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A backcasting approach for matching regional ecosystem services supply and demand

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ABSTRACT

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
Software availability: LPL academic license available on purchase, http://www.virtual-optima.com/en/index.html; CPLEX academic license available at no charge, http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/index.html
Software required for linked modules: NLOGIT 5, Econometric Software Inc. (Education license available on purchase, http://www.limdep.com/products/nlogit/); R x64 3.1.0: A language and environment for statistical computing, R Core Team, Foundation for Statistical Computing (Available at no charge, http://www.r-project.org/)

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

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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; Robèrt, 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 and Robert, 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. Robèrt, 2005; Mattila and Antikainen, 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., 2013b; Bagstad et al., 2014; Castro et al., 2014; Schulp et al., 2014; Stürck 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., 2010; Voinov et al., 2014), or mixed approaches (Vollmer et al., 2015), are applied to asses 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, 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., 2013) 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.

1.1. Case study region

The case study region is located in the Central Valais, a continental mountain area in the Swiss Alps (Fig. 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 443.3 km^2 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 8 ha of agricultural land and housed around seven livestock units. Only 7% of the farms cultivated more than 0.5 ha of arable crops (FOAG, 2008). Agriculture is highly subsidized, farmers in the region receive annual direct payments of around 3200 CHF/ha (SFSO, 2015). 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,

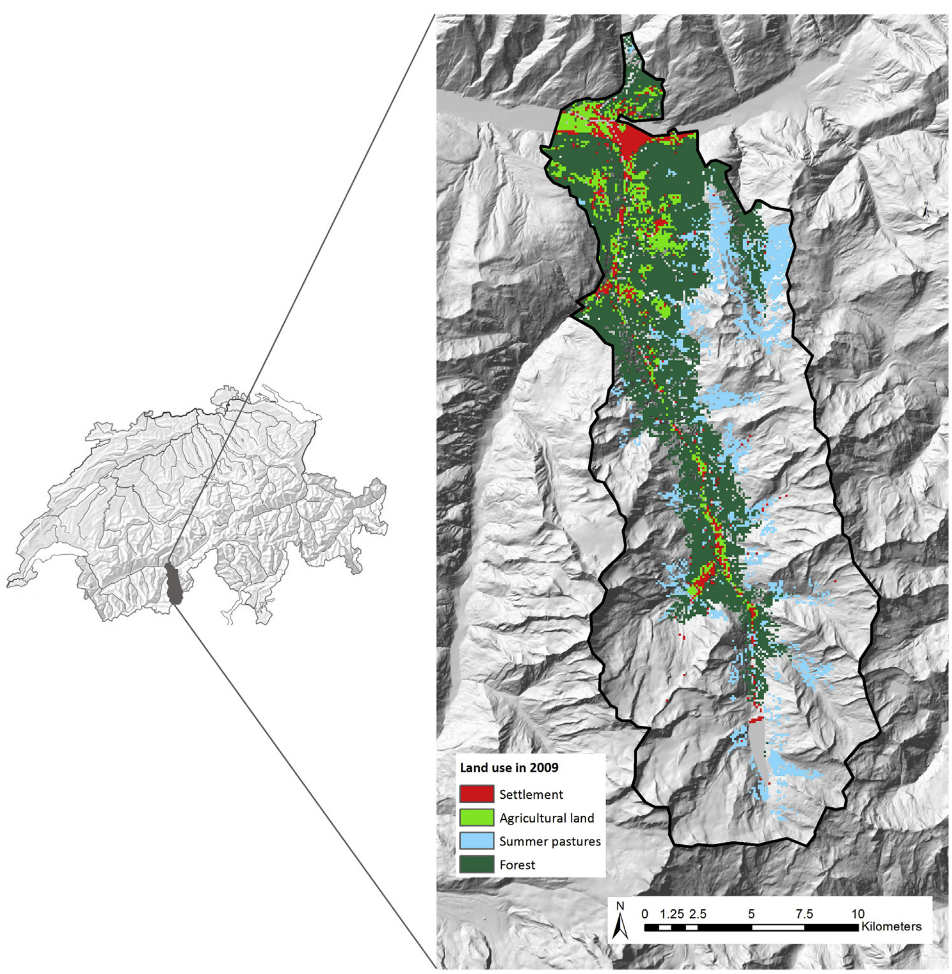

Fig. 1. The case study region in the Central Valais, southwest of the Swiss Alps.

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 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 et al., 2010).

2. Methods and data

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. Fig. 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.

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

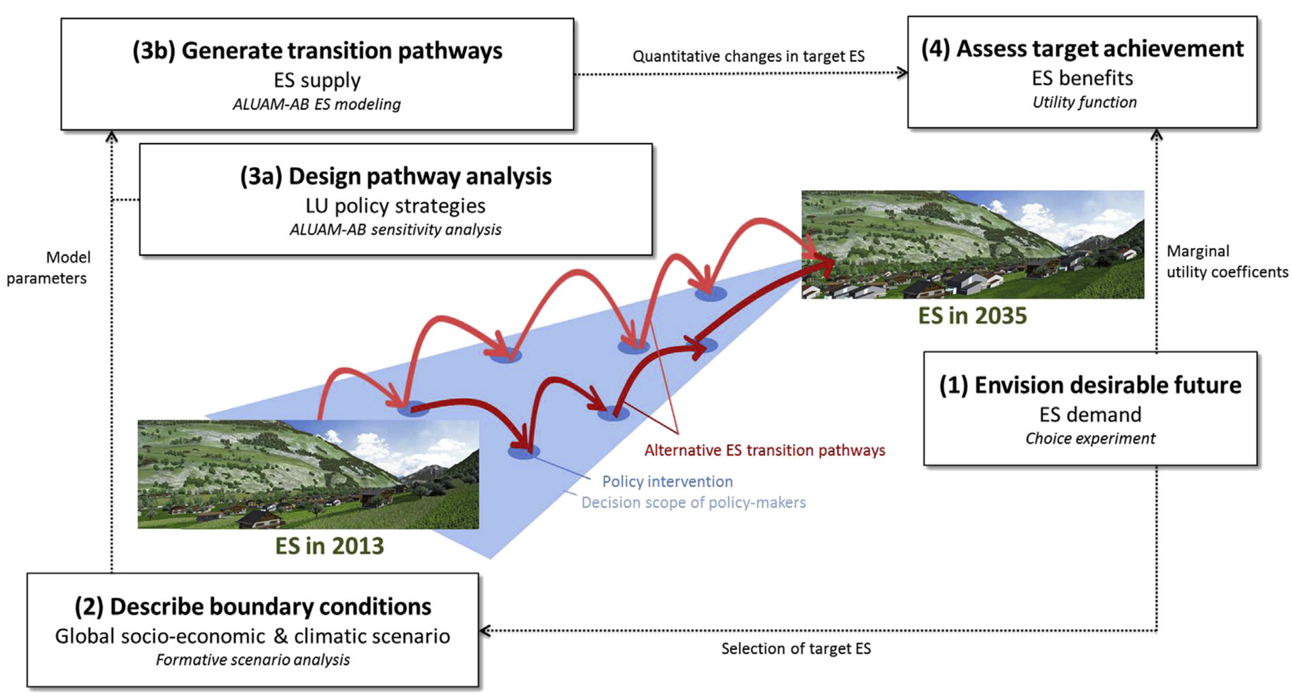

Fig. 2. Outline of the integrated backcasting approach: Bold titles delineate four generic steps of a backcasting analysis, subtitles show operationalization based on land use (LU) and ecosystem services (ES) in a welfare economic context, methods used in this study are given in italic. Arrows show qualitative and quantitative information exchanged between modules.

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.

2.2. Choice experiment

To elicit future ES demand, we conducted a discrete choice experiment with local residents (Fig. 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 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 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 A1, Appendix A). 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 Fig. A1, Appendix A 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 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 (Fig. 2).

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 (Fig. 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

Table 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.

Choice experiment				Transition pathway modeling
ES	ES indicators	Indicator type	Marginal utility coefficient (β_i) for 1% increase in indicator	ES indicators in ALUAM-AB (I_i)
Cultural heritage	Number of farms	verbal	0.031**	Number of farms
Mass flow regulation	Number of natural hazard incidents	verbal	−0.016**	General forest protection index
Habitat protection	Area of dry meadows	verbal	0.011**	Area of extensive meadows
Aesthetics	Forest area	visual	−0.232*	Forest area
	Settlement area	visual	−0.164**	Settlement area
	Intensive grassland area	visual	−0.021**	Area of intensive grassland
	Forest die-off	visual	*Not significant*	*Not modeled*

*$P < 0.05$, **$P < 0.001$.

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 socioeconomic 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 B1, Appendix B) based on national development scenarios (SFSO, 2011) 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.

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, 2013; 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 socioeconomic 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 ($100 \text{ m} \times 100 \text{ m}$), 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 C). 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 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 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 general forest protection index that describes the ability of a parcel to provide protection from all gravitational hazards (Briner et al., 2013). 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.

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 (Fig. 2, step 3a). We identified the most important exogenous factors affecting model outcome 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., 2013). 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 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. 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 B2 (Appendix B).

2.4.2. Modeling ecosystem services transition pathways

Based on the elaborated set of policy interventions (Table 2), we modeled various pathways of ES supply (Fig. 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 B3 (Appendix B) provides an overview on the sequencing of interventions in all performed model runs.

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; Fig. 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).

The change in the utility ΔU_{tot} was computed as the sum of the product of modeled changes in the Indicator I of each ES i between the reference year (2013) and the planning horizon (2035) and the corresponding marginal utility coefficients β_i using the software R

Table 2
Basic set of policy interventions implemented in ALUAM-AB, based on which the impact of land-use policy strategies on ecosystem services (ES) supply was modeled.

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

[a] 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.

x64 3.1.0:

$$\Delta U_{tot} = \sum \beta_i \cdot \Delta I_i \quad (1)$$

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. Positive changes of ΔU_{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.

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.

3.1. Changes in utility over time

Figs. 3 and 4 show how different types of policy interventions (Figs. 3a and 4a), in different combinations (Figs. 3b and 4b) and related to different levels of structural interventions (Figs. 3c and 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 (Fig. 3) and by nearly 8 given a liberalization scenario (Fig. 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 (Fig. 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.

Fig. 4a illustrates the effect of the same interventions on ES utility given a liberalization scenario. The most distinct difference as compared to Fig. 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 (Fig. 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.

Fig. 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 (Fig. 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 policy makers 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 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.

Fig. 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 (Fig. 3b), and up to 6.5 given the liberalization scenario (Fig. 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

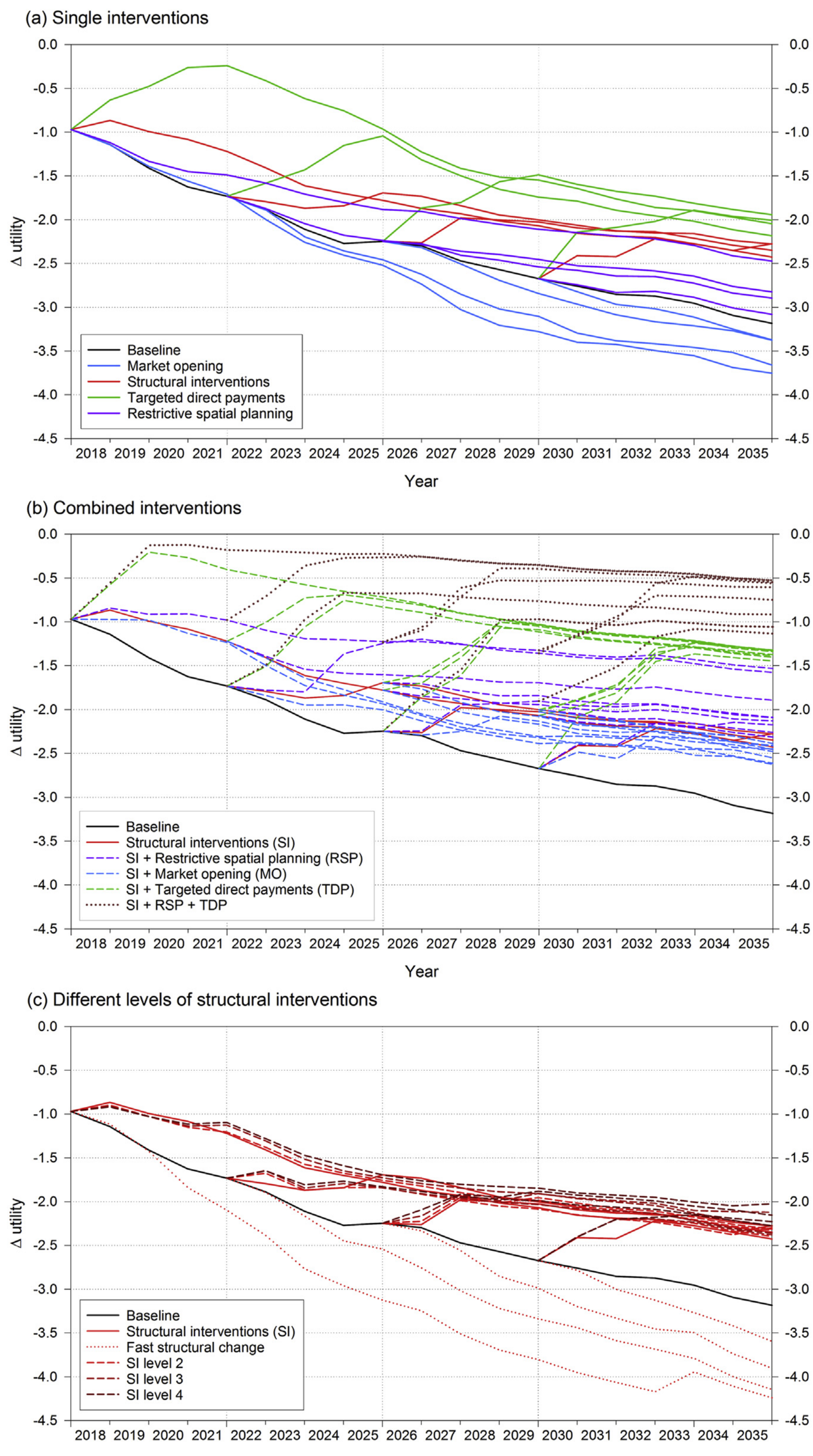

Fig. 3. Effect of different policy strategies on the utility of ES compared to 2013 in a business as usual scenario: (a) Single interventions, (b) combined interventions, (c) increasing levels of structural interventions and faster structural change.

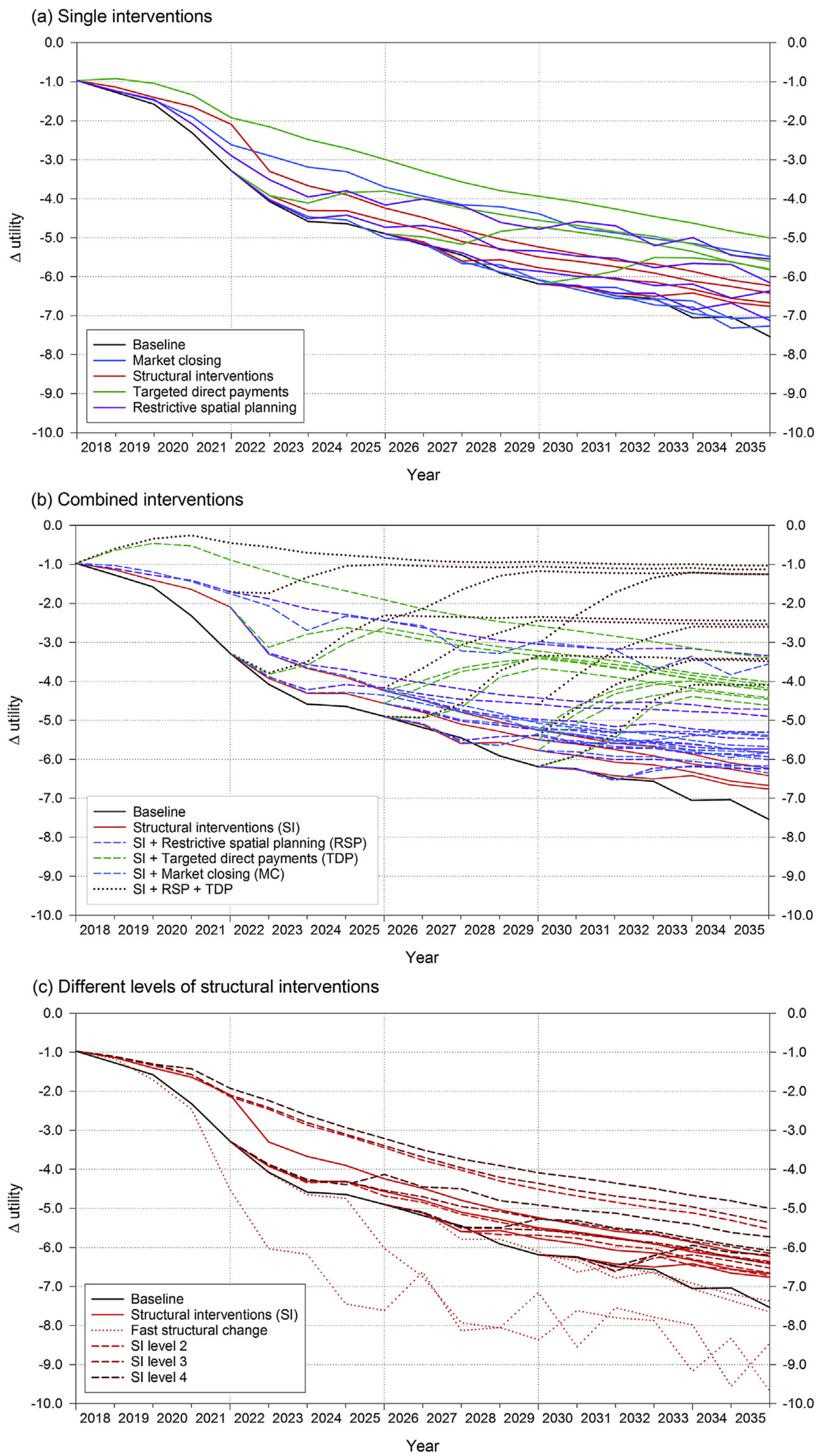

Fig. 4. Effect of different policy strategies on the utility of ES compared to 2013 in a liberalization scenario: (a) Single interventions, (b) combined interventions, (c) increasing levels of structural interventions and faster structural change. Note the different scaling of the axes than in Fig. 3.

on the utility as implied by the converging dashed lines in Fig. 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 Fig. 3c and 4c, the dotted line indicates 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.

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. As these mechanisms are alike in both global change scenarios, we present results illustrative only for the BAU setting. Fig. 5 shows how the supply of individual ES changes over time (left axis) and how strongly these changes translate into utility changes (right axis). 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 (Fig. 3a, black line) is caused by settlement development and forest expansion that reduce the aesthetics of the mountain region (Fig. 5c and d), as well as by a decline in the number of farms that negatively impacts the cultural heritage service (Fig. 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 Fig. 5a and b illustrate, the changes in agricultural land-use types contribute

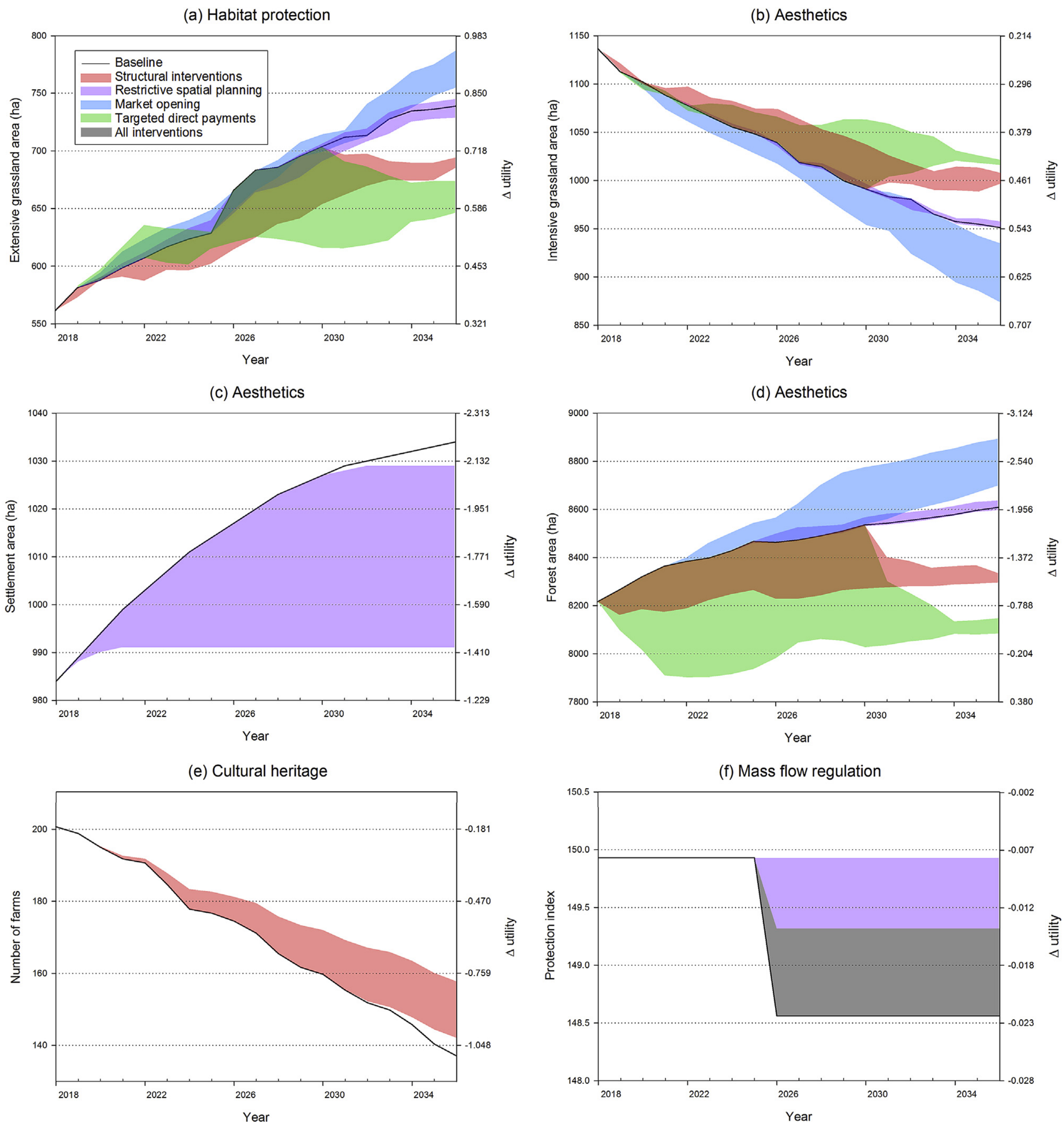

Fig. 5. Ecosystem services (ES) trade-offs caused by different policy interventions. Left hand axis shows how interventions change the supply of different ES, right hand axis illustrates corresponding changes in the utility. Different scales of the utility axes point at differing demand for ES. The colored bands show the range of changes that emerge from implementing an intervention at different points in time.

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 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 (Fig. 5d) as people expressed an aversion to forest expansion for aesthetic reasons (Table 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 (Fig. 5a and b). 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 (Fig. 5d). The resulting loss of the utility disproportionally diminishes the positive impact of this intervention on the increased share of extensive grassland (Fig. 5a and b). More restrictive spatial planning has only marginal effects on agricultural and forest land uses. The utility, however, increases compared to the baseline setting (Fig. 3a), since settlement development is attenuated with a positive effect on the aesthetics of the mountain region (Fig. 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 (Fig. 5e). As the right axes of Fig. 5c and d 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 (Fig. 5f).

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. Fig. 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 Fig. 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 (in the web version) 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-

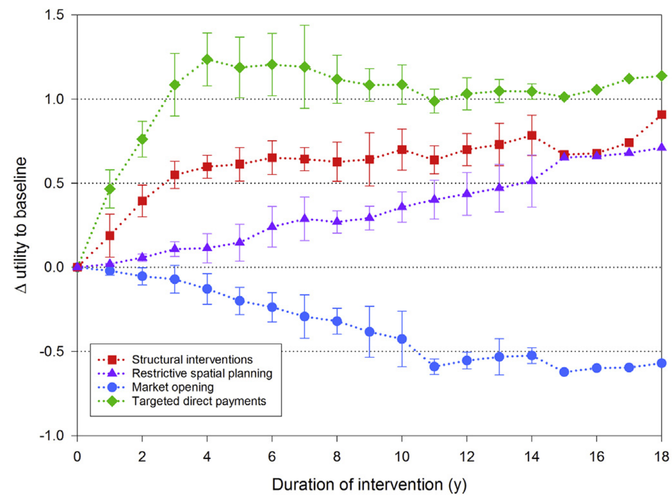

Fig. 6. Impact of different interventions on changes in the utility of ecosystem services compared to the utility of the baseline setting depending on the years being in action. Each rate is an average of the observed effects after implementing an intervention at four different points in time.

term planning horizon in 2035 (cf. Fig. 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.

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., 2015). 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 to 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 backasting 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. 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.

Acknowledgments

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Appendix A. Choice experiment

Table A1
Choice experiment attributes and levels defined based on an iterative stakeholder process.

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

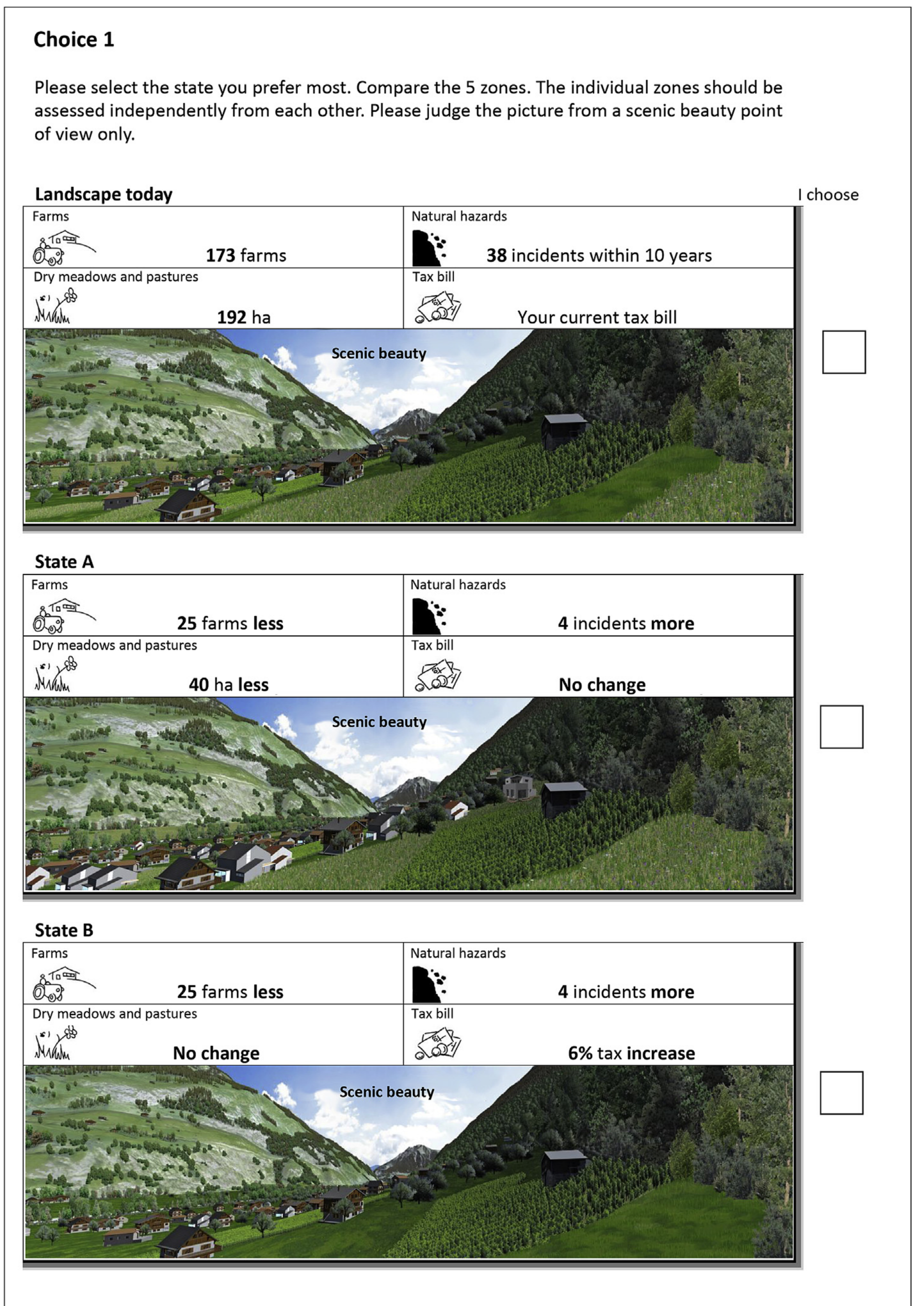

Fig. A1. Exemplary choice set (translated from German): participants had to choose between the current provision of ecosystem services (ES) and two alternative future sets of ES.

Appendix B. ALUAM-AB model specifications

Table B1
Qualitative levels of important exogenous factors (Walz et al., 2014) and related parameter values in the business as usual and the liberalization scenario.

Factor	"Business as usual" scenario		"Liberalization" scenario	
	Qualitative level	Parameter values	Qualitative level	Parameter values
Climate	A2	Crop yield and timber harvest according to Briner et al. (2012)	A1	Crop yield and timber harvest according to Briner et al. (2012)
Population CH Migration within CH Accessibility of mountain regions	7.5 Mio. Regional centers High increase	Regionally-downscaled medium growth population development scenario for Switzerland (SFSO, 2011)	9.5 Mio. Migration to agglomeration High increase	Regionally-downscaled large growth population development scenario for Switzerland (SFSO, 2011)
Agricultural markets	Stable prices (border protection)	Stable prices of all agricultural commodities according to Huber et al. (2014)	Large decline in prices (open markets)	Fast decline to 1.3 of EU price of all agricultural commodities according to Huber et al. (2014)
Agricultural policy	Reduced domestic support	Direct payment scheme according to the recently enacted federal agricultural policy directive (DZV, 2013)	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)
Spatial planning policy	Laisser-faire	Constant average settlement area granted per additional resident (SFSO, 2009, 2011)	Laisser-faire	Constant average settlement area granted per additional resident (SFSO, 2009, 2011)
Consumption patterns	Regional products	Constant opportunity costs and labor force according to Huber et al. (2014)	Global products	50% increase in opportunity costs and 50% decrease of labor force according to Huber et al. (2014)

Table B2
Parameter modifications in ALUAM-AB related to different interventions.

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

*In a liberalization scenario: Market closing and corresponding increase in prices.
**Values in brackets indicate additional levels of structural interventions modeled.

Table B3
Model runs performed with ALUAM-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. 0 = 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).

Run no.	Timing and sequencing of interventions	Run no.	Timing and sequencing of interventions
Business as usual (BAU) baseline		*Liberalization (LIB) baseline*	
1	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0R0S0	74	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0R0S0
Single interventions, BAU		*Single interventions, LIB*	
2	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0R0**S1**	75	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0R0**S1**
3	M0T0R0S0 – M0T0R0S0 – M0T0R0**S1** – M0T0R0**S1**	76	M0T0R0S0 – M0T0R0S0 – M0T0R0**S1** – M0T0R0**S1**
4	M0T0R0S0 – M0T0R0**S1** – M0T0R0**S1** – M0T0R0**S1**	77	M0T0R0S0 – M0T0R0**S1** – M0T0R0**S1** – M0T0R0**S1**
5	M0T0R0**S1** – M0T0R0**S1** – M0T0R0**S1** – M0T0R0**S1**	78	M0T0R0**S1** – M0T0R0**S1** – M0T0R0**S1** – M0T0R0**S1**
6	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0**R1**S0	79	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0**R1**S0
7	M0T0R0S0 – M0T0R0S0 – M0T0 **R1**S0 – M0T0**R1**S0	80	M0T0R0S0 – M0T0R0S0 – M0T0 **R1**S0 – M0T0**R1**S0
8	M0T0R0S0 – M0T0 **R1**S0 – M0T0 **R1**S0 – M0T0**R1**S0	81	M0T0R0S0 – M0T0 **R1**S0 – M0T0 **R1**S0 – M0T0**R1**S0
9	M0T0 **R1**S0 – M0T0 **R1**S0 – M0T0 **R1**S0 – M0T0 **R1**S0	82	M0T0 **R1**S0 – M0T0 **R1**S0 – M0T0 **R1**S0 – M0T0 **R1**S0
10	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0**T1**R0S0	83	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0**T1**R0S0
11	M0T0R0S0 – M0T0R0S0 – M0 **T1**R0S0 – M0 **T1**R0S0	84	M0T0R0S0 – M0T0R0S0 – M0 **T1**R0S0 – M0 **T1**R0S0
12	M0T0R0S0 – M0 **T1**R0S0 – M0 **T1**R0S0 – M0 **T1**R0S0	85	M0T0R0S0 – M0 **T1**R0S0 – M0 **T1**R0S0 – M0 **T1**R0S0
13	M0 **T1**R0S0 – M0 **T1**R0S0 – M0 **T1**R0S0 – M0 **T1**R0S0	86	M0 **T1**R0S0 – M0 **T1**R0S0 – M0 **T1**R0S0 – M0 **T1**R0S0
14	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – **M1**T0R0S0	87	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – **M1**T0R0S0
15	M0T0R0S0 – M0T0R0S0 – **M1**T0R0S0 – **M1**T0R0S0	88	M0T0R0S0 – M0T0R0S0 – **M1**T0R0S0 – **M1**T0R0S0
16	M0T0R0S0 – **M1**T0R0S0 – **M1**T0R0S0 – **M1**T0R0S0	89	M0T0R0S0 – **M1**T0R0S0 – **M1**T0R0S0 – **M1**T0R0S0
17	**M1**T0R0S0 – **M1**T0R0S0 – **M1**T0R0S0 – **M1**T0R0S0	90	**M1**T0R0S0 – **M1**T0R0S0 – **M1**T0R0S0 – **M1**T0R0S0
Different levels of structural interventions, BAU		*Different levels of structural interventions, LIB*	
18	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0R0**S2**	91	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0R0**S2**
19	M0T0R0S0 – M0T0R0S0 – M0T0R0**S2** – M0T0R0**S2**	92	M0T0R0S0 – M0T0R0S0 – M0T0R0**S2** – M0T0R0**S2**
20	M0T0R0S0 – M0T0R0**S2** – M0T0R0**S2** – M0T0R0**S2**	93	M0T0R0S0 – M0T0R0**S2** – M0T0R0**S2** – M0T0R0**S2**
21	M0T0R0S1 – M0T0R0**S2** – M0T0R0**S2** – M0T0R0**S2**	94	M0T0R0S1 – M0T0R0**S2** – M0T0R0**S2** – M0T0R0**S2**
22	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0R0**S3**	95	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0R0**S3**
23	M0T0R0S0 – M0T0R0S0 – M0T0R0**S3** – M0T0R0**S3**	96	M0T0R0S0 – M0T0R0S0 – M0T0R0**S3** – M0T0R0**S3**
24	M0T0R0S0 – M0T0R0**S3** – M0T0R0**S3** – M0T0R0**S3**	97	M0T0R0S0 – M0T0R0**S3** – M0T0R0**S3** – M0T0R0**S3**
25	M0T0R0**S3** – M0T0R0**S3** – M0T0R0**S3** – M0T0R0**S3**	98	M0T0R0**S3** – M0T0R0**S3** – M0T0R0**S3** – M0T0R0**S3**
26	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0R0**S4**	99	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0R0**S4**
27	M0T0R0S0 – M0T0R0S0 – M0T0R0**S4** – M0T0R0**S4**	100	M0T0R0S0 – M0T0R0S0 – M0T0R0**S4** – M0T0R0**S4**
28	M0T0R0S0 – M0T0R0**S4** – M0T0R0**S4** – M0T0R0**S4**	101	M0T0R0S0 – M0T0R0**S4** – M0T0R0**S4** – M0T0R0**S4**
29	M0T0R0**S4** – M0T0R0**S4** – M0T0R0**S4** – M0T0R0**S4**	102	M0T0R0**S4** – M0T0R0**S4** – M0T0R0**S4** – M0T0R0**S4**
30	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0R0**S5**	103	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0R0**S5**
31	M0T0R0S0 – M0T0R0S0 – M0T0R0**S5** – M0T0R0**S5**	104	M0T0R0S0 – M0T0R0S0 – M0T0R0**S5** – M0T0R0**S5**
32	M0T0R0S0 – M0T0R0**S5** – M0T0R0**S5** – M0T0R0**S5**	105	M0T0R0S0 – M0T0R0**S5** – M0T0R0**S5** – M0T0R0**S5**
33	M0T0R0**S5** – M0T0R0**S5** – M0T0R0**S5** – M0T0R0**S5**	106	M0T0R0**S5** – M0T0R0**S5** – M0T0R0**S5** – M0T0R0**S5**
Combinations of two interventions, BAU		*Combinations of two interventions, LIB*	
34	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0**R1S1**	107	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0T0**R1S1**
35	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0**T1**R0**S1**	108	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0**T1**R0**S1**
36	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – **M1**T0R0**S1**	109	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – **M1**T0R0**S1**
37	M0T0R0S0 – M0T0R0S0 – M0T0R0**S1** – M0T0**R1S1**	110	M0T0R0S0 – M0T0R0S0 – M0T0R0**S1** – M0T0**R1S1**
38	M0T0R0S0 – M0T0R0S0 – M0T0**R1S1** – M0T0**R1S1**	111	M0T0R0S0 – M0T0R0S0 – M0T0**R1S1** – M0T0**R1S1**
39	M0T0R0S0 – M0T0R0S0 – M0T0R0**S1** – M0**T1**R0**S1**	112	M0T0R0S0 – M0T0R0S0 – M0T0R0**S1** – M0**T1**R0**S1**
40	M0T0R0S0 – M0T0R0S0 – M0**T1**R0**S1** – M0**T1**R0**S1**	113	M0T0R0S0 – M0T0R0S0 – M0**T1**R0**S1** – M0**T1**R0**S1**
41	M0T0R0S0 – M0T0R0S0 – M0T0R0**S1** – **M1**T0R0**S1**	114	M0T0R0S0 – M0T0R0S0 – M0T0R0**S1** – **M1**T0R0**S1**
42	M0T0R0S0 – M0T0R0S0 – **M1**T0R0**S1** – **M1**T0R0**S1**	115	M0T0R0S0 – M0T0R0S0 – **M1**T0R0**S1** – **M1**T0R0**S1**
43	M0T0R0S0 – M0T0R0**S1** – M0T0R0**S1** – M0T0**R1S1**	116	M0T0R0S0 – M0T0R0**S1** – M0T0R0**S1** – M0T0**R1S1**
44	M0T0R0S0 – M0T0R0**S1** – M0T0 **R1S1** – M0T0 **R1S1**	117	M0T0R0S0 – M0T0R0**S1** – M0T0 **R1S1** – M0T0 **R1S1**
45	M0T0R0S0 – M0T0 **R1S1** – M0T0 **R1S1** – M0T0 **R1S1**	118	M0T0R0S0 – M0T0 **R1S1** – M0T0 **R1S1** – M0T0 **R1S1**
46	M0T0R0S0 – M0T0R0**S1** – M0T0R0**S1** – M0**T1**R0**S1**	119	M0T0R0S0 – M0T0R0**S1** – M0T0R0**S1** – M0**T1**R0**S1**
47	M0T0R0S0 – M0T0R0**S1** – M0 **T1**R0**S1** – M0 **T1**R0**S1**	120	M0T0R0S0 – M0T0R0**S1** – M0 **T1**R0**S1** – M0 **T1**R0**S1**
48	M0T0R0S0 – M0 **T1**R0**S1** – M0 **T1**R0**S1** – M0 **T1**R0**S1**	121	M0T0R0S0 – M0 **T1**R0**S1** – M0 **T1**R0**S1** – M0 **T1**R0**S1**
49	M0T0R0S0 – M0T0R0**S1** – M0T0R0**S1** – **M1**T0R0**S1**	122	M0T0R0S0 – M0T0R0**S1** – M0T0R0**S1** – **M1**T0R0**S1**
50	M0T0R0S0 – M0T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1**	123	M0T0R0S0 – M0T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1**
51	M0T0R0S0 – **M1**T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1**	124	M0T0R0S0 – **M1**T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1**
52	M0T0R0**S1** – M0T0R0**S1** – M0T0R0**S1** – M0T0**R1S1**	125	M0T0R0**S1** – M0T0R0**S1** – M0T0R0**S1** – M0T0**R1S1**
53	M0T0R0**S1** – M0T0R0**S1** – M0T0**R1S1** – M0T0**R1S1**	126	M0T0R0**S1** – M0T0R0**S1** – M0T0**R1S1** – M0T0**R1S1**
54	M0T0R0**S1** – M0T0**R1S1** – M0T0**R1S1** – M0T0**R1S1**	127	M0T0R0**S1** – M0T0**R1S1** – M0T0**R1S1** – M0T0**R1S1**
55	M0T0**R1S1** – M0T0**R1S1** – M0T0**R1S1** – M0T0**R1S1**	128	M0T0**R1S1** – M0T0**R1S1** – M0T0**R1S1** – M0T0**R1S1**
56	M0T0R0**S1** – M0T0R0**S1** – M0T0R0**S1** – M0**T1**R0**S1**	129	M0T0R0**S1** – M0T0R0**S1** – M0T0R0**S1** – M0**T1**R0**S1**
57	M0T0R0**S1** – M0T0R0**S1** – M0**T1**R0**S1** – M0**T1**R0**S1**	130	M0T0R0**S1** – M0T0R0**S1** – M0**T1**R0**S1** – M0**T1**R0**S1**
58	M0T0R0**S1** – M0**T1**R0**S1** – M0**T1**R0**S1** – M0**T1**R0**S1**	131	M0T0R0**S1** – M0**T1**R0**S1** – M0**T1**R0**S1** – M0**T1**R0**S1**
59	M0**T1**R0**S1** – M0**T1**R0**S1** – M0**T1**R0**S1** – M0**T1**R0**S1**	132	M0**T1**R0**S1** – M0**T1**R0**S1** – M0**T1**R0**S1** – M0**T1**R0**S1**
60	M0T0R0**S1** – M0T0R0**S1** – M0T0R0**S1** – **M1**T0R0**S1**	133	M0T0R0**S1** – M0T0R0**S1** – M0T0R0**S1** – **M1**T0R0**S1**
61	M0T0R0**S1** – M0T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1**	134	M0T0R0**S1** – M0T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1**
62	M0T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1**	135	M0T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1**
63	**M1**T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1**	**136**	**M1**T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1** – **M1**T0R0**S1**
Combinations of three interventions, BAU		*Combinations of three interventions, LIB*	
64	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0**T1R1S1**	137	M0T0R0S0 – M0T0R0S0 – M0T0R0S0 – M0**T1R1S1**
65	M0T0R0S0 – M0T0R0S0 – M0T0**R1S1** – M0 **T1R1S1**	138	M0T0R0S0 – M0T0R0S0 – M0T0**R1S1** – M0 **T1R1S1**
66	M0T0R0S0 – M0T0R0S0 – M0 **T1R1S1** – M0 **T1R1S1**	139	M0T0R0S0 – M0T0R0S0 – M0 **T1R1S1** – M0 **T1R1S1**

(*continued on next page*)

Table B3 (*continued*)

Run no.	Timing and sequencing of interventions	Run no.	Timing and sequencing of interventions
67	M0T0R0S0 – M0T0 **R1S1** – M0T0 **R1S1** – M0 **T1 R1S1**	140	M0T0R0S0 – M0T0 **R1S1** – M0T0 **R1S1** – M0 **T1 R1S1**
68	M0T0R0S0 – M0T0 **R1S1** – M0 **T1 R1S1** – M0 **T1 R1S1**	141	M0T0R0S0 – M0T0 **R1S1** – M0 **T1 R1S1** – M0 **T1 R1S1**
69	M0T0R0S0 – M0 **T1 R1S1** – M0 **T1 R1S1** – M0 **T1 R1S1**	142	M0T0R0S0 – M0 **T1 R1S1** – M0 **T1 R1S1** – M0 **T1 R1S1**
70	M0T0**R1S1** – M0T0**R1S1** – M0T0**R1S1** – M0 **T1R1S1**	143	M0T0**R1S1** – M0T0**R1S1** – M0T0**R1S1** – M0 **T1R1S1**
71	M0T0**R1S1** – M0T0**R1S1** – M0 **T1R1S1** – M0 **T1R1S1**	144	M0T0**R1S1** – M0T0**R1S1** – M0 **T1R1S1** – M0 **T1R1S1**
72	M0T0**R1S1** – M0 **T1R1S1** – M0 **T1R1S1** – M0 **T1R1S1**	145	M0T0**R1S1** – M0 **T1R1S1** – M0 **T1R1S1** – M0 **T1R1S1**
73	M0**T1R1S1** – M0 **T1R1S1** – M0 **T1R1S1** – M0 **T1R1S1**	146	M0**T1R1S1** – M0 **T1R1S1** – M0 **T1R1S1** – M0 **T1R1S1**

Appendix C. Settlement module

The choice experiment revealed that settlement expansion was a significant factor negatively affecting landscape aesthetics (Table 1). We thus extended ALUAM-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 300 m 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, 2011). 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 2.3) and calculated annual demand for settlement parcels, assuming a constant average need of space for housing per person (SFSO, 2009).

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