impacts on land use and ES is important for anticipating future development trajectories and designing policies that might reduce the vulnerability of the SES. The results illustrate which areas in the valley bottom will become subject to the conflict between the region’s economic development and the preservation of desirable ES, and thus they help pinpoint areas that require special management attention and policy support. At the same time, my findings exemplify that in some places, changes in mountain agriculture and ES depend on external developments that can hardly be influenced. Therefore, the provided information can prevent policy-makers from investing their limited resources in areas that are subject to a relatively predetermined pathway. In addition, it can stimulate the discussion of whether the abandonment of summer pastures and forest encroachment at higher elevations should be prevented by alternative action plans to acknowledge the strong preferences of the residents for the maintenance of the status quo ES provision or whether such investments might not be feasible or necessary in future.

My results confirm the findings of other regional-scale case studies conducted across mountain regions in Europe. A majority of these studies report a continuation of the land-use changes observed in the past decades (Figure 1.1), especially a drop in the utilization of Alpine

<table>
<thead>
<tr>
<th>Region</th>
<th>Changes in ES benefits</th>
<th>Uncertainty of predictions</th>
<th>Path dependency</th>
<th>Major driver(s) affecting magnitude of changes</th>
<th>Major driver(s) affecting pattern of changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valley bottom</td>
<td>Gain in benefits</td>
<td>High</td>
<td>Low</td>
<td>Global/national socio-economic drivers (especially agricultural policy budget), preferences for ES</td>
<td>Climate change</td>
</tr>
<tr>
<td>Remote regions</td>
<td>Loss in benefits</td>
<td>Low</td>
<td>High</td>
<td>Regional/local socio-economic drivers (especially available regional workforce), climate change</td>
<td>Climate change</td>
</tr>
</tbody>
</table>

Table 8.2. Spatial pattern of changes in ecosystem services (ES) benefits, related uncertainties, and major drivers affecting magnitude and pattern of benefit changes.
Pastures and a related increase in reforestation. The loss of these highly valued areas is especially pronounced in locations with steep slopes, underdeveloped road infrastructures, a low proportion of full-time farms, and a low availability of agricultural labor force (Gellrich and Zimmermann, 2007; Bender et al., 2011; van Vliet et al., 2015). The fundamental driving forces that were the basis of the development in the past (Section 1.1) will continue to have a decisive influence on potential development pathways over the next 20 years. In particular, the political and market environments will continue to be the major drivers behind changes in mountain agriculture and ES, regardless of climatic changes (Briner et al., 2012; Westhoek et al., 2013). At the same time, there are significant differences at the regional level with regard to the development of farm structures and land use, and numerous local and regional peculiarities influence the small-scale development of abandoned areas (Flury et al., 2013). In summary, the macroeconomic and political environment is vital for the future development of mountain agriculture and ES while its impact is spatially heterogeneous. Consequently, the geographical scale plays an important role when evaluating the future of ES provision and designing adaptive policy strategies in our case study and across the Alps in general.

(3) Which policy strategies foster a desirable development of the mountain region against a wide range of global pressures and pulses?

Understanding the opportunities, limitations, and implications of policy interventions on ES provision through time and across space, and in many different situations is essential to improve our ability to manage ES sustainably and to shift the philosophy of SES stewardship from reactions to observed changes to proactive governance (Chapin III et al., 2009; Bennett et al., 2015). My results provide clear information on how specific policy alternatives will influence future ES supply and benefits in the case study region given a set of potential boundary conditions. To evaluate different strategies, my work addressed five major challenges identified as critical to developing policy roadmaps for sustainable land system futures (Rounsevell et al., 2012): (1) designing and implementing a scenario framework that links visions of desired futures to numerical models (Section 5), (2) engaging stakeholders on scenarios and visions (Section 5), (3) improving current mapping methods to analyze ES provision under alternative scenarios (Section 6), (4) identifying critical pathways to reach the desired outcomes (Section 7), and (5) deriving explicit policy recommendations (Section 7).

Results of the analyses suggest that, without interventions, the mountain SES is not resilient to providing desired ES against global change. Consequently, ES benefits will gradually fall, especially if agricultural markets are less protected and migration is less restricted. In such a liberalization setting, the provision of demanded ES becomes unstable if rates of farm abandonment suddenly accelerate, indicating that global settings influence how well the system can buffer pulses. The implementation of single policy instruments cannot sufficiently buffer the system against these global changes, but cross-sectoral efforts are necessary to sustain desired ES. Successful strategies include several measures that tackle three important stressors of mountain systems simultaneously: a direct payment scheme specifically targeted to mountain agriculture stabilizes income flows of farmers, structural interventions slow down farm abandonment (and thus grassland abandonment and forest encroachment), and spatial planning restrictions counteract the increasing land consumption of urbanization. The major effect of these policy actions is the mitigation of losses in highly valued cultural ES, especially in the aesthetic service of the region.

Assessing the time and context dependency of single interventions was a valuable approach for inferring an optimal sequencing of actions that is robust against various global change impacts. In general, all policy measures are slightly more effective when implemented early; however, the importance of timing differs across interventions. For example, changing the agricultural direct payment system provokes an immediate gain in ES benefits, but the effect levels off after the implementation period. This indicates that the reallocation of direct payments is a useful strategy if a rapid adaptation to ES demand is required in the region. By contrast, spatial planning restrictions continuously prevent losses in ES benefits. Policy-makers are thus well advised to restrict settlement development as early as possible. At the same time, the effect of interventions is to a differing degree sensitive to global boundary conditions. Changes in the agricultural policy schemes have a similar effect on ES benefits in all assumed global change scenarios, whereas spatial planning activities have a particularly pronounced positive impact in liberalization settings.

My results show that similar policy actions are robust and maintain ES benefits in several potential global change settings. Figure 8.1 synthesizes the sequence of interventions necessary to bring about a desirable future ES provision. The roadmap identifies milestones in time that need to be accomplished to reach a certain range
of ES benefits in the future and explicitly incorporates the uncertainties related to the development of global boundary conditions. For example, to ensure major losses in ES benefits (below -3) can be prevented in 75% of the assumed global chance scenarios, spatial planning restrictions have to be implemented as early as 2018, followed by structural interventions prior to 2026. My results thus suggest that options for responding to future uncertainties are enabled or constrained by choices made along the journey that change the path in ways that may be irreversible. Overall, the analyses of various policy pathways pinpoint key policy decisions that will influence ES provision in the case study region and highlight robust development pathways that lead most closely to desired futures. In the current era of accelerated and uncertain global change, policy-making urgently requires the ability to make such proactive, robust decisions that perform well under a multitude of circumstances (Chapin et al., 2010; Polasky et al., 2011).

My analyses did not include an in-depth assessment of costs related to alternative policy strategies, information that is highly important to decision-makers. A first estimation of agricultural payments necessary to maintain the ES provided by the mountain SES revealed that societal costs related with policy strategies are high, especially in more regionally oriented future scenarios. By contrast, in liberalization settings, farmers have lower monetary revenues for managing ES and thus bear the higher financial burden. Thus, although there are costs in delivering ES, it does not automatically mean that governments must bear these costs, but that socioeconomic settings and the choice of the strategy (e.g., regulation vs. direct payments) influence the distribution of costs across stakeholder groups. Clearly, to improve the efficiency and equity assessment of alternative actions and enhance its policy relevance, my approach requires a differentiated consideration of costs, preferences and objectives of stakeholders across different spatial scales (Geijzendorffer and Roche, 2014). Only if beneficiaries and cost bearers are identified in ES assessment can strategies that allocate investments to those who have their demand satisfied be designed. Techniques that could be used in the context of an economic valuation of ES include cost-benefit analyses, which assess the net difference between costs and benefits over the lifetime of an investment, or cost-effectiveness analyses (e.g., the least cost method that searches the cheapest way to achieve a goal; Silvis and van der Heide, 2013). Such cost-benefit analyses could also create valuable feedback in stakeholder workshops because people likely change their preferences when they learn about the investments needed to achieve visions expressed unrestrictedly (Vergragt and Quist, 2011; Celio et al., 2015). However, estimating public spending related to policy strategies remains a challenge due to often unpredictable transaction costs and the occurrence of undesirable side and off-site effects (Section 8.2.2).

8.2. Cross-cutting issues in the thesis
8.2.1. Bringing together ES supply and demand
A SES approach, as followed in this thesis, highlights the importance of moving beyond measuring the supply of services delivered by a region to metrics that provide an indication of the actual benefits gained by people. Analyzing ES benefits requires an understanding of both ES supply and demand to identify (mis)matches in the provision of services (Cowling et al., 2008; Reyers et al., 2013; Geijzendorffer et al., 2015). Despite their importance in definitions and commonly used frameworks, ES demand and benefits remain a poorly understood and quantified component in most of the applied studies (Carpenter et al., 2009; Paetzold et al., 2010; Seppelt et al., 2011; Bennett et al., 2015). Using BackES, I identified the match between ES supply and demand in terms of ES benefits received from services by local residents. The supply of services corresponds to a managed supply, provided by the combination of the potential supply and the impact of management, and was simulated spatially explicitly. The demand reflects the actual expression of the willingness of local stakeholders to obtain a certain service and was inferred as an aggregated value for the whole case study region. My results suggest that, without policy actions, ES benefits are likely to decrease; that is, mismatches between supply and demand will increase in the region (Section 8.1). Quantifying these mismatches and highlighting locations where they are
expected to occur can support the practical application of the ES concept in operational management and help find effective and targeted solutions for current resource exploitation. Furthermore, supply and demand are highly important topics in the sustainability debate. Integrating ES supply and demand can bridge the two perspectives on sustainable development, as an analytical concept to understand the complex interactions in SESs and as a normative approach to define the objectives of a well-functioning society (Sachs, 2015).

My approach allows for the detection of two types of mismatches between supply and demand: mismatches derived from the existence of trade-offs between services, which occurs when the managed supply leads to a set of services being supplied at the expense of others (Section 8.2.4), and unsatisfied demand, which occurs when the managed supply is not meeting the services demanded by stakeholders. However, mismatches can result from other origins such as temporal or spatial restrictions on access to the potential services (e.g., due to ownership constraints), from power relations among actors or from different preferences across stakeholder groups (Howe et al., 2014; Geijzendorffer et al., 2015). By contrast, mismatches might also be smaller than they appear through a local lens if demand for services at a larger scale and patterns of trade among regions or internationally are considered (Fisher et al., 2009; Power, 2010; Cumming et al., 2013). With regard to the mountain case study, three additional aspects of ES (mis)matches are of particular relevance: (1) The integration of ES demand from other relevant stakeholder groups, especially tourists, could potentially increase the identified local mismatches between supply and demand and help illustrate the seasonal dynamics of this imbalance. However, including international-level obligations (e.g., the halt of biodiversity loss promoted by the Alpine Convention or the Convention on Biological Diversity) and national-level agendas (e.g., the maintenance of valuable landscapes such as dry meadows and pastures) could help assess ES benefits at different spatial scales and put the local mismatch into a broader context. That is, several benefits might emerge at higher levels (Westhoek et al., 2013). (2) The spatial differentiation of ES demand could improve the assessment of spatial mismatches and the identification of service providing and benefiting areas (Syrbe and Walz, 2012). Accounting for proximity or accessibility is especially relevant for cultural services because they can only be enjoyed when people have access to the sites (Wolff et al., 2015). Considering such aspects in models includes some methodological challenges that are further elaborated on in Section 8.4. (3) Including a broader set of beneficiaries and improving the spatial assessment of services could not only advance the estimation of ES mismatches, but also contribute to designing and evaluating a broader set of policy instruments (Jack et al., 2008). For example, trading of demand and supply across regions could be considered as a strategy to satisfy distant needs and allow regions to maximize the supply of ES for which they are best fit. Markets and payments for ES from beneficiaries to providers have become an increasingly popular way to manage ES where local mismatches between supply and demand occur, but where benefits emerge in other regions (Farley and Costanza, 2010).

An integration of ES supply and demand needs indicators that are suitable to represent both sides of ES provision (Geijzendorffer et al., 2015). Indicators should be based on the characteristics of the SES and be reasonable to measure, observe, or model with the time and resources available (Seppelt et al., 2012). Useful guidelines or reviews on developing ES indicators are available (e.g., Egoh et al., 2012; Brown et al., 2014; Maes et al., 2016); however, they often focus on ES supply indicators. Finding appropriate indicators that can also be assessed from a demand perspective is particularly challenging because demand for ES - in contrast to more biophysically grounded ES supply - is often not directly measurable (Wolff et al., 2015). Experiences from my research show that it is particularly important to find indicators that relate to the actual benefits people derive from ES. This requires an engagement of stakeholders in deriving or at least reviewing indicators for ES. In this thesis, we progressed back-and-forth from services to indicators in an iterative stakeholder process and pilot-tested the indicators with members of intended participant groups to ensure the descriptions selected were clear for them. The resulting indicators were appropriate as attributes in the choice experiment to elicit ES demand and, at the same time, could be integrated into the model for simulating ES supply. They were sensitive to changes in land management, quantifiable, temporally explicit, and credible. However, not all indicators were spatially explicit, scalable, or suitable for other case study regions, additional criteria identified as being important for ES assessments (van Oudenhoven et al., 2012). The choice of indicators is thus valid for an assessment of ES mismatches in our case study region but not necessarily appropriate for other studies. Clearly, robust procedures and guidelines for selecting indicators that reflect both ES supply and demand are needed to promote integrated assessment approaches.

I used welfare economics as a common theory to integrate ES supply and demand. Correspondingly, I simulated ES
supply using linear programming and elicited demand for ES in a choice experiment. As outlined in Sections 2 and 3, several basic assumptions underlie the application of these methods. An important limitation in both methods is the assumption that farmers and local residents, respectively, are rational agents. Farmers will not always have the time, information, or ability to make fully rational decisions but instead rely on simple heuristics. In addition, a change in the global boundary settings, as modeled in this thesis, will most likely be associated with more risks in farmers’ decisions, and these risks are not accounted for in the analysis. The choice experiment assumes that individuals have well-defined and consistent preferences. However, biased preferences may result from the hypothetical situation and nonbinding character of the survey, as well as from framing effects (Kahneman, 2003). Another critical aspect of the choice experiment is the assumption that participants are able to reflect on their future preferences. Demand for ES is embedded in a complex relationship with other components of the SES. It is driven by, among other factors, socio-economic conditions, behavioral norms, marketing, demographic changes, and technological innovations. Changes in population size and composition can alter demand for ES by influencing the consumption patterns and preferences of the population. In fact, history has shown that economic growth and increasing wealth have been changing the nature of demand, from basic needs to more explicit attention for recreation services or aesthetic appreciation of landscapes (Villamagna et al., 2013). Finally, the chosen methods only allow considering a small subset of ES. We will, however, always face the situation that we do not have a full catalog of ES values or models that are sufficiently comprehensive for capturing the whole set of ES in a case study. A focus on several target ES based on a prioritization by resource users and decision-makers, as done in this thesis, is an appropriate way to address this challenge (Honey-Rosés and Pendleton, 2013).

A largely understudied issue in the context of an integration of demand and supply in ES literature is the fact that demand acts as a driver of ES supply. Similar to most ES assessments, I used demand for ES as a normative concept to value ES supply along different development pathways. At the regional scale, however, multifunctional agricultural landscapes and periurban areas provide clear evidence of land-use changes driven by demands for multiple ES. In these landscapes, traditional, production-driven forms of land uses are replaced by a mix of land uses that meet demands such as aesthetic and recreational values or nature conservation (Wolff et al., 2015). A better understanding of how preferences for ES drive socio-economic changes that impact land management and which aspects of well-being are most important in motivating changes in governance and policy is necessary to understand complex SESs and transition to more sustainable development trajectories (Reyers et al., 2013).

8.2.2. Interdisciplinary, multisectoral, and cross-scale approach

It is well recognized that natural resource issues occur at the intersection of social and ecological systems and that adaptation to global change requires the tackling of short- and long-term threats and uncertainty that cross policy sectors and scales (Colloff et al., 2017). Despite this recognition, conventional empirical approaches to analyze environmental management, ES provision, and governance continue to follow disciplinary lines, providing knowledge segregated to specific ecosystems or policy sectors (Virapongse et al., 2016).

The systemic approach taken in this thesis transcends several boundaries, typically set in such traditional assessments: (1) The framework used for addressing the research questions in this thesis (Figure 2.1) explicitly addresses the complex interactions between social and ecological systems. The environment is conceptualized as an open system in which ecological and social processes and elements are linked through forces such as management practices, resource demand, or political and economic conditions that occur on multiple scales. (2) The operationalization of the framework required an interdisciplinary scientific approach that integrated multiple knowledge sources, data, and methods. In addition, some methods and the evaluation of model results were contingent on the collaboration of science and society. (3) The conducted research is simultaneously context specific and longitudinal over time periods long enough to elucidate temporal dynamics. In particular, it integrates longer-term dynamics such as climatic changes, shorter-term policy cycles, and annual management decisions of farmers. (4) Furthermore, the analyses included the impact of drivers across institutional and spatial scales. The interactions among global and national socio-economic and political settings, regional biophysical limitations, and local management strategies were simulated via an agent-based model in BackES. (5) In the assessment of ES changes, attributes of both suppliers and beneficiaries of services provision were considered. The characteristics and motivations of land managers (farmers) were included on the supply side and preferences for different ES of local residents on the demand side. (6) Finally, the effect of cross-sectoral policy strategies on the SES was tested. Different
interventions from the agricultural and spatial planning sector were integrated to explore the benefits of such policy arrangements.

However, in the face of an increasingly connected world, my modeling system, similar to many other ES studies, misses one central aspect: Distant forces are only studied as exogenous variables that impact the mountain case study and feedback from the regional scale on the national scale and telecoupling effects were not considered (Scholes et al., 2013). For example, I only accounted for the in situ benefits of mountain ES, whereas effects of changes in local ES management on downstream ecosystems and livelihoods were not considered (see also Section 8.2.4). Similarly, the effects of changes in national policy schemes were only assessed within the case study region despite the fact that they would impact management costs and ES provision in other parts of Switzerland. Accounting for such distant benefits and costs in the conducted policy assessments would help better evaluate the efficiency and equity of alternative strategies (Liu et al., 2013). In conclusion, my approach provides a more holistic system and problem definition and an advanced analysis of cross-scale effects as compared to traditional approaches, factors that can enhance the understanding of causalities in SESs and improve the accuracy and reliability of findings (Zermoglio et al., 2005). However, a more sophisticated integration of distant interconnections and feedback is needed, particularly in the context of ex ante policy evaluations.

### 8.2.3. Scenarios and uncertainty

Scenario analysis has emerged as a means of characterizing and exploring the future of SESs and its uncertainties in a structured, yet creative and flexible way (Carpenter et al., 2006; Rounsevell et al., 2012). In this thesis, I integrated two types of exploratory, expert-based scenarios with one type of normative, stakeholder-defined scenario to investigate the magnitude and uncertainty of future changes in the mountain case study (Table 8.3). Socio-economic and climatic global scenarios based on the IPCC SRES scenarios were used to describe plausible, alternative boundary settings in the longer term. In addition to commonly used press scenarios, I also included pulse scenarios to account for shocks that might create bifurcation in future socio-economic trajectories (Rounsevell and Metzger, 2010). Because these conventional scenarios are often criticized to be of minor policy relevance due to their long-term horizon and global perspective, I included policy strategies as a second type of exploratory scenario that matched the short-term nature of policy cycles that affect actions of decision-makers. This type of scenario allowed for the identification of different development pathways that lead to a similar outcome and could provide valuable insight into the robustness of a given action with respect to alternative boundary assumptions (Section 8.1). Although these scenarios are particularly appreciated by policy-makers because they offer a decision space for future actions, they have been rarely applied in literature (Bryson et al., 2010; Rounsevell and Metzger, 2010). Finally, I integrated visions as a normative goal and as a means to evaluate the performance of alternative policy strategies. The combination of these scenarios allowed me to account for uncertainties in various drivers of the SES, at different spatial scales, and related to decisions and processes at different temporal scales.

In general, scenario approaches have several benefits (Carpenter et al., 2009; Mahmoud et al., 2009; Scholes et al., 2013): The identification of key drivers, system vulnerabilities, and uncertainties that may shape the future can help identify the relevant scales for interventions and provide the means by which decision-makers can anticipate coming change and prepare for it in a responsive and timely manner. Comparisons of scenarios often highlight the trade-offs and synergies between ES or among stakeholders that might be less evident when a more limited suite of options is considered. Scenarios can be a very powerful way of engaging stakeholders in a discussion of the future, raising awareness among policy-makers and the public, and focusing people on the problem being addressed. They can ease communication because they can be readily simplified into qualitative storylines or visualizations. The combination of several scenarios in my approach can furthermore help highlight key actions needed to avoid undesirable future development trajectories and actions that are robust in the face of a range of very different futures and thus help guide the design of adaptive strategies. In addition, the large number of scenario runs offered the potential to investigate the outcome space from different perspectives and apply statistical techniques (Section 6).

An issue of debate within the scenario development community is whether likelihoods and probabilities should be associated with scenarios (Polasky et al., 2011). The backcasting perspective chosen in this work stresses the application of very different scenarios regardless of how likely or unlikely these events seem from today’s point of view (Robinson, 1990). Thus, I did not assign probabilities to either scenario type. On the one hand, assuming likelihoods of policy strategies could diminish their value and make them too akin to forecasts.
On the other hand, assigning a likelihood to global change scenarios could help improve the robustness analysis of policy strategies. For example, shocks generally reflect potentially high-impact events that have a low probability of occurrence. When evaluating the robustness of policy strategies in this study, I inherently assumed a similar likelihood of press and pulse scenarios (Section 7), which might overestimate the frequency of catastrophic changes in the future and result in an underestimation of the robustness of actions. Bayesian belief networks are techniques developed to incorporate probabilistic information into scenario modeling (Rounsevell and Metzger, 2010). However, in the application of these networks, the task of estimating probabilities, especially those of rare events, remains a difficult one, and scientists or experts naturally rely on a set of heuristics that may also result in biased outcomes (Uusitalo, 2007).

Although scenarios are one way to deal with uncertainty, scenario analysis is prone to great uncertainties. Specific causes of uncertainty include a lack of basic knowledge about future development, errors in data, model structures, model parameters, and inappropriate assumptions (Mahmoud et al., 2009; Rounsevell and Metzger, 2010). An important kind of uncertainty comes from the bias of the scenario developer. In this thesis, as in all scenario approaches, subjective judgment was required to reach consensus on key variables that may have several plausible values. In addition, a challenging issue in the construction of scenarios in a modeling-based approach is how to proceed from qualitative narratives to quantitative projection scenarios. Consequently, the entire data processing aspect is a great source of uncertainty. I tried to reduce these uncertainties by using quantitative scenarios that have been applied in previous studies, performing extensive sensitivity analyses, and basing my assumptions of data values on historical records. Clearly, the outcomes of this study depend to a large extent on the assumptions I have made when setting up these scenarios. Our experiences from the workshop have demonstrated that the scenario development process should be more transparent. Scenarios cannot be a “black box” approach; instead, stakeholders need to understand how scenarios were constructed, including who was involved, how they were derived, and who they are relevant to (Bryson et al., 2010). In this context, an advancement of the collaborative platform (Figure 3.6) could be interesting. In our workshop, a set of only six narratives was extracted from the outcomes of the scenario analysis and presented to stakeholders. For these scenarios, risks, rewards, and trade-offs could be explored by the participants. However, if technical resources were available, all runs could be integrated into the platform. The user interface could then be updated by a feature that allows stakeholders to interact with potential pathways via a series of sliders controlling the level of emphasis on different ecological, socio-economic, or political indicators. Such a functionality would allow treating scenarios not as a final end product presented by scientists to stakeholders, but as an iterative process in which scenarios can be refined by different actor groups (Robinson et al., 2011). This setting could promote learning processes that strengthen the ability of practitioners to include uncertainty into policy judgments and potentially foster adaptive management processes (Hou et al., 2013).

### 8.2.4. Trade-offs

Major barriers to effective resource management and planning arise due to a manifold set of trade-offs involved in the provision of ES (Hein et al., 2006). Identifying and quantifying these trade-offs is essential to foreseeing the impact of global and regional changes and policy and management interventions on ES supply and benefits (Braat and de Groot, 2012). The modeling system BackES inherently includes trade-offs in the calculation of ES provision. First, land-use demands from regional development (i.e., population growth and migration) and agriculture are likewise considered. Second, the farmers in the model are forced to make trade-offs between management activities when optimizing their income (e.g., between management for maximal food production and other desired outcomes).

<table>
<thead>
<tr>
<th>Term used in thesis</th>
<th>Type of scenario</th>
<th>Spatial scale</th>
<th>Time scale</th>
<th>Scenario development method</th>
<th>Number of scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenarios</td>
<td>Exploratory</td>
<td>Global to national</td>
<td>20 years</td>
<td>Formative scenario analysis (expert based combined with mathematical optimization)</td>
<td>4 press scenarios combined with 4 pulse scenarios</td>
</tr>
<tr>
<td>Policy strategies</td>
<td>Exploratory</td>
<td>National to regional</td>
<td>Implemented in 4-year policy cycles</td>
<td>Expert based</td>
<td>47 policy strategies</td>
</tr>
<tr>
<td>Visions</td>
<td>Normative</td>
<td>Regional</td>
<td>20 years</td>
<td>Choice experiment among residents, orthogonal main effect design</td>
<td>32 visions as a basis for choice experiment</td>
</tr>
</tbody>
</table>
or more biodiversity-targeted farming). Finally, trade-offs local residents made in choosing among ES under a budget constraint are included in the calculation of ES benefits.

In my analysis of future ES trade-offs, I addressed two of the three types of ES associations recently suggested in literature (Mouchet et al., 2014), supply-supply and supply-demand, while I did not investigate demand-demand trade-offs. With regard to supply-supply associations, in our case study, trade-offs between the cultural heritage and the habitat service (Figure 8.2a), as well as between the former and the aesthetics of grassland (Figure 8.2b), will become especially pronounced (see also Section 5).

By contrast, I found synergies between the maintenance of cultural heritage and the aesthetics at higher elevations related to a slower forest growth (Figure 8.2c) and between habitat protection and the aesthetics of grasslands (Figure 8.2d). Although not explicitly discussed and reported in the three papers, as of lower concern to the regional stakeholders, trade-offs between provisioning and cultural or regulation services that are regularly observed across different type of ecosystems (King et al., 2015) are also present (Figure 8.2e and f).

My results furthermore illustrate that the nature and strength of these trade-offs will substantially depend on global boundary conditions (Figure 8.2) and policy actions taken (Figure 5.5, Section 5). For example, in a liberalization scenario, certain trade-offs emerge differently than in other scenarios, indicating that these relatively strong global settings trigger the system to reach critical tipping points. Indeed, in the Growth and Convergence scenario, all full-time sheep farmers are forced to give up their business and both summer pastures and agricultural land at lower elevations substantially decrease as compared to other scenarios. The shift in the regional management structure and the concentration of agricultural activities in smaller areas cause changes in prevalent trade-offs.

Or, a change in the agricultural direct payment scheme will decrease habitat protection but increase aesthetics at the tree line, thus changing the bundles of provided ES (Figure 5.5). The socio-economic and policy settings will not only alter trade-offs among ES, but also among societal benefits and costs and private financial gains and investments of farmers (Section 7). Such an assessment of key trade-offs within various different socio-economic and political boundary conditions remains an important poorly investigated topic of ES research (Carpenter et al., 2009). Supply-demand trade-offs are discussed in detail in Section 8.2.1. In this context, a review of Howe et al. (2014) reveals that the analysis of how trade-offs emerge on the way from ES supply via ES benefits to human well-being, as provided in this study, is a significant gap in the literature on ES trade-offs. Overall, this thesis addressed important aspects of ES trade-offs, and the relatively simple visualization of changes in the supply of different ES and related changes in ES benefits are suitable to detect trends and communicate them to stakeholders. However, my analyses do not provide a quantification of the strengths of the associations between single services. Advantages and limits of more sophisticated methods to quantify trade-offs among ES are discussed by Mouchet et al. (2014).

Although recognized as being crucial to identifying the implications of trade-offs and viable and sustainable management solutions, few studies explicitly include demand-demand trade-offs resulting from divergent stakeholders’ interests (Geijzendorffer et al., 2015; King et al., 2015). Clearly, to enhance its practical relevance and significance, my approach needs to be amended by an improved empirical understanding about the diversity of stakeholders, their preferences for various ES, and the potential social conflicts and inequities arising from their differing access to specific ES. In our case study region, the tourism sector and residents might have similar preferences for services and favor development strategies that focus on heritage and environmental quality of the region (Brand et al., 2013). By contrast, the main interests of the regional industry on robust infrastructure, regional growth, and related expansion of the industrial and settlement area will likely cause trade-offs to these demands for cultural ES (see also Appendix D). Thus, as ES change along different potential development pathways, so do winners and losers. More recently, network analyses have been applied to visualize and quantify trade-offs and synergies among ES on the basis of different stakeholders’ perceptions and values (Hicks et al., 2009). This information must then be integrated with information about stakeholders’ relationships with one another and the prevailing entitlement structures that foster or hinder equality in access to and benefits from ES (Bennett et al., 2015). Finally, to better represent and integrate demand-demand trade-offs in the decision-making process, multi-criteria approaches would account for and unravel different values and preferences among stakeholder groups (Jacobs et al., 2016). A hierarchy of preferences and obligations across different spatial scales (e.g., enacted in international conventions, national laws or policy agendas, and expressed by different local stakeholders) could be helpful in structuring such efforts.

Another trade-off dimension that has become more important in the context of telecoupling (see Section 8.2.1) and political boundary conditions remains an important in the context of telecoupling.
8.2.2) relates to trade-offs between proximate and geographically distant or local and global benefits. The provision of regional highly valued services in our case study region might come at the cost of benefits for a wider group of people. For example, carbon sequestration or regulation of terrestrial albedo is higher when forests grow on former agricultural land (Munroe et al., 2013), a land-use transition very negatively valued by local residents. Or, in Alpine countries, the contribution to food security generated by agricultural commodities is of decreasing importance. Consequently, the production potential of mountain agriculture is currently not fully...
exploited. This is in contrast to a more global perspective, because populations in mountain regions and adjacent lowlands are growing, and food security is at risk for 40% of these mountain dwellers worldwide (Flury et al., 2013).

Finally, trade-offs between a desirable and ecologically viable ES provision might arise, especially in the longer term. Preferences of stakeholders do not always conform to what is ecologically feasible or sustainable (Atkinson et al., 2012). Although in this study, we specifically asked stakeholders to state preferences for ES in the future, assuming they care about their descendants, it is critical whether these preferences generate a vision that does not come at the cost of negative impacts on critical natural capital (Iwaniec et al., 2014). In addition, a changing array of ecological and social factors means that this negotiation process is never complete (Nelson et al., 2007). To ensure the viability and sustainability of the SES in the longer term, trade-offs among different ES have to be navigated in a way that does not compromise the natural capital needed to provide services in the future (Cavender-Bares et al., 2015). Enabling such development pathways requires new and flexible ways to evaluate and adaptively manage trade-offs between maintaining desirable aspects of current SESs and adapting to major biophysical changes to those systems (Colloff et al., 2017).

8.2.5. Resilience

Resilience has many alternative definitions and multiple levels of meaning: a metaphor related to sustainability, a property of dynamic models, and a measurable quantity that can be assessed in the field or modeled in studies of SESs (Carpenter et al., 2001). In this thesis, I analyzed social-ecological resilience operationalized as the capacity of the mountain SESs to maintain flows of desired ES given by ES demand during a specific period of time (Janssen et al., 2007; Biggs et al., 2012). Specifically, I modeled whether and how the system can cope with external disturbances and still continue to deliver demanded ES.

The mountain case study is not equally resilient to different presses and pulses. The SES is fairly resilient to climatic changes (i.e., continuous increase in temperature or higher frequency of dry summers). The impact of temperature extremes and related fluctuations in yields can be buffered because farmers have rapid adaptive dynamics at their disposal: the yearly changes in production decisions related to husbandry and grassland management. Furthermore, grasslands, especially extensive ones, maintain productivity over a broader range of conditions than monospecific crops due to greater functional and response diversity (Biggs et al., 2012). The mountain region is medium resilient to socio-economic changes. Although a sudden collapse in agricultural markets does not substantially impact this resilience, sustained presses related to a more liberalized setting make the SES more vulnerable to other type of shocks. By contrast, the system is not resilient to policy changes. Collapses in subsidy programs could trigger a collapse in production systems and substantially accelerate the rate of farm abandonment.

Compared to other Alpine regions where changes in land-use and agricultural structures have been substantially larger in the past decades (Flury et al., 2013), the Visp case study is rather resilient to ongoing and predicted disturbances. The in-depth analyses of system dynamics in this thesis revealed different sources of resilience that can be grouped into three types: (1) The most important political and institutional factors that help maintain the resilience to provide desired ES are the large governmental budget for agricultural subsidies, the cross-compliance-based payment scheme that grants financial aid only if specific demanded ES are provided, and the governmental protection of inland markets for agricultural commodities. Furthermore, the federalist policy system addresses emerging problems relatively quickly and within the geographically relevant scale, while still being nested within the national regulations. Such regionally oriented systems also provide broader levels of participation in resource governance and help capitalize on scale-specific knowledge (Folke et al., 2016). Indeed, assemblies of residents constitute the legislative branches of the municipalities and thus information and experiences are better shared among different stakeholders. (2) With regard to socio-economic and cultural aspects, the high number of part-time farming businesses resulting from a historical testamentary partition of land is a key factor in strengthening the regions’ resilience. Investment in diverse activities enables farmers to rebalance their activities when market or environmental conditions change or shifts in ES preferences occur. At the same time, the part-time business structure increases connectivity among different social groups which can support information sharing and develop trust and reciprocity necessary for collective actions (Biggs et al., 2012). The current agricultural structure is stabilized by an excellent infrastructure that guarantees fast access and short travel time to secondary jobs. (3) Environmental and geographic conditions that strengthen the resilience of the region include the availability of water (and related infrastructure), the small size and small-scale structure of the country, which contribute to short commuting distances and connectivity to regional centers (as compared to highly remote and isolated mountain regions), and a high landscape diversity.
Like high actor diversity, landscape diversity enhances options for responding to disturbances (Chapin et al., 2010). Furthermore, the region profits from a high in situ value of ES. That is, there is a perceived need for regional conservation of ES, and conservation is compatible or even coupled to tourism and the major income source of the valley.

The compilation of these factors illustrates that, similar to other European mountain regions, resilience relies on the current structure of mostly part-time famers and a highly subsidized agricultural sector (Oteros-Rozas et al., 2012; Schermer et al., 2016). Although such policies buffer the system against market globalization, they may also present barriers to traditional coping strategies with shocks and make mountain people more reliant on outside economic assistance. This reliance on outside funding and infrastructure can give SESs a false sense of security, making them more vulnerable to other drivers. Indeed, increasing the resilience of specific parts of the system to certain disturbances may cause the system to lose resilience in other ways and even enhance the likelihood of new kinds of instability (Nelson et al., 2007). Furthermore, the relatively rigid payment system does not trigger innovations and experimentation that help adapt to changes and that have repeatedly proven to be key to reducing vulnerability (Chapin et al., 2010).

Resilience in the previously outlined definition is the capacity of the SES to continually change and adapt, yet remain within critical thresholds. However, thresholds caused by non-linear dynamics are inherent properties of SESs. It is highly difficult, if not impossible, to identify the precise location of thresholds, and they may become apparent only as system transformation is occurring or after it has occurred (Cavender-Bares et al., 2015). In the longer term, the system is likely to cross such thresholds, often beyond the influence of local actors (Nelson et al., 2007). Therefore, in the longer term, resilience thinking and management has to broaden its meaning as a buffer for conserving what you have and recovering to what you were. Beyond this concept of persistence, resilience has to incorporate transformability of the system (i.e., the capacity to cross thresholds into new development trajectories; Folke et al., 2010; Wise et al., 2014). Transformation can be a desirable process or be associated with the effects of inadvertently crossing thresholds (Nelson et al., 2007). In the longer term, we need to plan for the deliberate former process to prevent the latter uncontrolled one. However, including transformation in policy and management strategies is not easy, particularly in SESs with strong identity or cultural beliefs, and often requires a shock or at least a perceived crisis (Chapin et al., 2010). Such events may open up opportunities for reevaluating the current situation, trigger social mobilization, recombine sources of experience and knowledge for learning, and spark novelty and innovation (Folke et al., 2010). Modeling non-linear dynamics to predict different transformational trajectories of an SES remains highly challenging (Cavender-Bares et al., 2015). Requirements to novel modeling approaches are further discussed in Section 8.4.

8.2.6. Decision support

The discussions in the previous chapters demonstrate that my approach is useful for generating information valuable in all phases of the environmental policy cycle (Figure 2.2). The elicitation of stakeholder preferences and the development of relevant and site-specific indicators as performance measures are crucial in the problem structuring phase. Furthermore, the analysis of the dynamics, vulnerabilities, and sensitivities of the SES in a spatially and temporally explicit manner renders information on the actual provision and possible future underprovision of ES and the necessity of policy actions. The development and iterative refinement of policy strategies and the estimation of their consequences on performance measures is a central activity in the evaluation phase. To support sound negotiations, the analyses specifically integrate the socio-economic and ecological dimensions across different hierarchical levels and policy influence from the international to the regional scale. Scenario analyses can reveal the effectiveness, efficiency, and robustness of alternative policy strategies given different boundary settings. The analyses furthermore serve as useful tools in making the effects of changes at higher scales transparent in terms of their influences at the local scale and give insights into the level of uncertainty with which policy-makers have to contend. All this information is useful in evaluating alternative courses of action. Finally, in the decision phase, multiple trade-offs need to be considered. My analyses provide quantitative and spatial information on important trade-offs and synergies between ES as a basis for negotiation and decision.

In summary, this work addressed four of the five widespread shortcomings of ES assessment with regard to their suitability for decision-making (Grêt-Regamey et al., 2016): (1) Site-specific indicators for ES benefits were elaborated, accounting for the specific social-ecological context in the case study, (2) uncertainties were addressed in the assessments, (3) the demand side of ES provision was integrated, and (4) policy constraints were accounted for at different governmental levels.
The focus on key ES despite the existence of many other services is a common weakness of ES assessments that could not be overcome in this thesis (see Section 8.2.1). Furthermore, from a policy-maker’s perspective, the previously discussed limitations of the approach with regard to ES demand require particular attention; that is, preferences for ES of different stakeholder groups and at higher geographic scales should be explicitly considered (Westhoek et al., 2013).

An unresolved issue across literature on decision support remains the role of valuation in informing decisions about ES management. Particularly, the question about the extent to which economic values can be a guide for decision-making or whether ecological constraints and social or cultural value dimensions should be considered has generated much debate (Atkinson et al., 2012). Economic valuation as used in this thesis is especially helpful in prioritizing alternative development options in cases in which the socio-economic and political contexts allow for alternative options for land use and management. Because economic valuation puts a great emphasis on comparing the effectiveness of strategies (rather than meeting a specified target), it can be very helpful in complex decision-making situations where other values cannot be established to any degree of validity (Kumar et al., 2013). However, although the relevance of economic values for determining the importance of ecosystems for society and guiding policy thinking is recognized, we need to acknowledge that other value dimensions (ecological, cultural, self-interest, electoral, or ethical) are also implicitly or explicitly part of the decision-making processes (Díaz et al., 2015; Kenter, 2016). Uncovering and eliciting these diverse values requires integrating diverse valuation approaches (Martin-López et al., 2014). The application of one single valuation method can hardly account for the ethical, moral, and justice dimensions of many environmental issues, especially in the context of power imbalances (Kenter et al., 2016). Some social actors get more power in the decision-making because their interests are represented by the valuation output (which is linked to the valuation method used), whereas others remain unheard. The choice of whose values need to be included for a purposeful yet realistic valuation is a daunting task (Jacobs et al., 2016). Because scientific studies are often limited in their integration of value dimensions, scientific knowledge can no longer be considered as neutral, but rather must be seen as entering societal and political arenas in which knowledge is contested. Such a view implies a shift away from recommendations on optimal resource use and policy actions and toward explorations of future options and scenarios that can facilitate negotiation processes among different stakeholder groups (Giller et al., 2008).

From this perspective, it is likely that my approach is useful for building awareness in decision-making processes and supporting negotiations, but the question of whether it can generate real transformation knowledge remains elusive. Literature on how to design decision-supportive research and on which factors affect the likelihood of success that ES assessments are implemented in decision-making is rapidly growing (Volk et al., 2010; McIntosh et al., 2011; Sojda et al., 2012; Rosenthal et al., 2015). Three crucial aspects are mentioned in all studies: legitimacy, collaboration, and credibility. However, despite this existing knowledge and although both the OPERAs and MOUNTLAND projects were set up as transdisciplinary projects, we encountered several obstacles in pursuing a truly legitimate, collaborative, and credible research approach. The following aspects affected the legitimacy of our work: An in-depth understanding of which policy alternatives can be investigated with the modeling system only evolved during the development and application of the model. Therefore, a clearly defined policy question could not be defined from the beginning of the research process. In particular, the evaluation of national and regional policy alternatives did not perfectly match the interests and decision space of locally involved decision-makers. A major problem with regard to collaboration was the difficulty encountered in engaging stakeholders. Mobilizing experts for the workshops proved to be very difficult despite (or maybe because of) their prior engagement in the research process. As a result, the regionally important tourism and industry sectors were not adequately represented. Another challenge was to ensure that stakeholders’ contributions were relevant and useful to refeed into ongoing research. Clearly, the ways knowledge is exchanged needs to be carefully planned. Problems with regard to credibility included the information overload and complicated processes underlying the results that raised some mistrust. Furthermore, the core topic of the analysis, the mismatch between ES supply and demand, was not perceived as a problem by all stakeholders. At the moment, mountain ES in the case study region are not scarce, and other policy issues have priorities. Finally, the resolution of the outcomes did not meet the expectations of the workshop participants who wanted representations of very local preferences and ES supply to take into account the specific characteristics of the valley’s municipalities. Despite these limitations, my research could generate some useful information for policy and society, which are discussed in the next section.
8.3. Relevance of the thesis to policy, society, and research

In Section 1, I briefly outlined some major challenges policy-makers, society, and scholars will face with regard to mountain regions in the near future: the increasing threat toward mountain ES, the highly complex place-based consequences of global trends, and the necessity of novel development strategies to ensure the sustainability of mountain regions. In this section, I revisit these issues by discussing the policy implications, societal relevance, and scientific impacts of my work.

8.3.1. Policy implications

The generalization and transferability of results from place-based research is limited, particularly in mountain regions, because the drivers and processes of land use are complex, and their outcomes are contingent on specific geographic context, including prevailing socio-economic, political, and cultural conditions (Tomás et al., 2016). Indeed, my results confirm that global socio-economic and environmental trends were filtered through the national and regional spatial and socio-economic context, which impacted local decisions leading to land abandonment and changes in ES. I thus approach the question of policy implications in three steps. First, I summarize generic policy-relevant preconditions needed for the maintenance of a cultural landscapes and ES in European mountain regions. Second, I discuss concrete policy recommendations for Switzerland, and third, I suggest some indicative ideas relevant to the EU policy. In this chapter, I assume that the maintenance of currently provided mountain ES has been set as a key policy goal (reflecting the preferences of stakeholders in our case study region, as well as the coarse line of most of the national and EU policy directives), whereas I elaborate on issues of alternative visions and development options for mountain regions in Section 8.3.2.

The topography, demographic patterns, and socio-economic characteristics vary greatly across mountain ranges of Europe and so did land-use changes in the past decades (see Figure 1.1; Schuler et al., 2004; Hazeu et al., 2010). Although still remarkable, the rates of farm abandonment and loss of ES were lower in our case study and German-speaking Alpine countries, in general, as compared to Italy and countries in the Carpathians and central European mountains. In these regions, political transformations in the 1980s and 1990s caused profound changes in agriculture, improvements in the welfare of societies, growth in the tertiary sector, and rural-to-urban migration that accelerated the observed patterns. I thus believe that the analysis of resilience-building factors in our case study (Section 8.2.5) can be indicative of some generic policy conditions that help retain agrarian cultural landscapes while allowing them to adapt to modern utilization. The following three factors are especially relevant in a policy context: (1) A large governmental budget for agricultural direct payments supports mountain farming in rough conditions and prevents from abandonment of farms. In particular, a subsidy system that is based on decoupled payments lowers the probability of farm disinvestments and encourages farmers to extensify their production rather than exit the sector (Huber et al., 2015). (2) A high density and quality of infrastructure guarantees fast access to urban structures, satisfactory public service provision, and higher education. Short commuting distances enable part-time farm businesses with diverse income sources and livelihood strategies that support diverse regional ES provision. However, the promotion of small-scale agriculture does not automatically guarantee the upkeep of ES. When farmers earn the main part of their income from other sources, they may well remain within the sector but still abandon traditional management practices (Flury et al., 2013). Furthermore, many governmental investments in infrastructure in mountain regions are dedicated to tackling capacity problems related to long-distance through-traffic and may do little to solve local or regional transport bottlenecks (Schuler et al., 2004). (3) Cross-sectoral and cross-level strategies with different operation mechanisms can simultaneously tackle several drivers of ES losses in mountain regions. That is, mountain agriculture must be viewed within the context of a well-designed landscape and regional development plan. In particular, better harmonization among agriculture, nature conservation, and spatial planning might be a promising strategy in European mountain regions. However, although this type of strategy is endorsed by different international initiatives, such as the UN’S Transforming Our World: The 2030 Agenda for Sustainable Development, reforms in global and national institutional settings and political contexts are required to sufficiently support such a cross-sectoral approach (Boas et al., 2016).

While the mountains of European industrialized countries are experiencing a decrease in their agriculturally adapted populations, a quite different situation prevails in the mountain regions of developing countries. Here, overwhelmingly rural and largely subsistence populations are experiencing rapid growth in total numbers. This is forcing the increasingly heavy use of marginal land despite considerable outmigration into urban lowlands. Consequently, policy programs will have different objectives, and the outlined principles cannot be easily transferred to these regions. Grêt-Regamey
et al. (2012) provide an overview on generalized policy strategies to balance ES demand and supply in different types of mountain SESs around the world.

With regard to Switzerland, my analyses allow relatively explicit policy recommendations. Without any reform, the recently enacted federal agricultural policy program (Section 4.3.1) will result in further extensification of grasslands in our mountain case study (indicative for similar mountain regions in Switzerland) and therefore accomplish three of the five formulated goals: conserving biodiversity, improving landscape quality, and developing close-to-nature management systems. However, my results reveal that many summer pastures will continue to become abandoned, resulting in a loss of cultural mountain landscapes. A reallocation of the federal budget (i.e., a doubling of payments for cultural hillside landscapes, summer pastures, and grassland-based milk and meat production at the cost of a reduction of all three subsidy schemes for ensuring food supply; Table 4.2) could counteract this trend in several places and increase overall ES benefits in mountain regions. However, such a policy change is likely to encounter opposition by both farmers and other powerful actors in the region (e.g., the Farmers Association and the political parties of the right wing), who have always been critical of increasing direct payments for cultural services at the cost of payments for food supply (Hirschi et al., 2013). Startup financial aid for young farmers at the regional level to prevent a loss in the number of mountain farms might find more acceptance. This intervention would result in similar ES benefits as a reform of the national payments system, with even higher effects in maintaining the cultural heritage of the region. At the same time, it would not threaten the traditional support for food supply and have less off-site effects in non-mountain agricultural regions. Spatial planners are well advised to strictly implement the new federal law on spatial planning and restrict building zones. My results indicate that the sooner the regional spatial planning strategy pursues densification in existing urban structures rather than settlement expansion, and the stricter the law, the better ES can be maintained.

My analyses furthermore provide spatially explicit information on where investments are of no use in the longer term. In particular, they highlight remote summer pastures that are likely to get abandoned in the longer term, independent of the strength and nature of forthcoming global and regional changes. Thus, policy interventions that support the agricultural sector in these areas are unlikely to counteract the projected changes. These results suggest that uniform direct payments for all pastures independent of their location, as currently paid in Switzerland, might no longer be a useful policy scheme. Instead, a regionalization of payments might ensure a landscape configuration that more optimally sustains desired ES over time. Although targeting policies to high potential areas may increase their effectiveness (Bennett et al., 2015), high transaction costs and information problems may complicate this solution (Nilsson et al., 2008). Optimal policy measures have to strike the right balance between transaction costs and effectiveness to achieve efficiency (Westhoek et al., 2013). In this context, ES contracting systems have been suggested as a highly efficient instrument based on the assumption that land owners will be those best able to judge whether their land is particularly suitable for providing specific ES (or faces the lowest opportunity costs). In such a system, actors can outbid competitors by offering better outputs or lower costs than their rivals, and the government could consequently ensure a certain level of overall ES provision at lowest costs. However, although proposals for this type of policy interventions have been made, no practical examples of such agreements exist (Atkinson et al., 2012).

At the European level, depending on the country, current policies that affect mountain areas may be at the EU or national scale, sectoral or integrated, and specifically focused on mountains or more generally focused on rural areas (Hazeu et al., 2010). The majority of these policy efforts try to find a balance between regional development and preservation of cultural landscape and related ES. My analyses suggest that in designing future policies, it is essential to pursue multisectoral mountain policies with increased emphasis on sectors other than agriculture. The great diversity of national settings will likely imply that such coordinated mountain policies will remain a national responsibility and future EU mountain policy should respect the principle of subsidiarity. Because the variation among Europe’s mountain areas is huge, policies need to be addressed and tailored to the situation in a specific rural context ideally involving all actors shaping mountain areas. For example, van Berkel and Verburg (2011) suggest a different policy focus for various remote areas based on characteristic assets. Central and Eastern European countries are competitive due to their highly productive agricultural conditions and limited restrictions. Incentives for modernization of agricultural production may maintain mountain agriculture and development options in these countries. Tourism development policies and payments for ES provision could be applied to Southern European countries to preserve their natural assets and ensure attractiveness for tourism in these regions. Finally,
conservation may be stimulated in mountain regions where an abundance of species is at risk (e.g., in Italy, France, or Germany). However, although the countries or even regions are good levels of implementation for mountain policies, the EU has to solve the problem of a minimum common approach with regard to mountain issues and the diversity of local contexts (Schuler et al., 2004).

As in Switzerland, agriculture policy is the fundamental mountain policy in Europe, in many countries still the only one, and the Common Agricultural Policy (CAP) provides the framework of action and the most extended set of measures addressed to mountain areas. Funding in CAP has not always succeeded in its objectives in mountain areas. In fact, several national assessments (Italy, French, Spain, Germany) have shown that the CAP is more favorable to lowland than mountain agriculture (Schuler et al., 2004). In the past decades, the EU went through similar comprehensive reforms of the CAP as Switzerland did with regard to its national agricultural policy program (Section 4.3.2). That is, the CAP reforms progressively decoupled subsidies away from agricultural production levels and toward land stewardship incentives. The latest CAP, agreed on in 2013, introduces a better targeted, more flexible, and greener architecture of direct payments that places the provision of ES at the core of the policy. Whereas the subsidies in pillar 1 ("general" and "greening" per hectare payments) are granted uniformly across EU countries, pillar 2 provides a catalogue of measures to help member states set up their regional development programs (EC, 2013). My analyses suggest that these measures should support an agriculture that adapts the supply of ES to the societal demand and harmonizes them in a spatially explicit manner. Here, as in Switzerland, regionalization of agri-environmental schemes could serve as a valuable strategy. However, because pillar 2 is partly co-funded by the EU, such an approach would likely result in budget allocation problems and equity discussions at the EU level. Furthermore, this approach could not resolve the existing struggle between precise and targeted policies and the need to reduce transaction costs, combined with the lack of proper information, as reflected in the current CAP proposals (Westhoek et al., 2013).

8.3.2. Societal relevance

A more implicit, overarching goal of this thesis is to stimulate the societal discourse on future development perspectives of mountain SESSs under global change. Adaptation to global change presents a profound societal challenge because it requires the tackling of short- and long-term threats, changes, and uncertainty that transcend sectors and scales (Colloff et al., 2017). The results of this study indicate that meeting the demand for cultural ES in our mountain case study in the future is becoming increasingly difficult and will be related to high societal costs. Society therefore has to address the questions of whether maintenance of the currently preferred status quo ES provision is efficient, sustainable, and desirable in the longer term and whether it is useful to continue the pathway chosen in the past decades. In our case study and in many rural areas of the Alps, mass tourism started as early as the 1960s, and the leisure industry is now established as a major economic factor. Farm abandonment can only be prevented by high subsidies. Although, as discussed previously, these mountain SESSs based on part-time farming and secondary incomes from tourism are currently rather resilient to ongoing changes, several drawbacks are becoming obvious. In the main valleys and tourist centers on the Alpine fringe, settlement space is getting scarce, building land prices are rising, and settlement coverage is becoming very compact. The skiing-based winter tourism has emerged for large parts of the Alps and resulted in a knock-out competition among tourist destinations (Bender et al., 2011). Only municipalities that invest continuously in their tourism portfolio will be able to achieve growth in the future. Climate change increasingly threatens winter tourism, first in lower-lying areas and, potentially later, in all tourist destinations (Beniston, 2003). About two decades ago, artificial snow was introduced to mitigate the lack of natural snow. Although this might be a successful adaptation strategy to the challenges of climate change, it is also linked to considerable environmental problems because it is related to high consumption of water and energy. It is questionable whether rising costs for winter skiing operations can be set off by even higher prices for the tourism portfolio or whether they will have to be met by the public. These factors demonstrate that the current course of development is related to risks and costs that have to be consciously negotiated by society. From a broader perspective, besides being "tourism traps", mountain areas face three other challenges in the context of globalization: they may be turned into "open museums", recreation areas, or nature preserves for industrialized societies, regarded as regions to be economically exploited, or abandoned altogether (Schuler et al., 2004).

A panacea solution is unlikely to prevent mountains from being trapped in such unsustainable development trajectories. Rather, this thesis suggests that society has to begin to have more diverse visions for the future of mountain regions. As van Berkel and Verburg (2011)
suggested, development of remote and mountain areas might in the future be more adapted to characteristic local assets and require regionalized management and policy strategies. For example, tourism could be further advanced in specific valleys and be maintained with investments in infrastructure but with less emphasis on nature preservation and the diversity of land use and farming systems. Main valleys along major European or national transport corridors, as the valley in which Visp is located, might turn into innovative industrial sites while agriculture further loses in importance. In other regions, traditional farming systems and cultural landscapes, the diversity of livestock production, or even new production forms could be advanced by targeted direct payments, compact village development, and only limited tourism possibilities. Finally, some highly remote areas might be abandoned completely and turn into wild ecosystems supporting wildlife populations, carbon sequestration, and other ES without any investments. Such regionalized development strategies could allow mountain regions to maximize the output of ES and other services they are best suited for and, in the context of an accelerating globalization, potentially contribute to enhance ES benefits at larger scales.

Terms such as sustainability, preserving biodiversity, or safeguarding ES are now in widespread use. This might reflect a heightened awareness of social and political responsibility, but the terms are not very specific and - as can be seen from the work in this thesis - their implementation is not without conflict. Creating a shared vision of a sustainable and desirable society, one that can provide permanent prosperity within the biophysical constraints of the real world in ways that are fair and equitable to humanity, to other species, and to future generations is an enormous challenge (Costanza, 2000; Wiek and Iwaniec, 2014). The task is even more complicated because in SESs not only dynamics within nature change over time, but also our conceptions of what is normal in our local environment, what is important, and what level of change is acceptable (Seppelt and Cumming, 2016). While defining sustainable development of mountain regions will thus need constant and broadly accessible negotiation processes, it is likely that adaptation to ongoing and future global change will entail fundamental shifts in mountain SESs (Folke et al., 2010). Such transitions might entail profound changes in dominant institutions, practices, technologies, policies, lifestyles, and thinking (Chaffin et al., 2016; Colloff et al., 2017). Recent studies claim that sustainable development requires a new way of thinking about the stewardship of resources. Stewardship can no longer be seen as the duty of a handful of ES managers; instead, it requires engaging people to collaborate across all levels and scales with a shared vision, creativity framed by proper institutions, and continuous learning processes that build capacity to live with change, adapt, and transform (Folke et al., 2016).

The goal of this thesis was to engage different stakeholders in thinking about the future of the mountain SES in which they live and initiate a broader discussion on potential development pathways of the mountain case study. I believe that our choice experiment helped raise awareness among the broader public of the valuable services mountain regions provide and of the trade-offs related to their future provision. In addition, our workshops prompted various experts to discuss the environmental and socio-economic challenges related to the development of the case study, as well as potential political or societal solutions, in creative and nonbinding ways that may have triggered knowledge exchange. Thus, the goal of OPERAs to better mainstream ES in society and the public and the goal of MOUNTLAND to foster mutual learning processes between scientists and stakeholders and among stakeholders have both been pursued. Whether these few interactions were enough to build capacity among actors in the region and generate transformation knowledge that enables them better cope with expected future changes remains an open question.

8.3.3. Scientific impact
This thesis is scientifically relevant because it conducted fundamental methodological research with regard to the integration of positive and normative approaches in ES research, spatially and temporally explicit modeling of mountain SESs, uncertainty analyses in combination with scenario approaches, and the operationalization of resilience in a SES context. Furthermore, it generated insights into global and regional change effects and into key sensitivities, ES trade-offs, and resilience-building factors in a mountain case study that can be indicative for similar mountain SESs. Although the pursued transdisciplinary process has faced some drawbacks, it can serve as a valuable example for other studies seeking to collaboratively explore necessary policy and management actions to induce desirable ecological and societal transition processes with regard to an envisioned future. The research conducted in this thesis resulted in the publication of three papers in high-impact journals in the field of land system science and environmental modeling.

In addition, my work contributed to existing major European science networks in environmental/land change and ES. During the past few years, I strongly
engaged in the OPERAs network, presented results in project-internal and international meetings and conferences, and co-authored different reports for the EU (e.g., on enhanced ES tools, mapping of ES or ES demand), as well as additional scientific publications (Brändle et al., 2015; Grêt-Regamey et al., 2016; Huber et al., 2017). Finally, my research can be found on the knowledge marketplace OPPLA, a shared online platform for scientists and practitioners that brings together the latest thinking on ES.

8.4. Outlook on future research and development in the field
The cross-cutting issues discussed in Section 8.3 revealed several caveats associated with the analysis of future ES trade-offs and the modeling of sustainable development pathways of SESs. The most important gaps in the context of this thesis are briefly outlined in the following.

Improved assessments of mismatches between ES supply and demand over space and time are necessary to inform sustainable ES management and policy decisions. This requires advances in spatially explicit quantification methods of both ES demand and supply. Current assessments of ES demand are either spatially explicit, but based on statistical socio-economic data, or stakeholder based, but regionally aggregated (Schägner et al., 2013). The former assessments typically used variables such as population density, income levels, or proximity to sites to account for spatial variations in ES values. The latter elicit preferences for ES among relevant actor groups in questionnaires and interviews (Wolff et al., 2015). A combination of these two approaches could be a promising strategy to construct sophisticated spatially corrected demand functions. For example, regional preferences elicited from stakeholders (as we did in a choice experiment) could be mapped by assuming decreasing values with lower accessibility of sites, longer travel distances, and increased remoteness. Such an approach requires an improved understanding of the processes underlying ES demand and of the spatial variation of different drivers, including demography, poverty, or ownership issues. Even more challenging is the modeling of ES demand over time. As previously stated, our conceptions of what is desirable, tolerable, and important is not inert but changes as our local and global environments change (Serpelt and Cumming, 2016). Studies on human behavior and societal change could contribute to an increased understanding of the interplay between socio-ecological change and demand for ES and improve the embedding of ES demand in modeling (Wolff et al., 2015). In the context of this study, applying discount rates to stakeholder values could be a first step toward a better integration of temporal aspects related to ES demand. However, even among economists, there are lively debates about the proper role of discounting applied to sustainability issues that affect different generations (Bateman et al., 2011; Cavender-Bares et al., 2015).

Current mapping studies of ES supply mostly describe spatial co-occurrence among services or between multiple ES and biodiversity and the processes that drive ES delivery and cause trade-offs or synergies often remain unclear (Kremen, 2005). Understanding whether trade-offs and synergies between ES result from common drivers impacting multiple ES or from true interactions among ES could substantially improve information for ES managers and allow an improved modeling of adaptation and feedback mechanisms (Bennet et al., 2009). Thus, information linking biodiversity and ecosystem function is required and needs to be integrated in models of ES supply. For example, simultaneously quantifying structural and functional components or simultaneously measuring functional trait variation and ecosystem fluxes such as carbon sequestration and nutrient cycling are promising approaches recently applied to unravel these mechanisms (Lavorel and Grigulis, 2012).

As discussed previously, transformation will be increasingly important to effectively manage the impacts of global socio-economic and climatic drivers on SESs. Enabling transformative development pathways requires novel anticipatory and truly transdisciplinary research approaches in which new options are co-created, explored, and experimented with (Colloff et al., 2017). Collaborative user platforms as used in the second workshop are a promising tool for exploring potential development pathways in participatory settings. However, to allow a more open discussion and negotiation on transformative pathways, new functionalities are necessary. Stakeholders need to be able to create their own scenarios and visions rather than being confronted with a fixed set of options prepared by scientists. Such a setup would, on the one hand, account for the fact that preferences can emerge as a result of learning about the system or from group interactions and allow to investigate such collaborative learning processes and the formation of shared values (Irvine et al., 2016). On the other hand, it could provide a virtual laboratory to study the dynamics of SESs and ensure that a wider set of policy options is considered, experimented with, and evaluated. In such a

setting, valuation is not simply considered as a process of preliminary value elicitation but of value formation and expression. Several studies have demonstrated that deliberative valuations enable more effective translation of values into policy and practice and that assessing and cultivating shared values lays the necessary foundation for effective action (Kenter, 2016). In this perspective, users and creators of models interact in a new way of co-designing solutions and co-producing knowledge.

At the same time, novel structures in social-ecological models that underlie such platforms are needed. Existing social-ecological models are not fully able to capture emergent and evolutionary changes of SESs through time and space or to integrate feedbacks, teleconnections, tipping points, thresholds, and regime shifts (Verburg et al., 2015). First, novel models need to better integrate feedbacks between the social and natural systems to generate system instability or critical transitions. However, feedbacks cannot easily be observed or measured, and both adequately incorporating them in the model structure and parametrizing them in the model is extremely difficult (Verburg, 2006; Dellink et al., 2014). The challenge is to identify the feedbacks that are important for the system dynamics and that are able to stabilize the system or move it toward desired outcomes. Such feedbacks might increasingly lie in the social system, and impacts of environmentally friendly behavior and policy and governance systems should be accounted for in models of SESs. As credibility and thus the ability of a model to simulate reality is a crucial feature of models, particularly if used for decision support, there will always remain a trade-off between tractability and incorporating feedbacks that change results in an unobserved way. However, the idea that everything we model needs to be testable has recently been questioned because it might become a barrier to understanding SESs (Verburg et al., 2015). Second, distant and cross-scale dynamics have to be better represented in models. That is, models such as BackES, which represents local SES dynamics in a global context, should not simply assume global conditions as exogenous. Linking models operating at different scales has been suggested as a way forward, but approaches to capture cross-scale dynamics by an explicit representation of scalar dynamics in a single model remain largely understudied. Furthermore, most of the efforts have been focused on better integrating local feedback in global-scale models, but the analysis of how altered global conditions refeed into local systems has not attracted much attention (Ewert et al., 2011; van Wijk, 2014). Third, models have to account for non-linearities in system dynamics and the provision of ES, including the non-linearity of relationships among ecosystem properties, functions, and services and in the perception and valuation of ES. Analysis of existing historic data might be a first step toward better understanding patterns of non-linearity in space and time in SESs. In the simulation of ES supply, the inclusion of landscape metrics in models has recently been suggested as a promising way to help detect ecological thresholds, beyond which certain land-use configurations cease to provide single ES (Grêt-Regamey et al., 2014). Metastudies (see below) of preferences for ES and benefit transfer from similar case studies could then help estimate non-linear utility functions to improve the valuation of services in social-ecological models.

Besides designing novel models, the potential of existing models should be exploited. With regard to my model, new management systems and technologies and shifts in the value systems could be explored by drastically varying elicited preferences and agent behavior beyond the values inferred from interactions with current actors. This might come at the cost of predictive ability over the short time used for model validation, but it could shed more light on the system response to changes that are outside the range of change the model has been calibrated. Algorithms that allow rules to change over time could capture adaptive elements of farmers' behavior and help test the system response to such behavioral changes. Furthermore, more drastic combinations of different socio-economic and biophysical driving variables could be simulated. Metrics to assess system instability and system change over time need to be designed. A first idea might be a regression analysis over different shorter modeling periods that relates a variable of interest to several exploratory variables. If the relationships (i.e., the regression coefficients) change drastically, this might induce a crossing of a threshold into an alternative system state where new dynamics govern the behavior of the SES. To a small extent, such a shift is already observable in my data where trade-off relationships suddenly change in a drastic liberalization setting (Figure 8.2).

As mentioned previously, the generalization and transferability of results from place-based research is limited, particularly in mountains where small-scale socio-economic and biophysical structures have a large influence on system dynamics. At the same time, calls for capturing generalized patterns of land-use change processes and their impacts have become more frequent (Magliocca et al., 2015a). Progress has been made in synthesizing the results of local studies worldwide through meta-analysis that aims to find general patterns across scales and the role of context in specific case study results; however, there remains...
a lot of potential (Magliocca et al., 2015b). Existing metastudies of land-use change focus on deforestation and biogeochemical cycles, whereas metastudies of socio-economic consequences are rare (Van Vliet et al., 2016). Much could be learned through meta-analyses of SESs in general and of mountains specifically. The comparative analyses can advance theories, help explain the complexities of SESs, identify further research needs, promote learning from the past, or inform policy-making on a larger scale (Magliocca et al., 2015a). At the same time, comparative analyses improve our models, either by parametrizing unknown variables or accounting for uncertainty in others. This is especially true when transferability potentials among case studies are taken into account based on an analysis of similarities in a range of environmental and socio-economic indicators (Tomás et al., 2016). To put the results of this study into a broader context, metastudies of the role of farmers in moderating land-use changes in mountain regions, in the importance of different drivers, and in preferences of local people for ES would be especially valuable.
APPENDICES
Phantasie ist wichtiger als Wissen, denn Wissen ist begrenzt.

Albert Einstein
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Appendix A: Exemplary questionnaire

Wie soll die Landschaft in Zukunft aussehen?
Zukünftige Landschaftszustände im Visper- und Saastal

Eine Umfrage durch

Eidg. Forschungsanstalt für Wald, Schnee und Landschaft (WSL)

ETH Zürich
ETH Zürich, Institut für Raum- und Landschaftsentwicklung,
Planning of Landscapes and Urban Systems PLUS

Georg-August-Universität Göttingen,
Abteilung für Umwelt- und Ressourcenökonomik
Was erwarten Sie von der zukünftigen Landschaft im Visper- und Saastal?

Liebe Einwohnerin, lieber Einwohner des Visper- und Saastals

Im Forschungsprojekt «Mountland» untersuchen wir, wie der Klimawandel und die soziale und wirtschaftliche Entwicklung die Landschaft im Visper- und Saastal beeinflussen.

Änderungen in der Landschaft des Visper- und Saastals werden sich unter anderem auf die Landwirtschaft, den Schutz vor Naturgefahren, auf die Vielfalt der Tiere und Pflanzen sowie Freizeit, Erholung und Tourismus auswirken. Wir möchten Ihnen in dieser Befragung verschiedene Möglichkeiten vorstellen, wie sich die hiesige Landschaft entwickeln könnte.

Bei dieser wissenschaftlichen Umfrage gibt es keine richtigen oder falschen Antworten; **es kommt ganz auf Ihre eigene Meinung an.** Eine anonymisierte Auswertung der Antworten von etwa 300 Befragten werden wir an lokale Entscheidungsträger/innen weitergeben und veröffentlichen. Ihre Antworten können so als Grundlage für die zukünftige Gestaltung der Landschaft und regionale Entscheidungen dienen.

Wir würden uns freuen, wenn Sie sich für die Befragung 20 bis 30 Minuten Zeit nehmen. **Die Befragung ist selbstverständlich strikt anonym.**

Die Befragung hat insgesamt **zwei Teile.** Im ersten Teil möchten wir Ihre Meinung zu verschiedenen Themen wie der Landwirtschaft oder dem Schutz vor Naturgefahren erfahren. Im zweiten Teil wählen Sie zwischen verschiedenen Möglichkeiten, wie die Landschaft in Zukunft aussehen könnte.

**Kontakt:**
Susanne Rewitzer, Dr. Jan Barkmann
Georg-August Universität Göttingen, Fakultät für Agrarwissenschaften, Umwelt- und Ressourcenökonomik
Telefon: 076 627 57 70
E-Mail: srewitz@uni-goettingen.de, j barkma@uni-goettingen.de
Teil 1: Einstellungen zu Landschaftselementen des Visper- und Saastals

Im ersten Teil der Umfrage stellen wir Ihnen Fragen zu vier Bereichen, die mit der Landschaft des Visper- und Saastals verbunden sind. Dies sind die Landwirtschaft, der Bereich der Naturgefahren, die Artenschutz auf Wiesen und Weiden sowie das Landschaftsbild.

1. Landwirtschaft

1.1 Wie stark stimmen Sie folgenden Aussagen zu?

<table>
<thead>
<tr>
<th>Aussage</th>
<th>stimme nicht zu</th>
<th>stimme eher nicht zu</th>
<th>mittel</th>
<th>stimme eher zu</th>
<th>stimme zu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die Landwirtschaft im Visper- und Saastal soll erhalten bleiben.</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Die Landwirtschaft ist ein wichtiger Teil der einheimischen Tradition.</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Die Landwirtschaft ist wichtig für die Erhaltung der Kulturlandschaft.</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Im Visper- und Saastal sollen auch zukünftig Nahrungsmittel produziert werden.</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Landwirtschaft gehört zur „Heimat“.</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

1.2 Kaufen Sie Lebensmittel aus der Region?
☐ Ja  ☐ Nein

1.3 Falls ja, welches sind für Sie die wichtigsten Lebensmittel aus der Region? (Mehrfachnennungen möglich)
☐ Fleisch  ☐ Wurst  ☐ Trockenfleisch  ☐ Früchte  ☐ Gemüse
☐ Käse  ☐ Wein  ☐ Brot  ☐ Eier  ☐ Honig
☐ andere Lebensmittel:
1.4 Falls Sie Lebensmittel aus der Region kaufen, geben Sie bitte an, wie stark folgende Aussagen auf Sie zutreffen.

<table>
<thead>
<tr>
<th>Ich kaufe Lebensmittel aus der Region...</th>
<th>trifft nicht zu</th>
<th>trifft eher nicht zu</th>
<th>mittel</th>
<th>trifft eher zu</th>
<th>trifft zu</th>
</tr>
</thead>
<tbody>
<tr>
<td>... wegen des Geschmacks</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>... aufgrund der Qualität der Produkte</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>... aus Heimatverbundenheit</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>... zur Stärkung der lokalen Landwirtschaft</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>... aus ökologischen Gründen</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

Können Sie noch aus anderen Gründen Lebensmittel aus der Region, die oben nicht aufgeführt sind? Falls ja, können Sie hier angeben, welche dies sind:

2. Schutz vor Naturgefahren

Wie stark fühlen Sie sich hier in der Region von Naturgefahren bedroht?

<table>
<thead>
<tr>
<th></th>
<th>gar nicht 1</th>
<th>wenig 2</th>
<th>mittel 3</th>
<th>stark 4</th>
<th>sehr stark 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steinschläge</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Murgänge (Schlammlawinen)</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Rutschungen</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Hochwasser</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Lawinen</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>
3. Artenvielfalt auf Wiesen und Weiden

3.1 Wie wichtig ist Ihnen eine Erhaltung möglichst vieler verschiedener Pflanzen- und Tierarten?
☐ völlig unwichtig  ☐ unwichtig  ☐ mittel  ☐ wichtig  ☐ sehr wichtig

3.2 Besonders viele verschiedene Pflanzen- und Tierarten kommen auf trockenen, nicht gedüngten und selten gemähten bzw. beweideten Wiesen und Weiden vor (Trockenwiesen und –weiden).
Kennen Sie solche Wiesen und Weiden im Visper- und Saastal?
☐ Ja  ☐ Nein

3.3 Wie wichtig ist Ihnen eine Erhaltung möglichst vieler Trockenwiesen und –weiden im Visper- und Saastal?
☐ völlig unwichtig  ☐ unwichtig  ☐ mittel  ☐ wichtig  ☐ sehr wichtig

4. Landschaftsschönheit

4.1 Wie oft halten Sie sich in der Landschaft des Visper- und Saastals (ausserhalb der Orte) auf?
☐ täglich  ☐ 1x wöchentlich  ☐ weniger als 2x im Monat
☐ 2 bis 3x wöchentlich  ☐ 2 bis 3x im Monat  ☐ gar nicht

4.2 Wenn Sie sich im Visper- und Saastal ausserhalb der Orte in der Landschaft aufhalten, wo ist das?
(Mehrfachnennungen möglich)
☐ Im Tal  ☐ An Flüssen  ☐ Bei Wiesen und Weiden
☐ In den Bergen  ☐ Im Wald  ☐ Im Bereich der Alpen
☐ Andere Orte:

4.3 Wie wichtig ist es Ihnen, in einer für Sie schönen Landschaft zu leben?
☐ völlig unwichtig  ☐ unwichtig  ☐ mittel  ☐ wichtig  ☐ sehr wichtig
Teil 2: Wahl zwischen verschiedenen Landschaften

In diesem Teil der Befragung wählen Sie zwischen verschiedenen Möglichkeiten, wie die Landschaft im Visper- und Saastal in den Jahren 2030 bis 2050 aussehen könnte.

Die möglichen Landschaftszustände, zwischen denen Sie wählen können, werden durch 1) die Anzahl der Landwirtschaftsbetriebe, 2) die Häufigkeit von Naturgefahren, 3) die Fläche an Trockenwiesen und -weiden und 4) Veränderungen des Landschaftsbilds beschrieben.

Diese Bereiche könnten sich aufgrund des Klimawandels oder sozialen und wirtschaftlichen Entwicklungen verändern. Für die Auswahl ist es wichtig, dass Sie mit den verschiedenen Bereichen vertraut sind. Wir werden Ihnen deshalb kurz vorstellen, wie sich diese Bereiche entwickeln könnten.

1) Anzahl der Landwirtschaftsbetriebe
Für die Landwirtschaftsbetriebe werden für die Befragung in Zukunft folgende Entwicklungen angenommen:
- 173 Betriebe (Keine Veränderung, entspricht heutiger Situation)
- 10 Betriebe weniger
- 25 Betriebe weniger
- 50 Betriebe weniger

2) Naturgefahren innerhalb von 10 Jahren
Die Anzahl der Ereignisse innerhalb von 10 Jahren könnte sich zukünftig folgendermassen entwickeln:
- 38 Ereignisse innerhalb von 10 Jahren (Keine Veränderung, entspricht heutiger Situation)
- 4 Ereignisse mehr innerhalb von 10 Jahren
- 4 Ereignisse weniger innerhalb von 10 Jahren
- 8 Ereignisse weniger innerhalb von 10 Jahren

3) Fläche an artenreichen Trockenwiesen und -weiden
Besonders wichtig für die Erhaltung der Artenvielfalt sind auch im Visper- und Saastal Trockenwiesen und -weiden. Auf ihnen kommen über 60% der Pflanzenarten in der Schweiz vor. Davon sind über ein Drittel selten oder bedroht und stehen auf der Roten Liste.

Im Visper- und Saastal gibt es 192 ha Trockenwiesen und -weiden von nationaler Bedeutung (1 ha entspricht etwa zwei Fußballfeldern).
Für die Trockenwiesen und –weiden könnten in Zukunft folgende Entwicklungen möglich sein:

- **192 ha** an Trockenwiesen und –weiden (Keine Veränderung, entspricht heutiger Situation)
- **40 ha** weniger
- **40 ha** mehr
- **60 ha** mehr

Beispiele für in der Region auf Trockenwiesen und –weiden vorkommende bedrohte Arten („Rote Liste“):

<table>
<thead>
<tr>
<th>Pflanze</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpur-Witwenblume</td>
</tr>
<tr>
<td>Kron-Lichtnelke</td>
</tr>
<tr>
<td>Rundblättriges Hasenohr</td>
</tr>
</tbody>
</table>

---

4) Schönheit der Landschaft


In den Ihnen gezeigten Ausschnitten spiegelt sich nicht wieder, wie sich die Zahl der Landwirtschaftsbetriebe, der Schutz vor Naturoffens und die Fläche der Trockenwiesen und -weiden verändern. Sie sollen auf ihnen davon unabhängig nur die Schönheit der Landschaft bewerten.

Nachfolgend sehen Sie für einen der Ausschnitte das heutige Landschaftsbild sowie ein Beispiel für eine mögliche Veränderung. In dem Beispiel für die zukünftige Entwicklung können Sie sehen, dass Wiesen und Weiden anders bewirtschaftet werden und die Bewaldung zunimmt.

**Heutiges Landschaftsbild**

**Mögliches Landschaftsbild in der Zukunft**

Für die Befragung werden in diesem Zusammenhang folgende zukünftige Veränderungen Ihrer jährlichen Steuerrechnung angenommen:
- Ihre jährliche Steuerrechnung sinkt um 6%.
- Ihre jährliche Steuerrechnung sinkt um 3%.
- Keine Veränderung Ihrer jährlichen Steuerrechnung
- Ihre jährliche Steuerrechnung erhöht sich um 3%.
- Ihre jährliche Steuerrechnung erhöht sich um 6%.

Um die Auswahl möglichst realistisch zu gestalten, bitten wir Sie, die folgende Tabelle mit Ihren persönlichen Angaben zu ergänzen. Aus der Tabelle können Sie außerdem ablesen, um welchen Betrag sich Ihre jährliche Steuerrechnung verändern könnte.

Als Hilfe bei der Beantwortung des folgenden Teils des Fragebogens können Sie die die Zeile markieren, die Ihrer letzten Steuerrechnung entspricht, und die für Sie zutreffenden Beträge ablesen.

Wenn Sie verheiratet sind und als Ehepaar eine gemeinsame Steuerrechnung erhalten, teilen Sie diesen Betrag bitte durch zwei.

Beispiel: Sie sind verheiratet und Ihre letzte gemeinsame Steuerrechnung betrug etwa 10’000 Franken. Sie teilen diesen Betrag durch zwei und erhalten 5000 Franken. Ihre Beiträge finden Sie also in Zeile 4.

**Wieviel Steuern haben Sie das letzte Mal bezahlt? Bitte kreuzen Sie die für Sie zutreffende Zeile an.**

<table>
<thead>
<tr>
<th>Ihre letzte jährliche Steuerrechnung in CHF entspreicht</th>
<th>3% entsprechen in CHF</th>
<th>6% entsprechen in CHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 □ weniger als 2000 CHF</td>
<td>weniger als 60</td>
<td>weniger als 120</td>
</tr>
<tr>
<td>2 □ 2000 bis 2999 CHF</td>
<td>60 - 89</td>
<td>120 - 179</td>
</tr>
<tr>
<td>3 □ 3000 bis 4499 CHF</td>
<td>90 - 134</td>
<td>180 - 269</td>
</tr>
<tr>
<td>4 □ 4500 bis 5999 CHF</td>
<td>135 - 179</td>
<td>270 - 359</td>
</tr>
<tr>
<td>5 □ 6000 bis 7999 CHF</td>
<td>180 - 239</td>
<td>360 - 479</td>
</tr>
<tr>
<td>6 □ 8000 bis 12’000 CHF</td>
<td>240 – 360</td>
<td>480 – 720</td>
</tr>
<tr>
<td>7 □ mehr als 12’000 CHF</td>
<td>mehr als 360</td>
<td>mehr als 720</td>
</tr>
</tbody>
</table>

- Vergleichen Sie die Zustände, wählen Sie denjenigen aus, der Ihnen am ehesten zusagt.
- Kreuzen Sie das dazugehörige Feld auf der rechten Seite an. Es ist wichtig, dass Sie pro Seite nur ein Kreuz machen.
- Insgesamt möchten wir Sie bitten, sechs Mal eine Auswahl zu treffen. Entscheiden Sie jedes Mal so, als ob es die einzige Entscheidung wäre, die Sie treffen müssten.

Machen Sie sich bitte bei der Auswahl der Zustände klar, dass Sie über die Steuerrechnung in den kommenden Jahren jeweils den entsprechenden Prozentsatz weniger oder mehr Geld zur Verfügung haben. Bei der heutigen Situation bleibt die Steuerrechnung gleich und ist daher immer +/- 0%.
### Auswahl 1

Bitte wählen Sie den Zustand aus, der Ihnen am ehesten zusagt. Wägen Sie dabei die 5 Bereiche gegeneinander ab. Die einzelnen Bereiche sind unabhängig voneinander zu betrachten. Bitte beurteilen Sie das Bild nur nach der Schönheit der Landschaft.

| Landschaft heute | \[\begin{array}{l}
\text{Landwirtschaftsbetriebe} \\
\quad \text{173 Betriebe}
\end{array}\] | \[\begin{array}{l}
\text{Naturgefahren} \\
\quad \text{38 Ereignisse innerhalb von 10 Jahren}
\end{array}\] |
|------------------|--------------------------------------------------|--------------------------------------------------|
| \[\begin{array}{l}
\text{Artenreiche Trockenwiesen und Weiden} \\
\quad \text{192 ha}
\end{array}\] | \[\begin{array}{l}
\text{Steuerrechnung} \\
\quad \text{Ihre *derzeitige* Steuerrechnung}
\end{array}\] |

---

### Zustand A

| Landwirtschaftsbetriebe | \[\begin{array}{l}
\quad \text{25 Betriebe weniger}
\end{array}\] | \[\begin{array}{l}
\text{Naturgefahren} \\
\quad \text{4 Ereignisse mehr}
\end{array}\] |
|--------------------------|----------------------------------|----------------------------------|
| \[\begin{array}{l}
\text{Artenreiche Trockenwiesen und Weiden} \\
\quad \text{40 ha weniger}
\end{array}\] | \[\begin{array}{l}
\text{Keine Veränderung}
\end{array}\] |

---

### Zustand B

| Landwirtschaftsbetriebe | \[\begin{array}{l}
\quad \text{25 Betriebe weniger}
\end{array}\] | \[\begin{array}{l}
\text{Naturgefahren} \\
\quad \text{4 Ereignisse mehr}
\end{array}\] |
|--------------------------|----------------------------------|----------------------------------|
| \[\begin{array}{l}
\text{Artenreiche Trockenwiesen und Weiden} \\
\quad \text{Keine Veränderung}
\end{array}\] | \[\begin{array}{l}
\text{6% Steuern mehr}
\end{array}\] |
### Auswahl 2

Bitte wählen Sie den Zustand aus, der Ihnen am ehesten zusagt. Wägen Sie dabei die 5 Bereiche gegeneinander ab. Die einzelnen Bereiche sind unabhängig voneinander zu betrachten. Bitte beurteilen Sie das Bild nur nach der Schönheit der Landschaft.

#### Landschaft heute

<table>
<thead>
<tr>
<th>Landwirtschaftsbetriebe</th>
<th>Naturgefahren</th>
</tr>
</thead>
<tbody>
<tr>
<td>173 Betriebe</td>
<td>38 Ereignisse innerhalb von 10 Jahren</td>
</tr>
<tr>
<td>Artenreiche Trockenwiesen und -weiden</td>
<td>Steuerrechnung</td>
</tr>
<tr>
<td>192 ha</td>
<td>Ihre derzeitige Steuerrechnung</td>
</tr>
</tbody>
</table>

![Landschaft heute](image)

#### Zustand A

<table>
<thead>
<tr>
<th>Landwirtschaftsbetriebe</th>
<th>Naturgefahren</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 Betriebe weniger</td>
<td>4 Ereignisse weniger</td>
</tr>
<tr>
<td>Artenreiche Trockenwiesen und -weiden</td>
<td>Steuerrechnung</td>
</tr>
<tr>
<td>40 ha weniger</td>
<td>3% Steuern weniger</td>
</tr>
</tbody>
</table>

![Zustand A](image)

#### Zustand B

<table>
<thead>
<tr>
<th>Landwirtschaftsbetriebe</th>
<th>Naturgefahren</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keine Veränderung</td>
<td>Keine Veränderung</td>
</tr>
<tr>
<td>Artenreiche Trockenwiesen und -weiden</td>
<td>Steuerrechnung</td>
</tr>
<tr>
<td>40 ha mehr</td>
<td>6% Steuern weniger</td>
</tr>
</tbody>
</table>

![Zustand B](image)
Auswahl 3

Bitte wählen Sie den Zustand aus, der Ihnen am ehesten zusagt. Wägen Sie dabei die 5 Bereiche gegeneinander ab. Die einzelnen Bereiche sind unabhängig voneinander zu betrachten. Bitte beurteilen Sie das Bild nur nach der Schönheit der Landschaft.

### Landschaft heute
- **Landwirtschaftsbetriebe**: 173 Betriebe
- **Naturgefahren**: 38 Ereignisse innerhalb von 10 Jahren
- **Artenreiche Trockenwiesen und -weiden**: 192 ha
- **Steuerrechnung**: Ihre derzeitige Steuerrechnung

### Zustand A
- **Landwirtschaftsbetriebe**: 10 Betriebe weniger
- **Naturgefahren**: 8 Ereignisse weniger
- **Artenreiche Trockenwiesen und -weiden**: 60 ha mehr
- **Steuerrechnung**: 6% Steuern weniger

### Zustand B
- **Landwirtschaftsbetriebe**: 50 Betriebe weniger
- **Naturgefahren**: Keine Veränderung
- **Artenreiche Trockenwiesen und -weiden**: 40 ha weniger
- **Steuerrechnung**: 6% Steuern mehr
Auswahl 4

Bitte wählen Sie den Zustand aus, der Ihnen am ehesten zusagt. Wägen Sie dabei die 5 Bereiche gegeneinander ab. Die einzelnen Bereiche sind unabhängig voneinander zu betrachten. Bitte beurteilen Sie das Bild nur nach der Schönheit der Landschaft.

<table>
<thead>
<tr>
<th>Landschaft heute</th>
<th>Ich wähle Landschaft</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Landschaft heute</strong></td>
<td><strong>Ich wähle Landschaft</strong></td>
</tr>
<tr>
<td>Landwirtschaftsbetriebe</td>
<td>173 Betriebe</td>
</tr>
<tr>
<td>Artenreiche Trockenwiesen und -weiden</td>
<td>192 ha</td>
</tr>
<tr>
<td><strong>Schönheit der Landschaft</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zustand A</th>
<th>Ich wähle Landschaft</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Zustand A</strong></td>
<td><strong>Ich wähle Landschaft</strong></td>
</tr>
<tr>
<td>Landwirtschaftsbetriebe</td>
<td>25 Betriebe weniger</td>
</tr>
<tr>
<td>Artenreiche Trockenwiesen und -weiden</td>
<td>60 ha mehr</td>
</tr>
<tr>
<td><strong>Schönheit der Landschaft</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zustand B</th>
<th>Ich Wähle Landschaft</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Zustand B</strong></td>
<td><strong>Ich Wähle Landschaft</strong></td>
</tr>
<tr>
<td>Landwirtschaftsbetriebe</td>
<td>50 Betriebe weniger</td>
</tr>
<tr>
<td>Artenreiche Trockenwiesen und -weiden</td>
<td>40 ha mehr</td>
</tr>
<tr>
<td><strong>Schönheit der Landschaft</strong></td>
<td></td>
</tr>
</tbody>
</table>
Auswahl 5

Bitte wählen Sie den Zustand aus, der Ihnen am ehesten zusagt. Wägen Sie dabei die 5 Bereiche gegeneinander ab. Die einzelnen Bereiche sind unabhängig voneinander zu betrachten. Bitte beurteilen Sie das Bild nur nach der Schönheit der Landschaft.

**Landschaft heute**

<table>
<thead>
<tr>
<th>Landwirtschaftsbetriebe</th>
<th>Naturgefahren</th>
</tr>
</thead>
<tbody>
<tr>
<td>173 Betriebe</td>
<td>38 Ereignisse innerhalb von 10 Jahren</td>
</tr>
<tr>
<td>Artenreiche Trockenwiesen und -weiden</td>
<td>Steuerrechnung</td>
</tr>
<tr>
<td>192 ha</td>
<td>Ihre derzeitige Steuerrechnung</td>
</tr>
</tbody>
</table>

**Zustand A**

<table>
<thead>
<tr>
<th>Landwirtschaftsbetriebe</th>
<th>Naturgefahren</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 Betriebe weniger</td>
<td>8 Ereignisse weniger</td>
</tr>
<tr>
<td>Artenreiche Trockenwiesen und -weiden</td>
<td>Steuerrechnung</td>
</tr>
<tr>
<td>Keine Veränderung</td>
<td>3% Steuern mehr</td>
</tr>
</tbody>
</table>

**Zustand B**

<table>
<thead>
<tr>
<th>Landwirtschaftsbetriebe</th>
<th>Naturgefahren</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keine Veränderung</td>
<td>8 Ereignisse weniger</td>
</tr>
<tr>
<td>Artenreiche Trockenwiesen und -weiden</td>
<td>Steuerrechnung</td>
</tr>
<tr>
<td>Keine Veränderung</td>
<td>3% Steuern weniger</td>
</tr>
</tbody>
</table>
### Auswahl 6

Bitte wählen Sie den Zustand aus, der Ihnen am ehesten zusagt. Wägen Sie dabei die 5 Bereiche gegeneinander ab. Die einzelnen Bereiche sind unabhängig voneinander zu betrachten. Bitte beurteilen Sie das Bild nur nach der Schönheit der Landschaft.

<table>
<thead>
<tr>
<th>Landschaft heute</th>
<th>Ich wähle Landschaft</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Landwirtschaftsbetriebe</strong></td>
<td><strong>Naturgefahren</strong></td>
</tr>
<tr>
<td>173 Betriebe</td>
<td>38 Ereignisse innerhalb von 10 Jahren</td>
</tr>
<tr>
<td><strong>Artenreiche Trockenwiesen und -weiden</strong></td>
<td><strong>Steuerrechnung</strong></td>
</tr>
<tr>
<td>192 ha</td>
<td>Ihre <em>derzeitige</em> Steuerrechnung</td>
</tr>
</tbody>
</table>

**Schönheit der Landschaft**

<table>
<thead>
<tr>
<th>Zustand A</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Landwirtschaftsbetriebe</strong></td>
<td><strong>Naturgefahren</strong></td>
</tr>
<tr>
<td>50 Betriebe <em>weniger</em></td>
<td>Keine Veränderung</td>
</tr>
<tr>
<td><strong>Artenreiche Trockenwiesen und -weiden</strong></td>
<td><strong>Steuerrechnung</strong></td>
</tr>
<tr>
<td>40 ha <em>mehr</em></td>
<td>Keine Veränderung</td>
</tr>
</tbody>
</table>

**Schönheit der Landschaft**

<table>
<thead>
<tr>
<th>Zustand B</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Landwirtschaftsbetriebe</strong></td>
<td><strong>Naturgefahren</strong></td>
</tr>
<tr>
<td><em>Keine Veränderung</em></td>
<td>4 Ereignisse <em>mehr</em></td>
</tr>
<tr>
<td><strong>Artenreiche Trockenwiesen und -weiden</strong></td>
<td><strong>Steuerrechnung</strong></td>
</tr>
<tr>
<td>40 ha <em>weniger</em></td>
<td><em>Keine Veränderung</em></td>
</tr>
</tbody>
</table>

**Schönheit der Landschaft**

---

153
Statistische Angaben

1. Sie sind: ☐ männlich ☐ weiblich

2. In welchem Jahr wurden Sie geboren? 19 _____

3. Welches ist Ihr höchster Abschluss?
☐ Obligatorische Grundschule
☐ Berufsvorlehr/berufsschule/Handelsschule
☐ Gymnasium/Berufsmatura/Diplommittelschule/Lehrerseminar
☐ Fachausweis/Fachdiplom/Meisterprüfung
☐ Universität/ETH/Fachhochschule


5. Zum Schluss bitten wir Sie um eine kurze Rückmeldung zum Fragebogen. Bitte kreuzen Sie an, wie stark die folgenden Aussagen auf Sie persönlich zutreffen.

<table>
<thead>
<tr>
<th>Die mögliche Entwicklung der Landschaft war gut beschrieben.</th>
<th>trifft nicht zu</th>
<th>trifft eher nicht zu</th>
<th>mittel</th>
<th>trifft eher zu</th>
<th>trifft zu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die Auswahl zwischen den verschiedenen Zuständen war schwierig.</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Die Bilder geben ein typisches Bild der Region wieder.</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Die Landschaftselemente in den Bildern entsprechen denjenigen im Visper- und Saastal.</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Die Unterschiede zwischen den Bildern waren gut zu erkennen.</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>


Herzlichen Dank für Ihre Teilnahme an der Umfrage!
Appendix B: Validation of ALUAM-AB

Table B.1. Error decomposition in the single best-performing output of ALUAM-AB. Root Mean Square Percentage Error (RMSPE) expressed as the proportion of the observed mean gives an estimate of the overall prediction error. This error can be decomposed into three components: the bias ($U^b$) arises from systematic under- or overestimation of the average change, the unequal variation ($U^s$) implies that the model and the observed data have different trends, the unequal covariation ($U^c$) indicates that the model and data are imperfectly correlated, that is, they differ point by point, but may have the same mean and trend.

<table>
<thead>
<tr>
<th>Output variable</th>
<th>Unit</th>
<th>RMSPE %</th>
<th>Bias ($U^b$)</th>
<th>Unequal variation ($U^s$)</th>
<th>Unequal covariation ($U^c$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animals</td>
<td>Livestock units</td>
<td>0.035</td>
<td>0.808</td>
<td>0.042</td>
<td>0.150</td>
</tr>
<tr>
<td>Sheep</td>
<td>Nr.</td>
<td>0.015</td>
<td>0.003</td>
<td>0.000</td>
<td>0.997</td>
</tr>
<tr>
<td>Cattle</td>
<td>Nr.</td>
<td>0.082</td>
<td>0.821</td>
<td>0.059</td>
<td>0.120</td>
</tr>
<tr>
<td>Intensive grassland</td>
<td>ha</td>
<td>0.057</td>
<td>0.810</td>
<td>0.002</td>
<td>0.188</td>
</tr>
<tr>
<td>Extensive grassland</td>
<td>ha</td>
<td>0.109</td>
<td>0.092</td>
<td>0.000</td>
<td>0.908</td>
</tr>
</tbody>
</table>

Table B.1 shows the results from the error decomposition to assess the single best output performance of ALUAM-AB with respect to the total number of animals measured in livestock units (LU), the number of sheep and cattle and the aggregated areas of intensive and extensive grassland. The overall errors of the model performance and the unequal variation error are small, thus, the model captures the mean and trends of the observed data satisfactorily. The mean percentage error of the simulation with respect to the output variables ranges between 1.5% for the number of sheep and 10.9% for the total amount of extensive grasslands.

The error in the modelled sheep production can be attributed to an unequal covariation, i.e., the simulation shows small lags in the reproduction of the observed data.
data (see also Figure B.1a). In contrast, the mean errors in the total number of livestock (3.5%), cattle (8.5%) and intensive grassland (5.7%) are associated with bias. The simulation results for the amount of cattle and intensive grassland are consistently lower than the actual number of dairy cows, sucklers and beef cattle (Figure B.1b) and the total amount of intensive grassland in the case study region (Figure B.1c), that is, there is a systematic error between simulation results and observed data. This bias is associated with the aggregation of agents’ resources, such as livestock housing capacities and workload, as well as fixed assumptions concerning technical parameters, such as nutrient requirements or mechanization. These assumptions are inevitable and could only be replaced by a data-intensive expansion of model parameters to smooth the linear production functions in the model, i.e., by adding more production activities and sub-types of these activities. The unequal variation error for these output categories, however, is small and thus no deviation from the trend could be detected.

The largest gap between model and observed data is found for the aggregated area of extensive grassland (Figure B.1d). The error can be attributed to the unequal covariation between simulation results and observed data indicating that the error is unsystematic. The model may not be able to fully capture the changes in the amount of extensive land use. In general, however, there is no systematic deviation from the trend.
Appendix C: ODD protocol for ALUAM-AB

Purpose
The purpose of ALUAM-AB is to simulate future changes in land use, including changes in grassland management intensity, settlement growth, farmland abandonment and resulting re-forestation in mountain landscapes, triggered by the combined effects of climate, market and policy changes while considering the individual preferences of farmers, and to estimate corresponding changes in ES supply. Thus, the impact of global climatic and socio-economic changes as well as of regional and national land-use policy strategies on mountain SES can be analyzed. Spatially explicit climate change impacts on grassland and forestry can be included via the linkage with the forest landscape model LandClim (or in earlier versions of ALUAM-AB via a crop yield model), while the effect of population growth and migration on land use and ES can be explored through a settlement module.

State variables and scale
Agents represent groups of farms. A farm agent has (1) its own state (i.e., land endowment, stable capacity, etc.) which is updated after each yearly simulation period and (2) its own decision-making mechanism for managing farm resources (in form of constraints to the optimization). The objective function and the set of constraints which define the solution space can formally be written as:

\[ Z = \sum_j (p_j - c_j) \cdot x_j \]  
\[ \sum_i a_{ij} \cdot x_j \leq b_{ij} \quad \forall i = 1 \ldots I \]  
\[ x_j \geq 0 \quad \forall j = 1 \ldots J \]

where \( Z \) is the income per farmer, \( x_j \) the agricultural farm activity \((j=1 \text{ to } I)\), \( p_j \) the returns of an activity \( j \), \( c_j \) the costs per activity \( j \), \( a_{ij} \) the technical coefficients required to produce \( x_j \) (of constraint \( i \) and activity \( j \)) and \( b_{ij} \) the available resources.

Information on farmer agents was derived from interviews with 15 local farmers and a farm survey \((n=111)\) combined with an analysis of agricultural census data (details are given in Brändle et al., 2015). Important parameters regarding individual characteristics of the agents are: the point of time of their retirement (65 years), the opportunity costs of labor, available family labor, additional workforce hired, a threshold for minimum income, farm size, the intention to increase farm size and livestock housing capacity (Table C.1). Given the high uncertainty related to changes in decision-making mechanisms of farmers in the process of succession, the temporal scale of the model is limited to approximately 25 years in our approach.

The smallest landscape unit in ALUAM-AB is an area of 100m x 100m. Spatially explicit parameters include natural conditions of the different land units, e.g., slope, altitude or soil suitability, as well as the distances to settlement, roads and the next farm. Agronomic parameters include yield losses, plant nutrient requirements \((N, P)\), manure production and production coefficients such as fodder intake, growth, birth, deaths of animals, labor requirements, etc., that are based on Swiss average data. Scenario parameters for prices and costs were derived from project-based context scenarios. These are consistent with the base assumptions of the existing set of global greenhouse gas emission scenarios (IPCC SRES) (Walz et al., 2014). The developments of the effective parameters were derived from previous predictions of socio-economic development in the case study region and in Europe (Abildtrup et al., 2006; Briner et al., 2012; Huber et al., 2014).

Process overview and scheduling
ALUAM-AB proceeds in annual time steps. The agents allocate their available resources to maximize their income (aggregated land rent). Thereby they consider natural, farm level and individual constraints as well as incentives and regulations from the market and policy instruments. Investments in production capacity made in previous years are considered as sunk costs representing path dependencies of the individual farm groups.

Structural change is modeled using a land market module (Lauber, 2006; Huber et al., 2013a). The module identifies land units that are no longer cultivated under the existing farm structure. There are three reasons why fields are attributed to the land market in the model: (1) units generate a land rent below zero, (2) the corresponding agent does not reach the minimum wage level, therefore the farm is abandoned and all its assigned land enters the land market or (3) the farmer retires in the simulation year and has no successor (Figure C.1). The land market module randomly assigns the land units to one of the other agents and then checks whether the agent shows the two following characteristics: The agent wants to expand his cultivated area (stated willingness to grow) and his shadow price for the land unit is positive. If these conditions are not met, the land unit is returned.
Appendices

Table C.1. Parametrization of agent characteristics in ALLUAM-AB. Agents are grouped according to different farm types: (1) production-oriented farmers, (2) ecological and landscape stewards, (3) part-time or leisure-oriented breeders, (4) traditionalist leisure farmers, (5) leisure-oriented farmers.

<table>
<thead>
<tr>
<th>Agent name</th>
<th>Farm type</th>
<th>Opportunity costs</th>
<th>Available work</th>
<th>Min. income</th>
<th>Number of farms</th>
<th>Average farm size</th>
<th>Slope &gt; 18°</th>
<th>Land per agent</th>
<th>Farm growth</th>
<th>Succession rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of x CHF</td>
<td>% of 2800h</td>
<td>CHF</td>
<td>ha</td>
<td>ha</td>
<td>ha</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MILAS 1</td>
<td>0.2</td>
<td>1</td>
<td>25000</td>
<td>7</td>
<td>42.1</td>
<td>5.4</td>
<td>295</td>
<td>Yes</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>MASA 1</td>
<td>0.2</td>
<td>0.6</td>
<td>25000</td>
<td>11</td>
<td>11.7</td>
<td>4.8</td>
<td>129</td>
<td>Yes</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>MUK 1</td>
<td>0.5</td>
<td>0.6</td>
<td>25000</td>
<td>3</td>
<td>24.9</td>
<td>12.5</td>
<td>75</td>
<td>Yes</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>MIAA 2</td>
<td>0.2</td>
<td>0.5</td>
<td>10000</td>
<td>44</td>
<td>5.2</td>
<td>2.8</td>
<td>227</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MILA 2</td>
<td>0.2</td>
<td>0.5</td>
<td>10000</td>
<td>10</td>
<td>13.1</td>
<td>6.1</td>
<td>131</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIAS 2</td>
<td>0.2</td>
<td>0.8</td>
<td>10000</td>
<td>14</td>
<td>6.8</td>
<td>2.7</td>
<td>95</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCH 2</td>
<td>0.2</td>
<td>0.5</td>
<td>100000</td>
<td>23</td>
<td>7.1</td>
<td>4.0</td>
<td>164</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIAAS 2</td>
<td>0.2</td>
<td>0.8</td>
<td>10000</td>
<td>6</td>
<td>15.6</td>
<td>8.3</td>
<td>93</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AUR 3</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>19</td>
<td>2.8</td>
<td>1.3</td>
<td>52</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEG 3</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>18</td>
<td>6.6</td>
<td>2.5</td>
<td>119</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MISCH 3</td>
<td>1.25</td>
<td>0.3</td>
<td>0</td>
<td>26</td>
<td>6.4</td>
<td>3.0</td>
<td>165</td>
<td>Yes</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>MILS 4</td>
<td>0.5</td>
<td>0.5</td>
<td>10000</td>
<td>4</td>
<td>26.1</td>
<td>11.0</td>
<td>104</td>
<td>Yes</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>AK 4</td>
<td>1</td>
<td>0.5</td>
<td>10000</td>
<td>26</td>
<td>6.5</td>
<td>1.8</td>
<td>170</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIL 5</td>
<td>0.2</td>
<td>0.3</td>
<td>0</td>
<td>40</td>
<td>4.0</td>
<td>2.4</td>
<td>162</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1981</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Agent name</th>
<th>Sheep</th>
<th>Dairy cows</th>
<th>Beef cattle</th>
<th>Suckler cows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number in the year 2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MILAS</td>
<td>237</td>
<td>215</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MASA</td>
<td>376</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUK</td>
<td>86</td>
<td>43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIAA</td>
<td>156</td>
<td>123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MILA</td>
<td>93</td>
<td>93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIAS</td>
<td>44</td>
<td>41</td>
<td>208</td>
<td></td>
</tr>
<tr>
<td>SCH</td>
<td>870</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIAAS</td>
<td>26</td>
<td>27</td>
<td>146</td>
<td></td>
</tr>
<tr>
<td>AUR</td>
<td>208</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEG</td>
<td>222</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MISCH</td>
<td>558</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MILS</td>
<td>38</td>
<td>27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AK</td>
<td>932</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3236</td>
<td>592</td>
<td>898</td>
<td>43</td>
</tr>
</tbody>
</table>

to the land market and assigned randomly to another farmer agent. Once again, the model checks whether the agent fulfills the conditions for the assignment of land. This procedure is repeated until all land units are assigned to a farm or none of the farms is willing to take the land units left on the market. Land units that are not transferred to other farms are defined as abandoned and natural vegetation dynamics get under way on these units (modeled in LandClim). If land-use allocation is optimal, farm capacities and livestock are updated and the next annual time step is initialized using the scenario parameters (prices, costs, direct payments,...) of the following year.

**Design concepts**

**Emergence:** Changes in farm activities emerge from an endogenous development determined by prices, policies, and decision-making type, which are given exogenously. In addition, land-use patterns (intensity levels of land use) emerge from structural changes on agent level and spatially explicit climate-induced changes of yield quantities.
Adaptation: Agents respond to climatic, socio-economic and policy changes by adjusting their production activities, applying new production technologies (e.g. irrigation), increasing (or reducing) land size and adjusting land-use intensities. In addition, agents exit the sector if their income falls below a minimum threshold.

Prediction: The agents’ objectives are characterized by an overall farm income optimization approach which governs the allocation of an agent’s available resources to production considering natural, farm-level and individual constraints as well as incentives and regulations from the market and policy scenarios. Thus, the fundamental concept underlying the approach is rational economic behavior (land rent maximization) and no learning patterns exist. However, the consideration of individual constraints, such as opportunity costs, minimum income wage and limited time resources, includes non-economic goals in the decision-making process.

Interaction: The interaction between agents is based on the land market described in the process overview. Interaction between agents and the environment is based on the model linkage of LandClim and ALUAM-AB. Detailed information on spatially explicit natural conditions (e.g. grassland and forest yields) under different climatic scenarios is provided by the LandClim model. The corresponding maps are used as an input for ALUAM-AB (Figure C.1).

Initialization
Initial attributes for households were defined using information from the survey, interviews and farm census data (see above). Based on the distribution of the farm characteristics in the census data, we assigned the observed age structure in the case study region to each agent type. This age structure is updated after every simulation period. The initial allocation of land units to agents is based on a random assignment of parcels in which the share of parcels according to the slope corresponds to the real world distribution (Filatova et al., 2013): The accumulative share of land cultivated by different agent types was determined for three slope strata (<18°, 18°-35°, >35°) based on the census data. Within these strata, the land units were then allocated to the agents according to their relative land tenure with the help of a random number. Sensitivity tests with repeated random assignments showed marginal impact of the initial land distribution to agents on simulation outcomes. Model versions initialized with an allocation based on alternative or multiple stratification criteria (e.g., agricultural zone, municipality, elevation) performed badly compared to the observed data.

Input
Information with respect to spatially explicit natural conditions are based on national data sets or are simulated by the LandClim model (in earlier model versions by a crop yield model, as described below). In addition, the settlement module spatially defines land units that are no longer available for agriculture and thus do not enter the optimization process. Developments of socio-economic parameters, e.g. of prices or costs, were derived from scenarios for the European agricultural sector (Abildtrup et al., 2006) and previous projections in the case study region (Briner et al., 2012; Huber et al.,
biomass growth was limited by monthly temperature then simulated in monthly time steps and monthly non-woody meadow plants. Herbaceous growth was cell had one generic herbaceous cohort representing all and a new meadow management module. Each grid meadows using a modified herbaceous growth formula used reducing factors as for trees. For Paper II (Section 6), we is simulated annually and is limited by the same growth shade tolerance and drought tolerance. Biomass growth is represented by multiple herbaceous functional groups distinguished by different parameter values for overstory (Thrippleton et al., 2016). Understory vegetation is characterized by the mean biomass of an individual tree and the number of trees in the cohort.

At run time of this PhD project, LandClim was further developed to include herbaceous vegetation for examining competition between the understory and overstory (Thrippleton et al., 2016). Understory vegetation is represented by multiple herbaceous functional groups distinguished by different parameter values for maximum biomass growth, maximum biomass size, shade tolerance and drought tolerance. Biomass growth is simulated annually and is limited by the same growth reducing factors as for trees. For Paper II (Section 6), we used LandClim to simulate spatially explicit yields on meadows using a modified herbaceous growth formula and a new meadow management module. Each grid cell had one generic herbaceous cohort representing all non-woody meadow plants. Herbaceous growth was then simulated in monthly time steps and monthly biomass growth was limited by monthly temperature and precipitation. Light limitation is not an issue for meadows since frequent cutting prevents from tree growth. Meadows that are harvested more than once in a season typically yield less biomass in each subsequent cut. This was simulated by reducing the spatially explicit maximum grass biomass by a user-defined parameter for each cut after the first one. For each land unit, yields of three meadow management regimes were transferred to ALUAM-AB: intensive, mid-intensive and extensive. Intensive meadows were assumed to be harvested three times a year and to be heavily fertilized. Mid-intensive meadows were assumed to be harvested twice a year and to receive only a small amount of fertilizer, while extensive meadows were harvested only once at the end of the season and were unfertilized.

Crop yield model: For Paper I (Section 5) and Paper III (Section 7), future yields of relevant crops and grassland were calculated using FAO (Food and Agriculture Organization of the UN) data on optimal and absolute crop growing conditions (Briner et al., 2012). The minimum and maximum temperature and precipitation values that support optimal crop growth and threshold values that define crops’ temperature and precipitation extremes, were extracted from the FAO crop data base EcoCrop (FAO, online http://ecocrop.fao.org). These four values formed the basis for a relative crop yield curve dependent on temperature and precipitation values using an incomplete beta distribution. The species-specific crop yield curves were then used to calculate the yield of six crop and meadow types based on monthly precipitation and temperature values for each land unit in the case study region (Briner et al., 2012).

Settlement module: The settlement module includes a selection algorithm that defines the most suitable parcels for settlement development to account for changes in the settlement area (for details see Appendix 5C). Prior to the optimization process each parcel is characterized by five location factors: elevation, slope, distance to road, distance to centers and view on mountains (Swisstopo, 2004, 2005). A suitability score for settlement development is then assessed for each parcel based on normalized scores for each location factor, an equal weighing of all factors and a neighborhood effect (Garcia et al., 2009; Abdullah, 2014). If population development, as defined in the socio-economic scenarios, demands additional settlement parcels, the land units with the highest suitability score are assigned to the settlement area in each simulation year.
### Appendix D: Relevant stakeholders and sectors in the case study region

**Table D.1. Importance and interests of different stakeholders and sectors in the case study region (based on Brand et al., 2013; Hirschi et al., 2013; Aebi et al., 2015).**

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Subsector</th>
<th>Importance in Visp</th>
<th>Importance in Saastal</th>
<th>Main Interests</th>
<th>Future development</th>
<th>Opportunities</th>
<th>Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmers</td>
<td></td>
<td>Low</td>
<td>Medium</td>
<td>Depending on farmer type, maintaining traditional farming and cultural landscape</td>
<td>Decreasing number of farms</td>
<td>Cooperation with tourism, local products, agrotourism</td>
<td>No successors, lower subsidies, liberalization</td>
</tr>
<tr>
<td>Residents</td>
<td>Winter tourism</td>
<td>High</td>
<td>High</td>
<td>High life quality, attractive job situation, healthy environment</td>
<td>Depending on socio-economic perspective and migration</td>
<td>Qualified positions in tourism and industry</td>
<td>Migration to urban centers</td>
</tr>
<tr>
<td></td>
<td>Summer tourism</td>
<td>Medium</td>
<td>High, increasing</td>
<td>High-quality, competitive tourism</td>
<td>Maintenance of originality and quality</td>
<td>High potential due to aesthetic landscape</td>
<td>Melting glaciers, (inter)national competition</td>
</tr>
<tr>
<td>Industry</td>
<td>Primarily biotechnology and chemistry</td>
<td>High</td>
<td>Low</td>
<td>Qualified employees, solid transport infrastructure, fast connections to lowland</td>
<td>Maintenance of regional importance</td>
<td>Many qualified employees due to good transport infrastructure</td>
<td></td>
</tr>
<tr>
<td>Forestry</td>
<td></td>
<td>Low</td>
<td>Low</td>
<td>Maintenance of protective forest</td>
<td>Constant</td>
<td>Protection service of increasing importance</td>
<td>Reduction of federal/cantonal subsidies, low timber prices</td>
</tr>
<tr>
<td>Trade</td>
<td>Public transport</td>
<td>Medium</td>
<td>Low</td>
<td>Flourishing tourism and industry</td>
<td>Increase of synergies with tourism and industry</td>
<td>Migration to centers, increasing summer tourism</td>
<td>Stricter spatial planning policy, decline in tourism</td>
</tr>
<tr>
<td>Wine industry</td>
<td></td>
<td>Low</td>
<td>Low</td>
<td>High-quality wines</td>
<td>Focus on quality rather than quantity</td>
<td>Increasing demand for regional wines, higher temperatures</td>
<td>Change in consumption patterns</td>
</tr>
<tr>
<td>Energy</td>
<td>Electricity (hydro-power)</td>
<td>Medium</td>
<td>Low</td>
<td>High electricity prices</td>
<td>Expansion hydropower, photovoltaik</td>
<td>Potential for hydropower, solar energy, cooperation between municipalities</td>
<td>Low prices</td>
</tr>
<tr>
<td>Infrastruct. and Transport</td>
<td>Public transport</td>
<td>High</td>
<td>High</td>
<td>Good regional connections</td>
<td>Maintenance of current schedules</td>
<td>Shorter travel times, increasing summer tourism</td>
<td>Reduction of subventions, decline in tourism</td>
</tr>
<tr>
<td>Planning</td>
<td></td>
<td>High</td>
<td>Medium</td>
<td>Qualitative growth of infrastructure, strengthening of Visp as regional center, maintenance of life quality</td>
<td>Investments in tourism, strengthening of Visp as regional center</td>
<td>Good traffic connections</td>
<td>Urban sprawl, outmigration</td>
</tr>
<tr>
<td>Nature conservation</td>
<td>Increasing</td>
<td>Increasing</td>
<td>Maintenance of close to nature cultural landscape</td>
<td>Increasing importance</td>
<td></td>
<td>Urban sprawl, temperature increase, decreasing number of farms</td>
<td></td>
</tr>
</tbody>
</table>
Curriculum Vitae

Sibyl Hanna Huber
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Professional Experience

Mar 2013 - ongoing

ETH Zurich, Institute for Spatial and Landscape Development
Co-task leader EU-Project OPERAs and lecturer in the masters program REIS (20%)

May 2010 - Feb 2013

ETH Zurich, Institute for Spatial and Landscape Development
Personal research assistant of Prof. Dr. Adrienne Grêt-Regamey, Planning of Landscape and Urban Systems Group
> Project-based research in landscape planning
> Writing of papers and research proposals
> Preparation of lectures and supervision of students
> Presentation of results at (inter)national conferences and workshops

May 2009 - Apr 2010

ETH Zurich, Department of Environmental Sciences
Project manager (80%) and research assistant (20%)
> Project manager organizing the Peer-Review 2010 of the department
> Administrator of the Strategic Planning Committee of the department
> Project-based research in Biogeochemistry and Pollutant Dynamics


High School Freudenberg, Zurich
Chemistry teacher

Jan 2007 - Jul 2007

Norwegian Institute of Air Research, Tromsø, Norway
Research assistant, Polar Environmental Physics Group


ETH Zurich, Department of Environmental Sciences
Teaching assistant in the integrative lecture introduction in dealing with environmental systems

Mar 2003 - Jun 2003

Swiss Federal Institute of Aquatic Science and Technology, Dubendorf
Assistant in field and laboratory work, Environmental Chemistry Group

Professional Education

Mar 2013 - May 2017

PhD candidate, ETH Zurich
Planning of Landscape and Urban Systems Group, Prof. Dr. Adrienne Grêt-Regamey
Thesis: Social-ecological modeling of Alpine ecosystem services

Jan 2007 - Apr 2009

Master of Science ETH in Environmental Sciences, ETH Zurich
Major in Biogeochemistry and Pollutant Dynamics passed “with honor”

Oct 2003 - Jan 2007

Bachelor of Science ETH in Environmental Sciences, ETH Zurich
System focus on Atmosphere and Climate

Aug 1996 - Sep 2002

Gymnasium Freudenberg, Zurich
Major in Latin and English awarded “best student of the year”
## Publications

### 2017


### 2016


### 2015


### 2013


### 2012


<table>
<thead>
<tr>
<th>Year</th>
<th>Author(s)</th>
<th>Title</th>
<th>Journal Details</th>
</tr>
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Mountains are the beginning and the end of all natural scenery.

John Ruskin