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ORIGINAL ARTICLE

Broadening the horizon in land use change modelling: Normative scenarios for nature positive futures in Switzerland

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Abstract

Within scenario-based research of social-ecological systems, there has been a growing recognition of the importance of normative scenarios that define positive outcomes for both nature and society. While several frameworks exist to guide the co-creation of normative scenario narratives, examples of operationalizing these narratives in quantitative simulation modelling are still limited. To address this gap, this paper presents an example of how aspects of normative scenarios can be realized within a spatial model of land use and land cover change. This is achieved through a combination of data-driven approaches to encapsulate scenario-specific differences in local and global scale phenomena, as well as iterative expert elicitation to quantify descriptive trends from narratives. This approach is demonstrated with a case study simulating five scenarios of landscape change (three normative and two exploratory) in Switzerland between 2020 and 2060. The resulting maps of future land use and land cover exhibited distinct variations between the scenarios, notably with regard to the prevalence of areas of heterogeneous semi-natural land, such as alpine pastures and grassland, often considered culturally emblematic of Switzerland. While the simulation results were generally consistent with the outcomes expressed in the scenario narratives, following a process of expert feedback, we reflect that there are clear challenges in leveraging such results to elicit further discussions as to the desirability and plausibility of future scenarios. Specifically, the need to summarize spatial simulations in a manner that is easily interpretable and encourages consideration of the broader patterns of change rather than focusing on fine-scale details.

Keywords Scenario modelling · Land use change · Cellular Automata · Normative scenarios

Introduction

In recent decades, research envisioning future scenarios for the combined natural and human environments, referred to as socio-ecological systems (SES), has tended towards pessimistic predictions (Hjerpe and Linnér, 2009; Robbins and Moore 2013; Bennett et al. 2016; Whyte 2018). While it is arguable that such negative outlooks are justified in the face of the increasing severity of global environmental degradation in the twenty-first century, at the same time they offer little input in terms of developing solutions to achieve more positive outcomes for nature and society (McPhearson et al. 2016).

In response to this, there has been a growing recognition of the importance of positive SES scenarios that incorporate a plurality of normative goals for the future and attempt to encapsulate possibilities for transformative change (Nassauer and Corry 2004; Bennett et al. 2016; McPhearson et al. 2016; Luederitz et al. 2017; Iwaniec et al. 2020). The rationale is that such positive scenarios not only offer explicit input for decision-makers but if they are derived through an inclusive, participatory, process they have the potential to foster a wider public will to action (McPhearson et al. 2016; Lavorel et al. 2019). In order to mainstream the development of normative SES scenarios, several frameworks have been proposed such as the Sustainable Future Scenarios (SFS) framework (Iwaniec et al. 2020) as well as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Nature Futures Framework (IPBES-NFF: Pereira et al. (2020)). The IPBES-NFF in particular has already been applied in several examples to

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Extended author information available on the last page of the article produce scenario narratives and visions (Lembi et al. 2020; Kuiper et al. 2022; Durán et al. 2023; Mayer et al. 2023). However, while qualitative scenario descriptions are a useful starting point, to progress towards the implementation of the changes they describe, narratives should ideally be distilled into evidence-based goals and targets (McPhearson et al. 2016).

In this regard, operationalizing SES scenarios through quantitative simulation modelling to explore the spatial–temporal impacts on critical aspects of the study system is often highly useful (Verburg et al. 2004, 2006). The goal of modelling in this context should not be to provide an absolute representation of the scenarios but rather it should be part of an iterative process of scenario refinement whereby the models and their outputs act as "boundary objects" (Castella et al. 2014; Verburg et al. 2019) to foster discussions with stakeholders. Two important aspects that simulation modelling can help elucidate are the coherency of scenarios (Volkery et al. 2008) and the balance between their perceived desirability and plausibility (Iwaniec et al. 2020). This is of particular importance for normative SES scenarios which, by virtue of striving for desirable outcomes, often necessitate radical changes from the status quo and hence may be considered to lack plausibility as compared to exploratory scenarios that simply extrapolate current trends (Wiek and Iwaniec 2014). Furthermore, simulation modelling is also important in the case of scenarios that would likely result in trade-offs that must be negotiated by society (Rounsevell et al. 2012; McPhearson et al. 2016).

Within the broad domain of SES scenario simulation research, the modelling of land use and land cover change (LULCC) is a prominent field, likely because of the long acknowledged contribution of anthropogenic LULCC as a driver of intersecting global environmental challenges (Ojima et al. 1994; Mahmood et al. 2014; Molotoks et al. 2021). Nevertheless, within this field, most studies have focused on exploratory scenarios with limited attention paid to the normativity of both their framing and outcomes (Verburg et al. 2019; Dou et al. 2023). However, in recent years, there have been some attempts to move beyond exploratory scenarios with several studies (Murray-Rust et al. 2013; Wolff et al. 2018; Wu et al. 2019; Schirpke et al. 2020; Peng et al. 2021) including scenarios framing environmentally positive outcomes although none of these were presented as explicitly normative (i.e. they were not created through a participatory process involving discussion as to the desirability of the outcomes). Whereas Verkerk et al. (2018) do deliberately explore scenario normativity, but here the authors evaluate normative visions against modelled scenarios from another source in an *ex-post* fashion rather than modelling their own visions. Perhaps, the two most comprehensive studies engaging with normative scenario creation with subsequent quantitative LULCC modelling are that of Vannier et al. (2019) and Dou et al. (2023). Vannier et al. (2019) demonstrate a participatory approach to integrate multi-scale socio-economic, climate and ecological dynamics in France. Whereas Dou et al. (2023) simulate LULCC scenarios for Europe that characterize different normative value perspectives on Nature using the IPBES-NFF and including policy-based sustainability targets. The fact that there are so few examples of the application of co-constructed normative scenarios, given the increasing frequency of studies published over the last decade (Tong and Feng 2020), shows that there is still a clear need within LULCC modelling to incorporate a greater diversity of perspectives beyond the focus on the extrapolation of current trends.

Within the field of LULCC modelling, Constrained Cellular Automata (CCA) are a class of models that have enjoyed enduring popularity for scenario simulation (Triantakonstantis and Mountrakis 2012; Aburas et al. 2016; Brown et al. 2022). Thompson et al. (2020) ascribe this popularity to the fact that CCAs represent LULCC as a phenomenon rather than as a process, i.e. they abstract the actions of the actors involved, which can make them easier to explain to non-experts. In addition, they offer a relatively extensible framework, as demonstrated by the diverse features that have been incorporated in recent years such as the integration with other model types (He et al. 2005), uncertainty quantification methods (Şalap-Ayça et al. 2018) and 3D dynamics (Qian et al. 2020). At the highest level of abstraction, LULCC-CCAs treat landscapes as a pixelated grid of cells of individual LULC states with cells changing state over time typically through the combination of two mechanisms: Firstly, the spatial distribution of potential LULCC is determined through the calculation of cellular probabilities of change to alternate land use land cover states, often referred to as transition potential (TP) (White and Engelen 1997). The method by which this is achieved differs between popular LULCC-CCAs, although it is commonly based on the quantification of correlative relationships with explanatory variables such as biophysical, socio-economic and neighbourhood (focal) predictors using a statistical model (Tobler 1979; García-Álvarez 2018; Ren et al. 2019). Secondly, the amount of cellular LULCCs that occur in a given simulation time step is prescribed by values of transition rates extrapolated from historic LULC data, with a model-specific allocation algorithm selecting the required number of cells to change based upon their transition probabilities (Mas et al. 2018).

The two general mechanisms of LULCC-CCAs offer several opportunities to instantiate aspects of scenarios. Firstly, the data supplied to predict cellular TP values can be both specific to the different scenarios being modelled as well as dynamic over the simulation time steps (Liao et al. 2023). For example, in scenarios contrasting differential levels of climatic change, the data provided may come

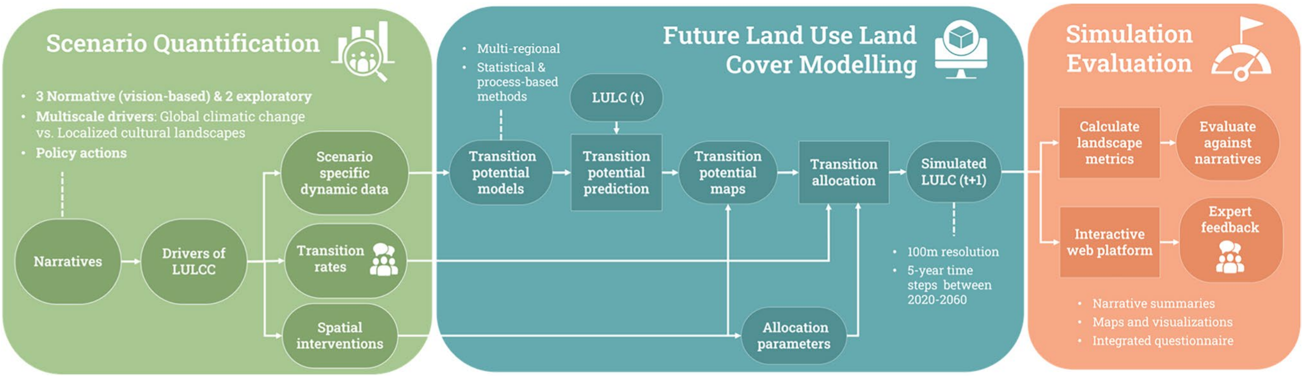

Fig. 1 Overview of the three stages of the approach used to model normative future scenarios of landscape change for Switzerland

from exogenous climatic models of different Relative Concentration Pathways (RCPs) (Song et al. 2019). A second method is to alter predicted cellular TP values; this can be done directly: such as spatially designated land management policies, for example, reducing the potential for transition to urban LULC states inside environmental protection areas (Poelmans and Van Rompaey 2010; Gharbia et al. 2016; Price et al. 2017; Clerici et al. 2019; Daneshi et al. 2021; Peng et al. 2021; Frank et al. 2023), or indirectly by altering the influence of variables within the statistical model used to calculate TPs (Troupin and Carmel 2016; Gago-Silva et al. 2017). Another means is to adjust parameters of the LULCC-CCA's allocation algorithm that may, for example, increase the creation of new patches of LULC class cover relative to the expansion of existing areas (Prieto-Amparán et al. 2019). Finally, scenarios can be instantiated through individual specification of the transition rates determining the quantities of LULCC (Shrestha et al. 2018; Cheng et al. 2020; Schirpke et al. 2020; Peng et al. 2021; Kiziridis et al. 2023; Molinero-Parejo et al. 2023). Despite these multiple means of operationalizing different facets of scenarios in LULCC-CCAs, Brown et al. (2022) note that most studies typically explore only a small subset of scenario components.

In summary, within SES scenarios research, there has been a general call for greater exploration of scenarios that focus on normative nature-positive outcomes as a means to effect discussions of solutions to current environmental crises. However, especially with regard to LULCC modelling, as a field within this domain, there has been relatively little progress towards this, despite potential methodological means. Thus, the aim of this research is to present an approach to modelling normative, nature-positive scenarios of land use change using an LULCC-CCA model that substantively operationalizes scenario components including dynamic data to represent variations in future climatic, economic and demographic trends; multi-region modelling of LULC transitions combining both statistical and process-based techniques; and mechanisms to realize the effect of spatial policies such as the expansion of nature conservation areas. We demonstrate this approach through a case study for the country of Switzerland by simulating five scenarios framing the development of a national Ecological Infrastructure between 2020 and 2060, recently elaborated by Mayer et al. (2023). We discuss the main trends that characterize the scenario simulations and notable differences between them. Finally, we illustrate the challenges of utilizing simulation results to prompt feedback from the stakeholders involved in the creation of the scenarios.

Methods

Overview of methodological approach

To perform scenario-based simulation of future LULCC in Switzerland between 2020 and 2060, this research employed three key processes illustrated in Fig. 1. First, a combination of quantitative methods and expert participation was used to translate statements related to trends and drivers of SES change in the scenario narratives into quantitative LULCC model inputs ("Scenario operationalization" section). The scenarios were then simulated using a comprehensive LULCC-CCA model created by combining the statistical programming software R (4.2.2) (R core team 2022) with the environment modelling software Dinamica EGO (7.2.0) (Leite-Filho et al. 2020). In the interest of open science, the LULCC-CCA model (https://zenodo.org/doi/10.5281/zenodo.12698470) along with the research data (https://doi.org/10.5281/zenodo.8263509) have been made available alongside this manuscript. Figure 1 includes a simplified overview of the processes taking place within the LULCC-CCA model, although a more expansive representation is provided by ESM Fig. 4. Subsequent sections ("Land use land cover transition identification", "Transition potential prediction", "Cellular automata parameter calibration") summarize the details of the model processes; however, for brevity, some material has been presented as accompanying electronic supplementary materials (ESM). The final step was to incorporate the results of the simulation modelling into an interactive web platform, as a means to gather expert and stakeholder feedback on their plausibility and coherency ("Simulation evaluation").

Overview of scenarios

To address nationally declining biodiversity, in 2012, the federal government of Switzerland ratified the Swiss Biodiversity Strategy (SBS) (FOEN 2012). One of the goals of the SBS is the development of Switzerland's Ecological Infrastructure (EI) as a "network of protected and connected areas that contribute to safeguarding the essential services of ecosystems for society and economy … and form the basis for a rich and resilient biodiversity" (FOEN 2012). To contribute towards the implementation of this goal, Mayer et al. (2023) defined five narrative scenarios to frame the development of EI in Switzerland between 2020 and 2060 alongside expected demographic, economic and climatic changes in Switzerland. The scenarios were produced through a participatory process with the aim of envisioning nature-positive outcomes using the IPBES Nature futures (IPBES-NFF) (Pereira et al. 2020; Durán et al. 2023). As such, three of the scenarios are explicitly normative and encapsulate the development of EI from different perspectives of societal-nature relationships according to the axes of the IPBES-NFF: EI for Nature (EI-NAT) is centred around intrinsic value perspectives on nature; EI for Society (EI-SOC) emphasizes instrumental value perspectives; and EI as Culture (EI-CUL) focuses on relational value perspectives (Mayer et al. 2023). The remaining two scenarios are exploratory and are meant to serve as a contrast to the others. Business-as-Usual (BAU) assumes the continuation of current trends and an instrumental value perspective on nature, whereas Growth and Extinction (GR-EX) represents a worst-case environmental scenario where existing trends in negative drivers are amplified and existing measures to mitigate negative environmental trends are rolled back. For the full narratives of the scenarios, readers should refer to Mayer et al. (2023); however, a short summary of each is provided in ESM B and a selection of the narrative statements related to key drivers are presented in ESM Table 8.

Land use land cover transition identification

The first step in preparing the LULCC-CCA model was to identify relevant LULC transitions which consist of pixel-level changes from an "initial" LULC class in one time point to a different "final" LULC class in a subsequent time point. To do this, we utilized the classified LULC datasets for all four time points of the Swiss area statistics (SFSO 2021): 1981–1985, 1992–1997, 2004–2009, 2013–2018. It is important to note that the date range for each dataset is the extent of the data collection period, and each product actually represents a single LULC map. In this regard, for simplicity, we will henceforth refer to the datasets by the latter year of the data collection period only (i.e. 1985, 1997, 2009 and 2018). The LULC data is originally presented as spatial point data generated from aerial photography; however, for the purpose of modelling, all maps were converted to 100 m resolution rasters. Given that transitions are identified between two time points, having four historic LULC maps meant that we had three LULC transition periods with which to calibrate our model: 1985–1997, 1997–2009 and 2009–2018, henceforth referred to as calibration periods.

The original LULC data uses a classification scheme that identifies 72 LULC classes (SFSO 2018). Including all possible transitions between these classes is not realistic for modelling purposes, as it would result in a large number of possible transitions ($71 \times 72 = 5112$, excluding instances of persistence). Therefore, following the approach of Black et al. (2023), we aggregated the original 72 LULC classes to 10 classes: alpine pastures, closed forest, glacier, grassland, intensive agriculture, open forest, shrubland, permanent crops, urban/amenities, and static (see ESM C for a table of class aggregations).

Instances of LULC transitions were identified by overlaying the maps for each calibration period and extracting pixels according to changes from their initial LULC class (start map) to their final class (end map). With 10 aggregated classes, this gives the potential for 100 possible class-class transitions which would still be unfeasible for modelling. Thus, as per Black et al. (2023), we filtered to viable LULC transitions for each period by first excluding illogical transitions, for example, sealed surfaces such as roads (represented by the static class) are unlikely to be converted to semi-natural surfaces (e.g. the grasslands class). Following this, we applied a threshold to remove transitions that led to a change in less than 0.5% of the total area of the initial class as these would represent highly imbalanced datasets, unsuitable for predictive modelling.

The instances of LULC transitions were then combined with instances of non-transitions (i.e. pixels with the corresponding initial class for a given transition but a non-corresponding final class), to give separate datasets for each transition. To reflect the potential for regionalized differences in LULCC processes, the datasets were subdivided according to the six biogeographical regions of Switzerland (Gonseth et al. 2001). The bioregions encapsulate differences in floral and faunal distribution which is a proxy for spatial differences in climate and topography that impact the choice of location for agriculture and settlement development. Notably, not all transitions occurred in all regions (for example, because some regions contained no glacial area) or across all calibration periods. A table detailing the transitions identified for each of the calibration periods is included as ESM D.

Transition potential prediction

The method of creating the statistical models to be used to iteratively predict cellular TP within the LULCC-CCA was refined from that of Black et al. (2023). The predictors chosen for the modelling were grouped into two categories: Firstly, those related to land suitability and accessibility. Secondly, neighbourhood predictors capturing the influence of localized LULC composition on the occurrence of LULC transitions. The details of the suitability and accessibility predictors are provided in ESM E (Table 5), which also details which of the predictors were treated as static (i.e. unchanging) during simulations and which were dynamic (see "Dynamic predictors" section).

The approach for the preparation of neighbourhood predictors was also adopted from Black et al. (2023). In summary, 5 LULC classes were selected as active classes (i.e. logically perceived to influence LULC transitions, for example, new urban area tends to develop in proximity to existing urban area) and a set of 25 Pythagorean matrices of varying size (9–121 cells) with randomized central values and decay rates were applied as focal moving windows over the LULC layers, masked for these classes, for each calibration period. This resulted in a total of 125 neighbourhood predictor layers at 100-m resolution for each period.

In order to increase the efficiency of TP prediction within the LULCC-CCA simulations, a two-step predictor variable selection approach was applied to derive parsimonious (i.e. compact and non-redundant) predictor sets for each regionalized transition dataset (Black et al. 2023). This approach involved pairwise correlation–based filtering using univariate regression models followed by model-embedded filtering using the Guided Regularized Random Forests algorithm (Adde et al. 2023; Black et al. 2023).

Following predictor variable selection, the Random Forests (RF) algorithm (Breiman 2001) was used to create TP models for each regionalized transition dataset using the *randomForest* R package (Liaw et al. 2022). The accuracy of the RF TP models was assessed independently of the CCA model, using hold-out validation (70:30 training and test set splits using proportional random sampling without replacement) with multiple performance metrics in a process that Black et al. (2023) refer to as stage 1 validation. This allowed for hyper-parameter tuning to derive the optimal RF specification, which was found to be 500 tree forests under the default classification settings for minimum size of terminal nodes and number of variables sampled at each split with tree-level proportional sampling used to mitigate class imbalance (Black et al. 2023). The final RF TP models, re-trained using the full datasets, were incorporated in the LULCC-CCA with the corresponding TP model from each calibration period used for parameter calibration ("Cellular automata parameter calibration" section) and the models from the most recent period (2009–2018) used for future simulation steps ("Scenario operationalization" section).

The exception with regard to TP prediction was the transition from the glacier class to the static class. Instead of using an RF model, this transition was realized using spatially explicit predictions of future glacier evolution by Zekollari et al. (2019). The reason for this was that there were very few instances of this transition within the calibration periods, whereas future climatic change will likely result in a substantial loss of glacial area. Hence, the reliability of an RF model trained on this data would be questionable and using a process-based model should provide greater accuracy. Technical details of the predictions of Zekollari et al. (2019) are provided in ESM F, with these being implemented deterministically in each simulation step following the allocation of the other transitions.

Cellular automata parameter calibration

Dinamica EGO uses a combination of two algorithms, Patcher and Expander, for allocating cellular LULC transitions, which represent the processes of the creation of new patches of LULC classes and the expansion of existing patches respectively (Leite-Filho et al. 2020). These algorithms require the calibration of 5 parameters (henceforth referred to as allocation parameters) for every transition: mean patch size, patch size variance, patch isometry and the relative % of transitions to be allocated by each algorithm (i.e. % by patcher, % by expander). The process and results of the calibration of these values are presented in ESM G. The calibrated parameter values were used as the basis for all future simulations with some scenarios involving deliberate modifications of values ("Spatial interventions in transition potential and allocation parameters" section).

Scenario operationalization

As highlighted in Fig. 1 (and in more detail in ESM Fig. 4), there were three approaches by which statements from the scenario narratives describing trends and drivers related to LULCC were realized as inputs to the LULCC-CCA model. These were temporally dynamic variants of variables used for cellular TP prediction (dynamic predictors); transition rates to control the amount of cellular changes under each transition, and mechanisms to manipulate TP values and allocation parameters (spatial interventions). The methodological details of these approaches are provided in the subsequent sub-sections ("Dynamic predictors", "Transition rates", "Spatial interventions in transition potential and allocation parameters" respectively) with Table 1 providing a summary of the differences in how these approaches were implemented between the five scenarios.

We made the decision to use a 5-year time step to simulate LULCC for each of the five scenarios between 2020 and 2060. The rationale for this is that the computation required for regionalized TP prediction of 21 LULC transitions as well as the calculation of dynamic predictors within every time step makes the use of smaller time steps, such as an annual basis, very time consuming without offering a clear benefit in terms of improved accuracy. This 5-year time step resulted in eight simulated LULC maps for each scenario.

Dynamic predictors

We produced scenario-specific dynamic predictor data for the drivers of climate change, population development and economic development with the corresponding suitability and accessibility variables marked as "dynamic" in ESM E: Table 5. The majority of the sources of data utilized for these drivers ((Broennimann and Guisan 2024), Cretegny and Müller (2020) and (SFSO 2020), see symbols note in Table 1) presented their own internal scenarios and as such it was necessary to match the source-specific scenarios to our scenarios. For example, the (SFSO 2020) population projections contained 3 scenarios: high, reference and low which were matched to our scenarios based upon their narratives. All of these correspondences are presented as the entries under these drivers in Table 1. Additional data manipulation was required to align the future projected data sources with that of the equivalent historical variables, which is described in ESM H. Additionally, the focal LULC neighbourhood predictors were also updated during each simulation time step, utilizing the same focal moving window approach as the historic versions ("Transition potential prediction" section) but instead used the simulated LULC map from the previous simulation time step as input.

Transition rates

The cellular transition allocation process in Dinamica EGO is constrained by input in the form of rates of transitions (the % of the initial class area to be converted) for each time step in the simulation. Given that the scenarios were devised through a participatory process, we did not want to estimate the future transition rates for each using only quantitative extrapolations based on historic rates. As such, we devised an approach that used historical extrapolations as a basis to inform expert elicitation of future rates; the details of which are presented in ESM I.

Spatial interventions in transition potential and allocation parameters

The spatial interventions were derived by extracting statements from the scenario narratives (Mayer et al. 2023), grouped according to drivers, that pertained to spatialized differences in the locations of LULCC processes. These statements were used to create eight corresponding spatial intervention mechanisms, which were modified across the scenarios to give a total of 19 different interventions. As mentioned above, the majority of these interventions functioned by directly altering cellular transition probabilities during the simulation time steps. However, one intervention focused on the spatial segregation of land use activities in the landscape, instead involved alteration of the Dinamica EGO allocation parameters, which was performed prior to the start of the simulations (see ESM Table 8: Intervention ID "spatial zoning"). The details of the spatial interventions are expansive and as such are presented in ESM J.

Simulation evaluation

Given that the results of future simulations cannot be empirically validated, we follow the recommendations of Rykiel (1996) who suggested that evaluation should instead seek to establish whether the results meet the intended purpose of the model. In this case, the purpose of the model was to provide a spatially explicit representation of differences in future LULCC in Switzerland described by the five scenarios. Thus, to evaluate the simulations, we analyzed the consistency of patterns and trends in the simulated maps against specific statements from the narratives. This was done through both spatial analysis ("Spatial analysis" section) as well as seeking feedback from experts ("Expert feedback" section).

Spatial analysis

Given that landscape fragmentation was a specific theme within the scenario narratives, we calculated two metrics to represent this using the R package *landscapemetrics* (Hesselbarth et al. 2019): Effective Mesh Size (Jaeger 2000) and Patch Cohesion Index (Schumaker 1996). Both metrics were calculated at both the landscape level (i.e. a value aggregated across all LULC classes in the spatial extent of analysis) and at the level of individual LULC classes (i.e. separate values for each LULC class).

In addition to this, to evaluate regional-specific trends in LULCC contained in the scenario narratives, we also produced three summary metrics to capture changes in specific regions, namely urban areas, mountainous areas, remote rural areas, and protected areas (PAs) (details of how these regions were spatially identified are included in ESM J). The first summary metric, dubbed "relative urban change",

Table 1 Overview of scenario drivers and the methods by which they were operationalized in the LULCC-CCA model

Driver	Operationalization method	EI-NAT	EI-CUL	EI-SOC	GR-EX	BAU
Climate change	Dynamic predictors	RCP 2.6†	RCP 2.6†	RCP 4.5†	RCP 8.5†	RCP 4.5†
Population development	Dynamic predictors	Low growth (2060: 9,5 million)‡	Low growth (2060: 9.5 million)‡	Reference growth (2060: 10.5 million)‡	High growth (2060: 11.5 million)‡	Reference growth (2060: 10.5 million)‡
Economic development	Dynamic predictors	Ecological awareness—Urban densification*	Ecological awareness—Central*	Combined technological acceleration and Ecological awareness—Urban densification*	Reference—Peri-Urbanisation*	Reference—Central*
Settlement development	Transition rates Spatial interventions Spatial interventions Spatial interventions	Moderate settlement development No further urban sprawl Development of small towns in mountain area Abandonment of settlements in remote rural areas	Slight settlement development No further urban sprawl Persistence of villages in mountainous areas Revival of settlements in remote rural areas	Strong settlement development No further urban sprawl Development of small towns in mountain areas Abandonment of settlements in remote rural areas	Moderate settlement development Increased levels of urban sprawl - -	Moderate settlement development Urban sprawl similar to present Rural exodus from mountain communes to cities -
Agricultural activities	Transition rates Spatial interventions	Subsidies for biodiversity promotion above production Abandonment of poorly accessible marginal land	Subsidies for biodiversity promotion above production Extensive cultivation of poorly accessible marginal land	Subsidies for production over biodiversity promotion Abandonment of poorly accessible marginal land	Subsidies for biodiversity promotion above production Crop production on all arable soils with livestock farming on all grassland areas	Subsidies for biodiversity promotion above production Abandonment of poorly accessible marginal land
Protected areas	Spatial interventions	20% of Swiss land area protected by 2030, 30% by 2060, new sites selected for importance for biodiversity	17% of Swiss land area protected by 2030, 25% by 2060, new sites selected for cultural heritage preservation	17% of Swiss land area protected by 2030, 22% by 2060, new sites selected for high NCP provision	-	-
Land management	Spatial interventions	Strong limitation of land fragmentation	-	Land management is spatially zoned: areas for agriculture, residence, recreation	-	-

Symbols: *Swiss future population growth scenarios 2020–2050 (SFSO 2020); † Future climate change under different Representative Concentration pathways (RCPs), adapting data from Broennimann and Guisan 2024; ‡ Future economic scenarios from Cretegny and Müller 2020

corresponded to the % area change in the urban/amenities class between 2020 and 2060 in a given region relative to the change in the whole study area (to account for differences in overall change rates between scenarios). The second metric, "change in urban patches", equated to the % difference in the number of patches of urban/amenities class in the region in 2060 vs. 2020. Finally, "change in natural LULC class cohesion" was calculated as the mean difference in the Patch Cohesion Index value between 2020 and 2060 in PAs for the natural/semi-natural LULC classes (open forest, closed forest, grassland or meadows, overgrown/shrubland, alpine pastures and intensive agriculture).

Expert feedback

The second evaluation approach was to gather feedback on the simulation results from participants involved in the scenario creation process along with other experts chosen for their knowledge in fields related to landscape change in Switzerland. In total, 55 people were invited to provide feedback and a summary of the institutional/professional backgrounds of the invitees is provided in ESM K. To facilitate the feedback activity, we created a webpage where participants could interactively view the simulated maps, in addition to infographics summarizing the LULCC trends, with the option to view multiple scenario outputs alongside each other. This webpage was used to directly collect anonymous feedback from the participants based on a series of open-ended questions framing key aspects of each scenario. The feedback questions have also been included in ESM K.

Results and discussion

As described in the "Simulation evaluation" section, we evaluated the simulation results by comparing their concurrence with the scenario narratives through both spatial analysis and expert feedback. In terms of the spatial analysis, the "Scenario simulation overview" section characterizes the overall trends displayed by the scenarios in relation to the narratives and highlights the possible societal implications of these, whereas the "Realization of scenario-specific spatial trends" section focuses on specific spatial trends in landscape fragmentation and segregation, regionalized LULCC, and the expansion of protected areas. The "Expert feedback" section discusses the results of the expert feedback activity which prompted reflection on the research process as to the challenges and opportunities of modelling normative scenarios which are discussed in the "Challenges and opportunities in normative scenario modelling" section.

Scenario simulation overview

Figure 2 contains bar charts (A) and a mosaic plot (B) which show the % difference in LULC class area between 2020 and 2060 and % coverage of each LULC class respectively the main trends of which will be summarized for each scenario below. In addition, Fig. 2A. shows the maps of simulated LULC in Switzerland in 2060 under all five scenarios although given the large scale of the study region readers are urged to explore the interactive versions of the maps using the web platform devised for feedback: https://valpar.ch/land-use-change-scenarios/.

The EI-NAT scenario is characterized by a relatively low rate of urban growth with a strong increase in the area of closed forest. Figure 2 indicates that this increase in closed forest area is being driven primarily by the natural succession from open forest. However, the transitions from alpine pastures and overgrown/shrubland areas also represent substantial contributions. These trends, in combination with the reduction of land area utilized for intensive agriculture and permanent crops, collectively represent the loss of the open heterogeneous landscapes traditionally considered culturally emblematic in Switzerland (Stotten 2016). This loss could result in a decline of perceived landscape quality amongst the population as such landscapes are highly valued under current conceptions (Wartmann et al. 2021; Mann et al. 2023). However, this would theoretically be countermanded by the societal change towards a more nature-oriented perception of landscape quality proposed under the EI-NAT narrative. Of course, such a change in Switzerland is likely to be contentious and require societal negotiation (Bauer et al. 2009), as exemplified by the recent failure of an initiative to establish a new national park with strict nature-focused management (Michel et al. 2022).

Distinctive features of the EI-CUL scenario are that it exhibits the smallest loss of both alpine pastures and intensive agricultural land, as well as the greatest increase in grassland area. As described above, these LULC classes are the basis of the cultural landscape of Switzerland and hence their preservation (relative to other scenarios) is coherent with the normative focus of the EI-CUL scenario, i.e. maintaining the societal importance of agriculture. This is further exemplified by EI-CUL being the only scenario to present an increase (2.99%) in the area of permanent crops, of which a prominent example is vineyards, which are recognized as a characteristic cultural landscape in Switzerland (Rodewald et al. 2014).

The EI-SOC scenario displays the greatest loss of overgrown/shrubland areas of all scenarios. This is in line with the scenario narrative which emphasizes spatial planning based on maximizing land use functionality and the provision of ecosystem services (referred to as Nature Contributions to People: NCPs). Thus, under EI-SOC, overgrown areas should be expected to be brought back into a more productive state such as managed grassland, pastures or forest that are perceived to better contribute to ecosystem service provision.

The two exploratory scenarios, BAU and GR-EX, share many of the same defining characteristics, the foremost of which being a substantial increase in urban area (25.32% and 40.61% respectively, as compared to 2020) at the expense of a loss in area of almost all of the natural and semi-natural LULC classes. Closed forest is the only natural class to increase in area under both scenarios, whereas grassland area does increase under GR-EX, given additional time this grassland would likely also transition to forest. Perhaps the strongest difference between the exploratory scenarios is that

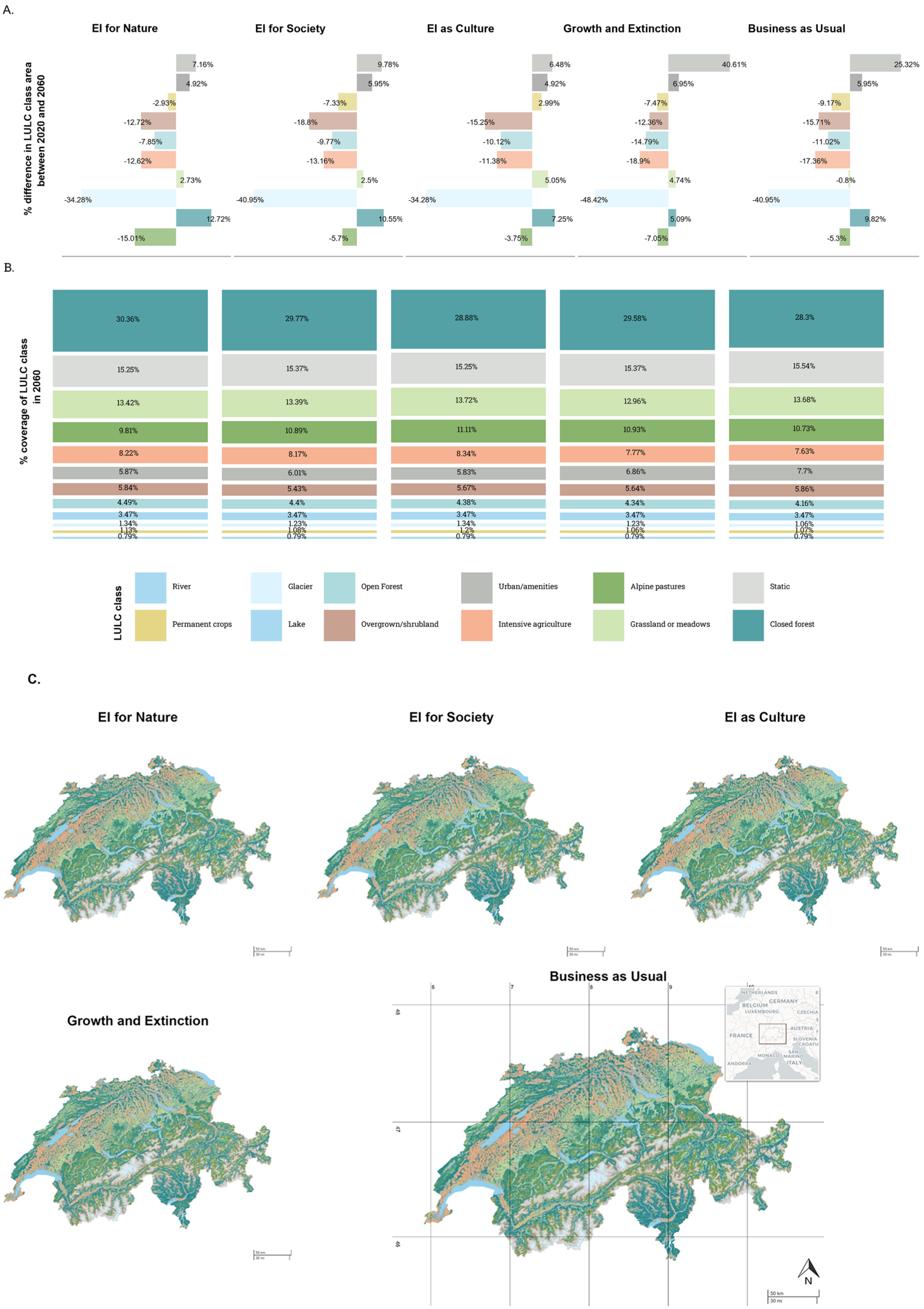

Fig. 2 Bar charts (**A**) showing the % difference in LULC class area between 2020 and 2060, mosaic plot (**B**) showing the % coverage of each LULC class and maps (**C**) of simulated LULC in Switzerland in 2060 under each of the five scenarios

BAU exhibits a higher increase in closed forest area because under GR-EX closed forest is converted to urban, intensive agriculture, and permanent crop areas, which are change that do not appear to occur under BAU. This, in combination with the fact that GR-EX displays a much greater rate of transitions across many classes (i.e. more instances of land use changes occurring in total, demonstrated in ESM Fig. 5), is emblematic of the lack of cross-sectoral collaboration in spatial planning highlighted in the scenario narrative (Mayer et al. 2023).

In terms of common trends across scenarios, all exhibited an increase in the area of the closed forests, which is to be expected given that none of the narratives specified a divergence from the current status quo of a national policy of conservative forest management (Mather and Fairbairn 2000). Indeed, this result is in concordance with previous LULCC studies in Switzerland (Gago-Silva et al. 2017; Price et al. 2017; Gerecke et al. 2019) as well as Europe-wide studies (Rounsevell et al. 2006).

The loss of glacial area was also relatively high across all scenarios which was to be expected as our model incorporated results from glacial change predictions that indicate that glaciers are to lose between ca. 2/3 to almost the entirety of their volume by the end of the twenty-first century (Zekollari et al. 2019). However, a limitation of our results is that we were unable to address the implications of this trend in terms of future LULC in the newly de-glaciated areas. The reason for this is that the predictions of glacial change incorporated in the LULCC-CA model only specified future glacier presence or absence and indeed the historical data of glacial transitions from the LULC maps contained too few instances to train robust statistical models to predict class to class transitions. In practical terms, this meant that all de-glaciated areas were assigned the Static LULC class (which encompasses categories such as “bare rock” in ESM Table 3). This is not a major limitation given that the area of de-glaciation in the most extreme scenario (GR-EX) equates to less than 0.5% of the total area of analysis in Switzerland. However, there would be scope for future research to understand how this land might be utilized differently under each scenario, e.g. through the prioritization of energy infrastructure (Farinotti et al. 2019) vs. creation of conservation areas (Bosson et al. 2023). As such, additional research is needed to understand the potential for this newly accessible land.

Realization of scenario-specific spatial trends

Focusing on the more detailed spatial trends described in the scenarios: both EI-SOC and EI-NAT contained statements related to the landscape being spatially segregated according to land use (i.e. settlement areas separated from agricultural areas) and the avoidance of landscape fragmentation (ESM Table 8) whereas, by contrast, GR-EX posits “uncoordinated” landscape management (Mayer et al. 2023). To analyze whether these trends are evident in the simulation results, Fig. 3 shows the values of two different landscape aggregation metrics: Patch Cohesion Index and Effective Mesh Size (higher values correspond to greater aggregation and hence lower fragmentation). Figure 3 shows that EI-NAT and EI-SOC do exhibit less landscape fragmentation than the EI-CUL and GR-EX scenarios, displaying the greatest values across both metrics (Fig. 3A, C). Vice versa, also in accordance with the scenario narrative, GR-EX exhibits the most pronounced landscape fragmentation (i.e. low metric values). The fact that BAU also presents low levels of landscape fragmentation, comparable to EINAT and EI-SOC, is somewhat surprising as it did not involve specific interventions intended to induce this effect as was the case in the normative scenarios. However, examining the class level values of the metrics, it is clear that the landscape level values for BAU are being driven primarily by high values for the Urban/amenities class in the case of the Patch Cohesion Index (Fig. 3B) and closed forest for Effective Mesh Size (Fig. 3D). Although the high BAU Patch Cohesion Index value for the urban/amenities class is likely because this scenario exhibited substantially greater increase in the area of this class, as compared to the normative scenarios, hence it is more likely that patches of greater size would be formed. This highlights the need for caution when using landscape pattern metrics at the landscape scale to compare scenarios with different LULCC rates as the values may be biased due to strong differences in single classes.

Table 2 presents several metrics (“Spatial analysis” section) to analyze scenario-specific regionalized LULCC trends (“Spatial interventions in transition potential and allocation parameters” section). The three normative scenarios all contained the statement “No further urban sprawl” which is juxtaposed by the statement “Increase in buildings outside the construction zone, Industrial areas develop in an uncoordinated manner” in the GR-EX scenario. While these statements are subjective, Table 2 shows that the interventions intended to operationalize them in the simulations had the intended effect as the normative scenarios show a substantially greater value of relative urban change inside the current designated building zones (ARE 2022) compared to both the BAU and GR-EX scenarios.

Furthermore, EI-CUL specified a trend of “Revival of settlements in remote rural areas”. Looking at the relative urban change value for rural municipalities alone would suggest that this does not appear to have been realized as EI-CUL exhibited the smallest increase in comparison to the other scenarios. However, the value of change in urban patches provides evidence to the contrary. While all scenarios indicated a negative value of change in urban patches in rural municipalities (i.e. fewer patches in 2060 than in 2020), this is somewhat misleading given that some patches in the

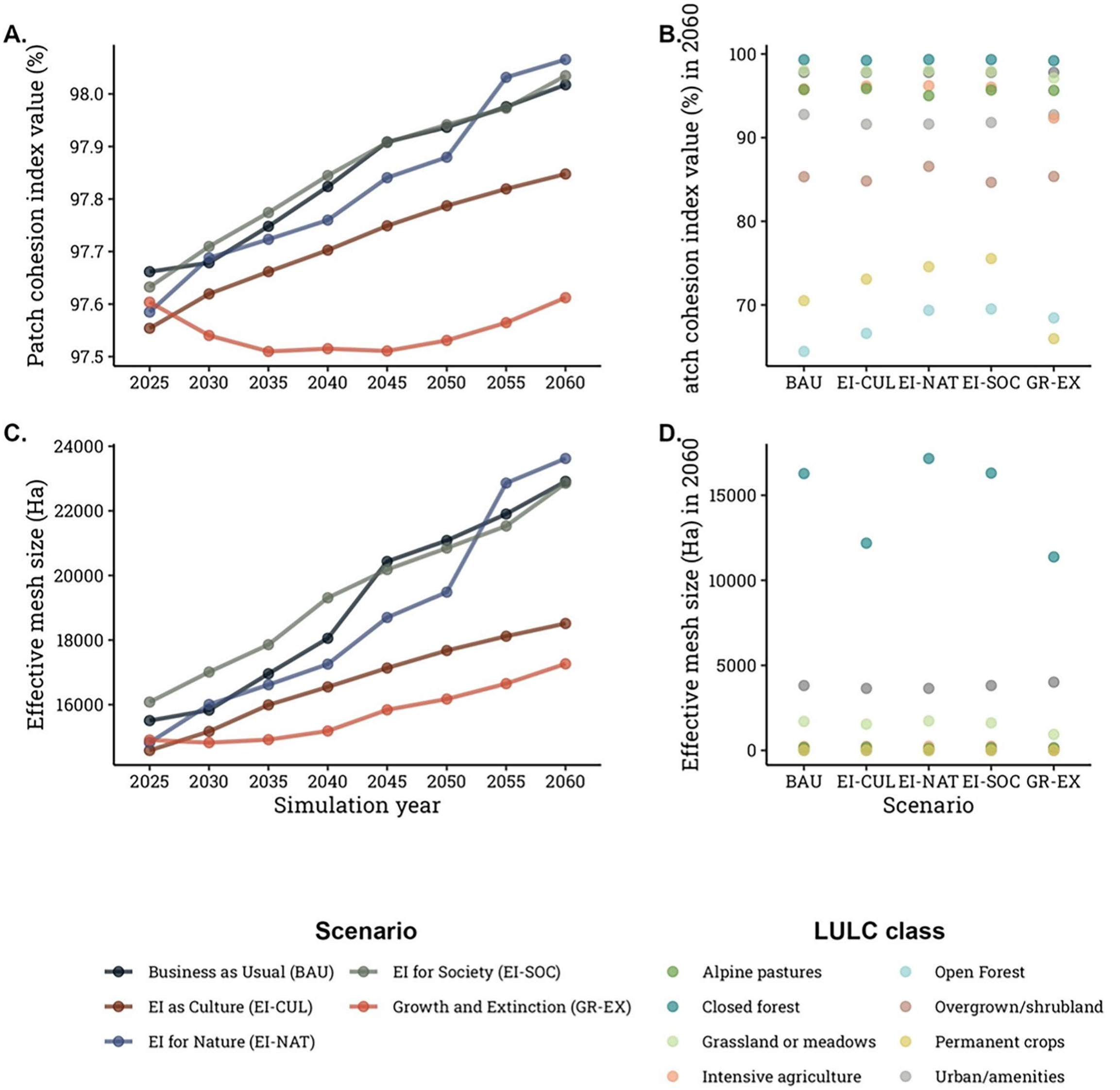

Fig. 3 Plots of differences in landscape metric values between scenarios at both the landscape and class scale: Patch Cohesion Index (landscape: **A**, class: **B**); Effective Mesh Size (landscape: **C**, class: **D**)

2060 map will be new and others will represent the amalgamation of multiple patches from 2020. On this basis, the fact that EI-CUL exhibits the smallest (relative) decrease in patch number, combined with a value of urban area change, which is similar to the other scenarios, should correspond to a greater proportion of the remaining patches in 2060 being new patches. This would suggest that the scenario trend of revival of settlements in rural areas has been at least partly achieved despite the fact that some urban areas have disappeared. Similarly, EI-NAT and EI-SOC both included the statement: "Development of small towns in mountain areas". However, the values of relative urban change and change in urban patches in mountainous areas for these scenarios (Table 2) imply that this trend has not been achieved as both sets of values are lower than for EI-CUL.

The trend of the expansion of PAs was implemented differently under each normative scenario according to the details in the narratives regarding their extent, siting and proposed management (ESM J.1). Thus, to identify differences between the normative scenarios, it is necessary to utilize comparisons to the BAU and GR-EX scenarios as neither involved changes in PAs. In this regard, Table 2 shows that the expansion of PAs under each of the normative scenarios led to substantially lower values of relative urban change, alongside higher values of change in natural LULC class cohesion in PAs as compared to the BAU and GR-EX scenarios. Both of these results are positive in terms of the normative priorities and goals for PA expansion expressed in the scenario narratives, namely biodiversity protection (EI-NAT), NCP provision (EI-SOC) and cultural heritage

Table 2 Measures of LULC change trends between 2020 and 2060, in spatial regions, across scenarios

Spatial trend in region	EI-NAT	EI-SOC	EI-CUL	BAU	GR-EX
Building zones					
Relative urban change*	39.83%	38.58%	40.75%	26.81%	17.36%
Change in urban patches†	−4.86%	−5.54%	−4.28%	−7.36%	−6.57%
Rural municipalities					
Relative urban change	14.85%	14.43%	13.77%	14.25%	15.59%
Change in urban patches	−4.18%	−5.54%	−2.54%	−8.54%	−6.04%
Mountainous municipalities					
Relative urban change	3.56%	3.64%	3.79%	5.98%	6.2%
Change in urban patches	−6.16%	−8.85%	−5.85%	−20.71%	−19.55%
Protected areas					
Relative urban change	4.78%	0.08%	14.99%	-	-
Relative urban change	26.6%	24.92%	25.78%	-	-
Relative urban change	28.51%	27.14%	27.85%	-	-
Change in natural LULC class cohesion‡ under scenario	2.75%	2.11%	1.87%	-	-
Change in natural LULC class cohesion under BAU	1%	0.64%	1.09%	-	-
Change in natural LULC class cohesion under GR-EX	0.01%	−0.27%	0.16%	-	-

There are no spatial trend values for BAU and GR-EX under protected areas because neither scenario involved interventions in this region and hence the PA maps from the other scenarios were retrospectively applied for comparison

Symbols: *% area change in Urban/amenities class between 2020 and 2060 in region relative to the change in the entire study area; †% difference in the number of patches of urban/amenities class in 2060 vs. 2020; ‡Mean difference in cohesion index value between 2020 and 2060 in region for LULC classes: open forest, closed forest, grassland or meadows, overgrown/shrubland, alpine pastures, and intensive agriculture

protection (EI-CUL) (ESM J.1). The former result, equating to the restriction of urban area increase inside PAs, is desirable as the potential negative impacts of urbanization on biodiversity and NCPs is well-acknowledged (Elmqvist et al. 2013). Vice versa, the corresponding increase in the connectivity of the natural and semi-natural LULC classes is typically beneficial for biodiversity and ecosystem services.

When comparing the scenarios, it is notable that the EI-SOC scenario resulted in considerably less relative urban change in PAs than the other normative scenarios (EI-NAT, EI-CUL). A possible explanation for this is that the PA areas chosen for EI-SOC are synergistic with other spatial interventions affecting urban development (e.g. the urban migration intervention: ESM Table 8) or that they overlap with a greater proportion of land inherently unsuitable for urbanization as compared to the PAs under the other scenarios. If one of the intentions of establishing additional PAs, as part of Switzerland's EI, is indeed to limit the impact of urbanization, then this finding suggests that selecting sites by also considering their value for the provision of NCPs could lead to better results than focusing on biodiversity value alone.

In summary, the fact that the simulation results show a concurrence with the scenario narratives with respect to the majority of the spatial trends suggests that they should be seen as generally credible representations of the scenarios, although it is still important to reflect upon what maybe causing the discrepancies between the narratives and the simulation results for the trends that did not align. Specifically, it should be considered whether these discrepancies are caused by deficiencies in the model (i.e. a trend not being implemented correctly), or whether they are in fact due to conflicting or contradictory trends in the scenario narratives (i.e. the effect is being "over-ridden" by more dominant trends in the model). In this regard, these points of difference in the simulation results are useful in prompting discussions with those involved in the scenario creation process to re-evaluate the coherency of the narratives and inform iterative refinements.

Expert feedback

The expert feedback activity achieved mixed results in terms of its intended purpose but nevertheless generated useful insights. On the one hand, the general feedback was positive, with participants noting that the web platform was helpful for interacting with the results without the need for specialist software experience. Furthermore, one respondent from the Federal Office for the Environment (responsible for coordinating Switzerland's EI planning at the national level) stated that: "I think they *[the simulation results]* could be extremely useful as a basis for a dialogue on the desirability of different land use scenarios".

However, on the other hand, few participants provided detailed answers in response to the specific feedback questions intended to validate the simulation results in light of the scenario narratives. Instead, many used the feedback to raise additional questions of understanding or to request further information on the underlying data and assumptions. Also, there was a tendency for participants to highlight what they perceived as inconsistencies in the occurrence of specific land uses in precise locations. This was likely exacerbated by the fact that participants were system experts with personal knowledge of specific locations, and further enabled by the fact that they were able to zoom down to the pixel level on the maps.

Collectively, these observations highlight that it was difficult for participants to engage with the results with respect to the intended purpose of discussing the coherency of broad, landscape scale, patterns of change exhibited across the scenarios. This is obviously no fault of the participants rather it should encourage reflection upon how the method of presenting the information to them could be improved. When developing the web platform used for feedback, considerable effort was spent in selecting the methods to present the simulation results and we settled on using a diversity of approaches including maps of both LULC in 2020 and 2060, "firefly" maps highlighting areas of change for each LULC class (see ESM L for examples), maps of protected area development, bar charts and Sankey diagrams. The fact that these approaches were not as successful as hoped is testament to the difficulty of capturing the complexity of the multi-faceted nature of LULCC. Indeed, we observed that even measures intended to summarize LULCC trends, such as landscape metrics, are difficult to interpret when comparing scenarios with different rates of change ("Realization of scenario-specific spatial trends" section). This suggests that if LULCC simulations are indeed to be used as a basis for dialogue on the desirability of different scenarios, then further work is needed to develop methods to present the results in a way that is more easily interpretable. In the "Challenges and opportunities in normative scenario modelling" section, we discuss some potential solutions for this as well as other opportunities to improve the utility of simulation modelling as part of the normative scenario development process.

Challenges and opportunities in normative scenario modelling

As mentioned in the "Introduction" section, there are relatively few examples of studies realizing normative scenarios in LULCC simulations. As such, we feel it is pertinent to offer reflections upon our experiences, specifically regarding incorporating participation in the scenario quantification process and eliciting feedback and discussion of the simulation results, in the hope that further research can build upon these areas.

The contribution of experts in devising the future LULC transition rates (ESM I) was crucial to the quantification of the scenarios as the alternative would have been to estimate future rates from additional mechanistic or numerical models (Luo et al. 2022) which add additional complexity and intransparency to the modelling procedure. Nonetheless, using expert elicitation to derive transition rates was challenging due to the relatively large number of transitions to be modelled. This prompted the decision to reduce the scope to focusing on overall LULC class changes; however, this created difficulties when it came to disaggregating these outputs back to rates for individual transitions. Similar difficulties in this process have been noted in other studies (Mallampalli et al. 2016; Karner et al. 2019) and in our case, this was validated by the fact that several respondents in the subsequent expert feedback noted that they did not necessarily find the rates of change of certain LULC classes realistic. A possible improvement to this process would be to use expert elicited values as a base point from which to sample a range of transition rate values and use these to perform repeated simulations under each scenario resulting in a spread, or ensemble, of future LULCC projections. This could be combined with permutations of other aspects of the model, such as the temporality and intensity of the spatial interventions, as well as the addition of other system "shocks" (e.g. extreme climatic events affecting land cover). Such an ensemble simulation approach could provide stakeholders with better insights into the plausibility of the scenarios but also the impacts of deliberate and uncontrolled changes to aspects of the system and the implications of these for the scenario outcomes (Uusitalo et al. 2015; Verkerk et al. 2018).

The main lesson learnt with regard to using simulation results as a boundary object to discuss the coherency and desirability of scenarios is that the resolution at which the results are formulated must be suited to the purpose of the scenarios. The scenarios utilized in this research were intended to serve a more strategic purpose by highlighting the broad implications of societal developments and policies on landscape change in Switzerland, rather than an operational purpose of highlighting exactly which areas should be prioritized for policy interventions (Tira et al. 2011). In this sense, we found that presenting the results as high-resolution, user-controllable, maps was not the best approach for this goal. Instead, more emphasis should be placed upon developing creative measures to summarize the results in a manner that is both interpretable and allows for easier objective evaluation. Given that the scenarios of our study are ultimately focused around the maintenance of biodiversity and ecosystem service provision, using output measures based on these, such as the landscapes' ability to provide clean water, or the extent to which it supports pollinators, would likely have been more effective than measures of LULCC. This consideration is particularly pertinent if the discussion of the desirability of scenarios is to be broadened to a wider audience beyond just experts. It is also a practical choice given that LULC is commonly a factor underpinning the quantification of ecosystem services (Burkhard et al. 2009; Newbold et al. 2015; Gerecke et al. 2019; Gomes et al. 2021). In addition to this, Dou et al. (2023) note the importance of focusing on highlighting areas of similarities across scenarios. In the case of this study, this would involve identifying areas of the landscape which exhibit desirable characteristics under all of the normative scenarios, thereby serving as a point of cohesion between the different value perspectives and reconciling the interests of different actors which has been identified as being a prominent challenge to the implementation of EI in Switzerland (Wicki et al. 2023).

Overall, this research has demonstrated that the most challenging aspect of realizing normative scenarios of SES development, such as those devised using frameworks like the IPBES-NFF, within quantitative simulation models is not the technical implementation, as this can be achieved through considered use of existing methods such as the LULCC-CCA created for this study. Rather, the challenge is for modellers to think critically about how to better present the results of their models such that outcomes and features of the scenarios can be interpreted and discussed by diverse audiences.

Conclusions

The importance of increasing the prevalence of explicitly normative future scenarios within the field of landscape research is clear as they create the ground to consider different worldviews and thus negotiate value systems (Pascual et al. 2023) as well as explore solutions. The LULCC simulations of this study will hopefully highlight to decision-makers the opportunities, as well as potential conflicts, that may occur under the different scenarios of the development of a national Ecological Infrastructure in Switzerland. Beyond these results, this research has sought to demonstrate a replicable approach to operationalizing and modelling normative scenarios of landscape change. While the modelling technique employed, constrained cellular automata is not novel, the extent and depth to which the different aspects of scenarios were realized represent an innovative contribution to the field. Notably, these aspects included iterative expert participation in deriving model inputs, the linkage of local and global scale phenomena, and the combination of machine learning and process-based models for multi-regional spatial prediction of LULCC. Furthermore, the fact that the model and data have been made publicly available allows others to build on the methodology in line with the suggested improvements, namely to understand how simulation results can be made more interpretable to a broader range of stakeholders, to better facilitate discussions of the desirability of scenario outcomes and ultimately promote stewardship.

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Data availability In the interest of open science, the LULCC-CCA model (https://zenodo.org/doi/10.5281/zenodo.12698470) along with the research data (https://doi.org/10.5281/zenodo.8263509) have been made available alongside this manuscript.

References

Aburas MM, Ho YM, Ramli MF, Ash'aari ZH (2016) The simulation and prediction of spatio-temporal urban growth trends using cellular automata models: a review. Int J Appl Earth Obs Geoinformation 52:380–389. https://doi.org/10.1016/j.jag.2016.07.007

Adde A, Rey PL, Fopp F, Petitpierre B, Schweiger AK et al (2023) Too many candidates: embedded covariate selection procedure for species distribution modelling with the covsel r package. Ecol Inform 75:102080. https://doi.org/10.1016/j.ecoinf.2023.102080

Bauer N, Wallner A, Hunziker M (2009) The change of European landscapes: human-nature relationships, public attitudes towards rewilding, and the implications for landscape management in Switzerland. J Environ Manag 90:2910–2920. https://doi.org/10.1016/j.jenvman.2008.01.021

Bennett EM, Solan M, Biggs R, McPhearson T, Norström AV et al (2016) Bright spots: seeds of a good Anthropocene. Front Ecol Environ 14:441–448. https://doi.org/10.1002/fee.1309

Black B, Strien MJV, Adde A, Grêt-Regamey A (2023) Re-considering the status quo: improving calibration of land use change models through validation of transition potential predictions. Environ Model Softw 159:105574. https://doi.org/10.1016/j.envsoft.2022.105574

Bosson JB, Huss M, Cauvy-Fraunié S, Clément JC, Costes G et al (2023) Future emergence of new ecosystems caused by glacial retreat. Nature 620:562–569. https://doi.org/10.1038/s41586-023-06302-2

Breiman L (2001) Random forests. Mach Learn 45:5–32. https://doi.org/10.1023/A:1010933404324

Broennimann O, Guisan A (2024) CHclim25 - a spatially and temporally very high-resolution climatic dataset for Switzerland. Earth Syst Sci Data Discuss 1–13. https://doi.org/10.5194/essd-2024-79

Brown C, Seo B, Alexander P, Burton V, Chacón-Montalván EA et al (2022) Agent-based modeling of alternative futures in the British land use system. Earth's Future 10(11):e2022EF002905. https://doi.org/10.1029/2022EF002905

Burkhard B, Kroll F, Müller F, Windhorst W (2009) Landscapes' capacities to provide ecosystem services - a concept for land-cover based assessments. Landsc Online 15–15. https://doi.org/10.3097/LO.200915

Castella JC, Bourgoin J, Lestrelin G, Bouahom B (2014) A model of the science– practice–policy interface in participatory land-use planning: lessons from Laos. Landscape Ecol 29:1095–1107. https://doi.org/10.1007/s10980-014-0043-x

Cheng LL, Liu M, Zhan JQ (2020) Land use scenario simulation of mountainous districts based on Dinamica ego model. J Mt Sci 17:289–303. https://doi.org/10.1007/s11629-019-5491-y

Clerici N, Cote-Navarro F, Escobedo FJ, Rubiano K, Villegas JC (2019) Spatio-temporal and cumulative effects of land use-land cover and climate change on two ecosystem services in the Colombian Andes. Sci Total Environ 685:1181–1192. https://doi.org/10.1016/j.scitotenv.2019.06.275

Cretegny L, Müller A (2020) Scénarios par branche 2060 et leur régionalisation. Technical Report for the Swiss Federal Office for Spatial Development (ARE) Federal Office of Energy (FOE) State Secretariat for Economic Affairs (SECO). https://www.bk.admin.ch/dam/bk/de/dokumente/strategische-fuehrungsunterstuetzung/Wirtschaftsszenarien/branchenszenarien-2017-bis-2060.pdf.download.pdf/Branchenszenarien%202017%20bis%202060.pdf

Daneshi A, Brouwer R, Najafinejad A, Panahi M, Zarandian A et al (2021) Modelling the impacts of climate and land use change on water security in a semi-arid forested watershed using invest. J Hydrol 593:125621. https://doi.org/10.1016/j.jhydrol.2020.125621

Dou Y, Zagaria C, O'Connor L, Thuiller W, Verburg PH (2023) Using the nature futures framework as a lens for developing plural land use scenarios for europe for 2050. Glob Environ Chang 83:102766. https://doi.org/10.1016/j.gloenvcha.2023.102766

Durán A, Kuiper JJ, Aguiar APD, Cheung WWL, Diaw M et al (2023) Bringing the nature futures framework to life: creating a set of illustrative narratives of nature futures. Sustain Sci. https://doi.org/10.1007/s11625-023-01316-1

Elmqvist T, Fragkias M, Goodness J, Güneralp B, Marcotullio PJ et al (eds) (2013) Urbanization, biodiversity and ecosystem services: challenges and opportunities. Springer, Netherlands, Dordrecht. https://doi.org/10.1007/978-94-007-7088-1

Farinotti D, Round V, Huss M, Compagno L, Zekollari H (2019) Large hydropower and water-storage potential in future glacier-free basins. Nature 575:341–344. https://doi.org/10.1038/s41586-019-1740-z

Frank F, Volante J, Calamari N, Peri PL, González Chávez B et al (2023) A multi-model approach to explore sustainable food and land use pathways for Argentina. Sustain Sci 18:347–369. https://doi.org/10.1007/s11625-022-01245-5

Gago-Silva A, Ray N, Lehmann A (2017) Spatial dynamic modelling of future scenarios of land use change in Vaud and Valais, Western Switzerland. ISPRS Int J Geo-Inf 6(4):115. https://doi.org/10.3390/ijgi6040115

García-Álvarez D (2018) The Influence of Scale in LULC Modeling. A comparison between two different LULC Maps (SIOSE and CORINE). In: Camacho Olmedo MT, Paegelow M, Mas J-F, Escobar F (eds) Geomatic approaches for modeling land change scenarios, lecture notes in geoinformation and cartography. Springer International Publishing, Cham, pp 187–213. https://doi.org/10.1007/978-3-319-60801-3_10

Gerecke M, Hagen O, Bolliger J, Hersperger AM, Kienast F et al (2019) Assessing potential landscape service trade-offs driven by urbanization in Switzerland. Palgrave Commun 5:109. https://doi.org/10.1057/s41599-019-0316-8

Gharbia SS, Alfatah SA, Gill L, Johnston P, Pilla F (2016) Land use scenarios and projections simulation using an integrated GIS cellular automata algorithms. Model Earth Syst Environ 2:151. https://doi.org/10.1007/s40808-016-0210-y

Gomes E, Inácio M, Bogdzevič K, Kalinauskas M, Karnauskaitė D et al (2021) Future scenarios impact on land use change and habitat quality in Lithuania. Environ Res 197:111101. https://doi.org/10.1016/j.envres.2021.111101

Gonseth Y, Wohlgemuth T, Sansonnens B, Buttler A (2001) Die biogeographischen Regionen der Schweiz. Bundesamt für Umwelt BAFU, Bern. https://www.bafu.admin.ch/bafu/de/home/themen/thema-landschaft/landschaft--publikationen/publikationen-landschaft/die-biogeographischen-regionen-der-schweiz.html

He C, Shi P, Chen J, Li X, Pan Y et al (2005) Developing land use scenario dynamics model by the integration of system dynamics model and cellular automata model. Sci China Ser D: Earth Sci 48:1979–1989. https://doi.org/10.1360/04yd0248

Hesselbarth MHK, Sciaini M, With KA, Wiegand K, Nowosad J (2019) Landscapemetrics: an open-source R tool to calculate landscape metrics. Ecography 42:1648–1657. https://doi.org/10.1111/ecog.04617

Hjerpe M, Linnér B (2009) Utopian and dystopian thought in climate change science and policy. Futures 41:234–245. https://doi.org/10.1016/j.futures.2008.09.007

Iwaniec DM, Cook EM, Davidson MJ, Berbés-Blázquez M, Georgescu M et al (2020) The co-production of sustainable future scenarios. Landsc Urban Plan 197:103744. https://doi.org/10.1016/j.landurbplan.2020.103744

Jaeger JA (2000) Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation. Landscape Ecol 15:115–130. https://doi.org/10.1023/A:1008129329289

Karner K, Cord AF, Hagemann N, Hernandez-Mora N, Holzkämper A et al (2019) Developing stakeholder-driven scenarios on land sharing and land sparing – insights from five European case studies. J Environ Manag 241:488–500. https://doi.org/10.1016/j.jenvman.2019.03.050

Kiziridis D, Mastrogianni A, Pleniou M, Tsiftsis S, Xystrakis F et al (2023) Simulating future land use and cover of a mediterranean mountainous area: the effect of socioeconomic demands and climatic changes. Land 12:253. https://doi.org/10.3390/land12010253

Kuiper JJ, van Wijk D, Mooij WM, Remme RP, Peterson GD et al (2022) Exploring desirable nature futures for Nationaal Park

Hollandse Duinen. Ecosyst People 18:329–347. https://doi.org/10.1080/26395916.2022.2065360

Lavorel S, Colloff MJ, Locatelli B, Gorddard R, Prober SM et al (2019) Mustering the power of ecosystems for adaptation to climate change. Environ Sci Policy 92:87–97. https://doi.org/10.1016/j.envsci.2018.11.010

Lembi RC, Cronemberger C, Picharillo C, Koffler S, Sena PHA et al (2020) Urban expansion in the Atlantic forest: applying the nature futures framework to develop a conceptual model and future scenarios. Biota Neotropica 20:e20190904. https://doi.org/10.1590/1676-0611-BN-2019-0904

Liao J, Tang L, Shao G (2023) Coupling random forest, allometric scaling, and cellular automata to predict the evolution of LULC under various shared socioeconomic pathways. Remote Sens 15(8):2142. https://doi.org/10.3390/rs15082142

Liaw A, Wiener M (2022) randomForest: Breiman and Cutler's random forests for classification and regression. https://CRAN.R-project.org/package=randomForest. https://doi.org/10.1023/A:1010933404324

Luederitz C, Abson DJ, Audet R, Lang DJ (2017) Many pathways toward sustainability: not conflict but co-learning between transition narratives. Sustain Sci 12:393–407. https://doi.org/10.1007/s11625-016-0414-0

Luo M, Hu G, Chen G, Liu X, Hou H et al (2022) 1 km land use/land cover change of China under comprehensive socioeconomic and climate scenarios for 2020– 2100. Sci Data 9:110. https://doi.org/10.1038/s41597-022-01204-w

Mahmood R, Pielke RA Sr, Hubbard KG, Niyogi D, Dirmeyer PA et al (2014) Land cover changes and their biogeophysical effects on climate. Int J Climatol 34:929–953. https://doi.org/10.1002/joc.3736

Mallampalli VR, Mavrommati G, Thompson J, Duveneck M, Meyer S et al (2016) Methods for translating narrative scenarios into quantitative assessments of land use change. Environ Model Softw 82:7–20. https://doi.org/10.1016/j.envsoft.2016.04.011

Mann S, Hunziker M, Torregroza L, Wartmann F, Kienast F et al (2023) Landscape quality payments in switzerland: The congruence between policy and preferences. J Policy Model 45:251–265. https://doi.org/10.1016/j.jpolmod.2023.03.007

Mas JF, Paegelow M, Camacho Olmedo MT (2018) LUCC Modeling approaches to calibration. In: Camacho Olmedo MT, Paegelow M, Mas JF, Escobar F (eds) Geomatic approaches for modeling land change scenarios, lecture notes in geoinformation and cartography. Springer International Publishing, Cham, pp 11–25. https://doi.org/10.1007/978-3-319-60801-3_2

Mather A, Fairbairn J (2000) From floods to reforestation: the forest transition in Switzerland. Environ Hist 6:399–421. https://doi.org/10.3197/096734000129342352

Mayer P, Rabe SE, Grêt-Regamey A (2023) Operationalizing the nature futures framework for ecological infrastructure. Sustain Sci. https://doi.org/10.1007/s11625-023-01380-7

McPhearson T, Iwaniec DM, Bai X (2016) Positive visions for guiding urban transformations toward sustainable futures. Curr Opin Environ Sustain 22:33–40. https://doi.org/10.1016/j.cosust.2017.04.004

Michel AH, Pleger LE, Von Atzigen A, Bosello O, Sager F et al (2022) The role of trust in the participatory establishment of protected areas—lessons learnt from a failed national park project in Switzerland. Soc Nat Resour 35:487–505. https://doi.org/10.1080/08941920.2021.1994679

Molinero-Parejo R, Aguilera-Benavente F, Gómez-Delgado M, Shurupov N (2023) Combining a land parcel cellular automata (LP-CA) model with participatory approaches in the simulation of disruptive future scenarios of urban land use change. Comput Environ Urban Syst 99:101895. https://doi.org/10.1016/j.compenvurbsys.2022.101895

Molotoks A, Smith P, Dawson TP (2021) Impacts of land use, population, and climate change on global food security. Food Energy Secur 10(1):e261. https://doi.org/10.1002/fes3.261

Murray-Rust D, Rieser V, Robinson DT, Miličič V, Rounsevell M (2013) Agent-based modelling of land use dynamics and residential quality of life for future scenarios. Environ Model Softw 46:75–89. https://doi.org/10.1016/j.envsoft.2013.02.011

Nassauer J, Corry RC (2004) Using normative scenarios in landscape ecology. Landscape Ecol 19:343–356. https://doi.org/10.1023/B:LAND.0000030666.55372.ae

Newbold T, Hudson LN, Hill SLL, Contu S, Lysenko I et al (2015) Global effects of land use on local terrestrial biodiversity. Nature 520:45–50. https://doi.org/10.1038/nature14324

Ojima DS, Galvin KA, Turner BL (1994) The global impact of land-use change. BioScience 44:300–304. https://doi.org/10.2307/1312379

Pascual U, Balvanera P, Anderson CB, Chaplin-Kramer R, Christie M et al (2023) Diverse values of nature for sustainability. Nature 620:813–823. https://doi.org/10.1038/s41586-023-06406-9

Peng K, Jiang W, Ling Z, Hou P, Deng Y (2021) Evaluating the potential impacts of land use changes on ecosystem service value under multiple scenarios in support of SDG reporting: a case study of the Wuhan urban agglomeration. J Clean Prod 307:127321. https://doi.org/10.1016/j.jclepro.2021.127321

Pereira LM, Davies KK, den Belder E, Ferrier S, Karlsson-Vinkhuyzen S et al (2020) Developing multiscale and integrative nature–people scenarios using the nature futures framework. People Nat 2(4):1172–1195. https://doi.org/10.1002/pan3.10146

Poelmans L, Van Rompaey A (2010) Complexity and performance of urban expansion models. Compute Environ Urban Syst 34(1):17–27. https://doi.org/10.1016/j.compenvurbsys.2009.06.001

Price B, Kaim D, Szwagrzyk M, Ostapowicz K, Kolecka N et al (2017) Legacies, socio-economic and biophysical processes and drivers: the case of future forest cover expansion in the polish carpathians and swiss alps. Reg Environ Change 17:2279–2291. https://doi.org/10.1007/s10113-016-1079-z

Prieto-Amparán J, Villarreal-Guerrero F, Martínez-Salvador M, Manjarrez-Domínguez C, Vázquez-Quintero G et al (2019) Spatial near future modeling of land use and land cover changes in the temperate forests of Mexico. PeerJ 7:e6617. https://doi.org/10.7717/peerj.6617

Qian Y, Xing W, Guan X, Yang T, Wu H (2020) Coupling cellular automata with area partitioning and spatiotemporal convolution for dynamic land use change simulation. Sci Total Environ 722:137738. https://doi.org/10.1016/j.scitotenv.2020.137738

R core team (2022) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Ren Y, Lü Y, Comber A, Fu B, Harris P et al (2019) Spatially explicit simulation of land use/land cover changes: current coverage and future prospects. Earth-Sci Rev 190:398–415. https://doi.org/10.1016/j.earscirev.2019.01.001

Robbins P, Moore SA (2013) Ecological anxiety disorder: diagnosing the politics of the Anthropocene. cult geogr 20:3–19. https://doi.org/10.1177/1474474012469887

Rodewald R, Schwyzer Y, Liechti K (2014) Catalog of characteristic cultural landscapes of Switzerland. Swiss Foundation for Landscape Protection (SL-FP), Bern. https://www.sl-fp.ch/admin/data/files/asset/file/33/katalog_charakteristischekulturlandschaften_2014_lowres.pdf?lm=1535639708

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

Rounsevell MDA, Pedroli B, Erb KH, Gramberger M, Busck AG et al (2012) Challenges for land system science. Land Use Policy 29:899–910. https://doi.org/10.1016/j.landusepol.2012.01.007

Rykiel EJ (1996) Testing ecological models: the meaning of validation. Ecol Model 90:229–244. https://doi.org/10.1016/0304-3800(95)00152-2

Şalap-Ayça S, Jankowski P, Clarke KC, Kyriakidis PC, Nara A (2018) A metamodeling approach for spatio-temporal uncertainty and sensitivity analysis: an application for a cellular automata-based urban growth and land-use change model. Int J Geogr Inf Sci 32:637–662. https://doi.org/10.1080/13658816.2017.1406944

Schirpke U, Tscholl S, Tasser E (2020) Spatio-temporal changes in ecosystem service values: effects of land-use changes from past to future (1860–2100). J Environ Manag 272:111068. https://doi.org/10.1016/j.jenvman.2020.111068

Schumaker NH (1996) Using landscape indices to predict habitat connectivity. Ecology 77(4):1210–1225. https://doi.org/10.2307/2265590

Shrestha S, Bhatta B, Shrestha M, Shrestha PK (2018) Integrated assessment of the climate and landuse change impact on hydrology and water quality in the Songkhram River Basin, Thailand. Sci Total Environ 643:1610–1622. https://doi.org/10.1016/j.scitotenv.2018.06.306

Leite-Filho AT, Soares-Filho BS, Davis JL, Rodrigues HO (2020) Modeling environmental dynamics with Dinamica EGO. Centro de Sensoriamento Remoto. Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais. https://www.csr.ufmg.br/dinamica/dokuwiki/doku.php?id=guidebook_start

Song XD, Yang JY, Zhao MS, Zhang GL, Liu F et al (2019) Heuristic cellular automaton model for simulating soil organic carbon under land use and climate change: a case study in Eastern China. Agric Ecosyst Environ 269:156–166. https://doi.org/10.1016/j.agee.2018.09.034

Stotten R (2016) Farmers' perspectives on cultural landscapes in central Switzerland: how landscape socialization and habitus influence an aesthetic appreciation of landscape. Soc Nat Resour 29(2):166–184. https://doi.org/10.1080/08941920.2015.1058995

Swiss Federal Office for the Environment (FOEN) (2012) Swiss Biodiversity Strategy. Technical Report. Bern. https://www.bafu.admin.ch/bafu/en/home/topics/biodiversity/publications-studies/publications/swiss-biodiversity-strategy.html

Swiss Federal Office for Spatial Development (ARE) (2022) Swiss building zones harmonized geodata. https://www.kgk-cgc.ch/geodaten/geodaten-bauzonen-schweiz

Swiss Federal Office for Statistics (SFSO) (2020) Scenarios for population development in Switzerland and the cantons 2020–2050. Technical Report. SFSO, Neuchâtel. https://dam-api.bfs.admin.ch/hub/api/dam/assets/14963221/master

Swiss Federal Office for Statistics (SFSO) (2021) Areal statistics according to nomenclature 2004, surveys 1979–1985, 1992–1997, 2004–2009, 2013–2018. SFSO, Neuchâtel. https://www.bfs.admin.ch/bfs/de/home/dienstleistungen/geostat/geodaten-bundesstatistik/boden-nutzung-bedeckung-eignung/arealstatistik-schweiz.assetdetail.20104753.html

Swiss Federal Statistical Office (SFSO) (2018) Arealstatistik Standard (NOAS04). SFSO, Neuchâtel. https://www.bfs.admin.ch/bfs/de/home/statistiken/raum-umwelt/nomenklaturen/arealstatistik/noas2004.assetdetail.6948898.html

Thompson JR, Plisinski JS, Lambert KF, Duveneck MJ, Morreale L et al (2020) Spatial simulation of codesigned land cover change scenarios in New England: alternative futures and their consequences for conservation priorities. Earth's Future 8:e2019EF001348. https://doi.org/10.1029/2019EF001348

Tira M, Krabben Evd, Zanon B (2011) Land management for urban dynamics: innovative methods and practices in a changing Europe. Maggioli Editore, Santarcangelo di Romagna. https://www.cost.eu/publication/land-management-for-urban-dynamics-innovative-methods-and-practices-in-a-changing-europe/

Tobler WR (1979) Cellular geography. Springer Netherlands, Dordrecht, pp 379–386. https://doi.org/10.1007/978-94-009-9394-5_18

Tong X, Feng Y (2020) A review of assessment methods for cellular automata models of land-use change and urban growth. Int J Geogr Inf Sci 34(5):866–898. https://doi.org/10.1080/13658816.2019.1684499

Triantakonstantis D, Mountrakis G (2012) Urban growth prediction: a review of computational models and human perceptions. J Geogr Inf Syst 4(6):555–587. https://doi.org/10.4236/jgis.2012.46060

Troupin D, Carmel Y (2016) Landscape patterns of development under two alternative scenarios: implications for conservation. Land Use Policy 54:221–234. https://doi.org/10.1016/j.landusepol.2016.02.008

Uusitalo L, Lehikoinen A, Helle I, Myrberg K (2015) An overview of methods to evaluate uncertainty of deterministic models in decision support. Environ Model Softw 63:24–31. https://doi.org/10.1016/j.envsoft.2014.09.017

Vannier C, Bierry A, Longaretti PY, Nettier B, Cordonnier T et al (2019) Co-constructing future land-use scenarios for the Grenoble region, France. Landsc Urban Plan 190:103614. https://doi.org/10.1016/j.landurbplan.2019.103614

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

Verburg PH, Kok K, Pontius RG, Veldkamp A (2006) Modeling land-use and land-cover change. In: Lambin EF, Geist H (eds) Land-use and land-cover change: Local Processes and Global Impacts, Global Change - The IGBP Series. Springer, Berlin, Heidelberg, pp 117–135. https://doi.org/10.1007/3-540-32202-7_5

Verburg PH, Alexander P, Evans T, Magliocca NR, Malek Z et al (2019) Beyond land cover change: towards a new generation of land use models. Curr Opin Environ Sustain 38:77–85. https://doi.org/10.1016/j.cosust.2019.05.002

Verkerk PJ, Lindner M, Pérez-Soba M, Paterson JS, Helming J et al (2018) Identifying pathways to visions of future land use in Europe. Reg Environ Change 18:817–830. https://doi.org/10.1007/s10113-016-1055-7

Volkery A, Ribeiro T, Henrichs T, Hoogeveen Y (2008) Your vision or my model? Lessons from participatory land use scenario development on a European scale. Syst Pract Action Res 21:459–477. https://doi.org/10.1007/s11213-008-9104-x

Wartmann FM, Frick J, Kienast F, Hunziker M (2021) Factors influencing visual landscape quality perceived by the public. Results from a national survey. Landsc Urban Plan 208:104024. https://doi.org/10.1016/j.landurbplan.2020.104024

White R, Engelen G (1997) Cellular automata as the basis of integrated dynamic regional modelling. Environ Plan B: Plan Des 24(2):235–246. https://doi.org/10.1068/b240235

Whyte KP (2018) Indigenous science (fiction) for the Anthropocene: ancestral dystopias and fantasies of climate change crises. Environ Plan E: Nat Space 1:224–242. https://doi.org/10.1177/2514848618777621. publisher: SAGE Publications Ltd STM

Wicki S, Black B, Kurmann M, Grêt-Regamey A (2023) Archetypes of social-ecological-technological systems for managing ecological infrastructure. Environ Res Lett 19(1):014038. https://doi.org/10.1088/1748-9326/ad1080

Wiek A, Iwaniec D (2014) Quality criteria for visions and visioning in sustainability science. Sustain Sci 9:497–512. https://doi.org/10.1007/s11625-013-0208-6

Wolff S, Schrammeijer EA, Schulp CJE, Verburg PH (2018) Meeting global land restoration and protection targets: what would the world look like in 2050? Glob Environ Chang 52:259–272. https://doi.org/10.1016/j.gloenvcha.2018.08.002

Wu Y, Tao Y, Yang G, Ou W, Pueppke S et al (2019) Impact of land use change on multiple ecosystem services in the rapidly urbanizing Kunshan City of China: past trajectories and future projections. Land Use Policy 85:419–427. https://doi.org/10.1016/j.landusepol.2019.04.022

Zekollari H, Huss M, Farinotti D (2019) Modelling the future evolution of glaciers in the European alps under the EURO-CORDEX RCM ensemble. Cryosphere 13(4):1125–1146. https://doi.org/10.5194/tc-13-1125-2019

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