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ABSTRACT Landscapes have been changing at an increasing pace over the past century, with countless consequences for humans and their surrounding environments. Information on past and future land use change and the resulting alteration of landscape service provisioning are valuable inputs for policy making and planning. Land use transitions in Switzerland (2009–2081) were simulated using statistical models informed by past land use changes as well as environmental and socio-economic data (1979–2009). By combining land use types with additional contextual landscape information, eight landscape services, based on both (semi-)natural and artificial landscapes, were quantified and investigated on how they would evolve under projected land use changes. Investigation of land use transitions showed region-dependent trends of urban expansion, loss of agricultural area, and forest regrowth. Land-scapes cannot accommodate all services simultaneously, and this study sheds light on some competing landscape services, in particular (i) housing at the expense of agriculture and (ii) vanishing recreation opportunities around cities as city limits, and thus housing and job provisioning, expand. Model projections made it possible to pinpoint potential trade-offs between landscape services in a spatially explicit manner, thereby providing information on service provision losses and supporting planning. While future changes are presented as extrapolations of the patterns quantified in the past, policy changes might cause deviation from the projections presented here. A major challenge is to produce socio-economic and policy scenarios to inform projections that will differ from current landscape management. Given that urban sprawl is affecting many land surfaces globally, the approach used here could be generalized to other countries in similar situations.

Introduction

Global landscapes have been changing at an accelerating pace over the last decades, potentially threatening both the natural environment and human well-being (Vitousek et al., 1997; Foley et al., 2005; Turner et al., 2007; Lambin and Meyfroidt, 2011; Mahmood et al., 2014). Such land use changes have reshaped—and will continue to reshape—semi-natural and artificial environments occupied by the human population (Vitousek et al., 1997; Sala et al., 2000; MEA, 2005). Changes in the use of landscapes are generally driven by the growing demands for natural resources in a developing human society to foster an increase in standard of living for growing populations (Foley et al., 2005, Cumming et al., 2014). Quantifying the drivers underlying observed landscape transformations may provide a better understanding of the consequences of human activities for future landscapes (Rutherford et al., 2007; Pazúr and Bolliger, 2017). Furthermore, knowledge of the drivers of past land use change makes it possible to project potential future land use through land change models (Verburg, 2006; Verburg and Overmars, 2009). Models quantifying statistical relationships between landscape variables and land use change make it possible to project expected shifts in the provision of services within future landscapes (Pellissier et al., 2013). Model projections can be used to inform management, which can then potentially buffer adverse effects of change through appropriate mitigating policies (Lawler et al., 2014).

Abundant and detailed information on past land use exists for many countries and documents general past trends. For instance, recent land use change in the European Union has been dominated by urban growth and by agricultural land abandonment followed by spontaneous reforestation, to the detriment of cropland and grasslands, thus translating into the loss of agricultural production (Falcucci et al., 2007; Maes et al., 2015). Statistical analyses enable investigation of the underlying drivers of past land change trends (Verburg, 2006; Brown et al., 2013). Rutherford et al. (2007) documented a link between climatic factors and accessibility and the probability of transitions from managed grassland to forests in Switzerland, while Verburg et al. (2004) showed that land use changes in the Netherlands were best explained by variables representing accessibility and spatial policies. Furthermore, land use change models make it possible to project future landscape arrangements under specified scenarios of changes (Sterk et al., 2011; Brown et al., 2013; Pellissier et al., 2013; van Vliet et al., 2016; Pazúr and Bolliger, 2017). Hence, with a single analysis, one can couple the two purposes of land use change models, explanation and projection (Brown et al., 2013; Pazúr and Bolliger, 2017). For example, Lawler et al. (2014) and Price et al. (2015) projected rapid urban growth and the loss of agricultural land for the United States and Switzerland, respectively, unless appropriate shifts in management policy are applied. The spatial nature of land use change models facilitates mapping of where future changes are expected to happen, which can guide regional decision making (Lawler et al., 2014; Price et al., 2015).

The concept of ecosystem services (ESS) arose to assign values in terms of societal gains to natural systems that are not directly captured by market prices (Kareiva, 2011), while enabling the quantification of past and future landscape changes consequences on human well-being, such as material needs, social relations and security (MEA, 2005; Kienast et al., 2009; Bürgi et al., 2015). According to the most recent classification system (CICES 5.1, www.cices.eu), ESS include a wide array of services associated with economic values (Lawler et al., 2014), as well as cultural and regulatory services whose values have to be estimated with non-direct valuation methods, i.e., willingness to pay or contingent analysis. Nevertheless, the concept of ESS has not fully supported decision making and management as expected (Wallace, 2007; de Groot et al., 2010; Bennett et al., 2015; Boerema et al., 2017), possibly because the concept does not appeal to non-ecologists and does not encompass services directly related to artificial systems (Termorshuizen and Opdam, 2009). *Landscape services* (LSS) has been suggested as an alternative term to quantify services from both semi-natural and artificial environments within landscapes and express the idea that many ESS cannot be enjoyed at the plot level but rather in the context of neighboring plots, i.e., the landscape scale (Termorshuizen and Opdam, 2009; Gulickx et al., 2013; Vallés-Planells et al., 2014; Kienast et al., 2017). Most ESS/LSS assessment studies conducted so far (e.g., Kienast et al., 2009; Nelson et al., 2009; Lawler et al., 2014) have neglected services provided by artificial environments such as built-up areas including living and work spaces and transportation infrastructure. While trade-offs exist within traditional ESS (Haines-Young et al., 2012; Forsius et al., 2013; Kandziora et al., 2013; Früh-Müller et al., 2016), they are more prevalent between services from natural and built-up landscapes (De Groot, 2006; von der Dunk, 2011; Huber et al., 2017). Furthermore, Cumming et al. (2014) stated that the provision of services from non natural landscapes often depend on the state of traditional ESS and thus the two services are more connected than often perceived. Our aim was to broaden the understanding of perspective on the provisioning of services by analyzing the two types of services simultaneously. Thus, we use the term LSS instead of ESS to emphasis the considered combination of services from natural, semi-natural, and artificial landscapes.

Combining land use data with context information to quantify services improves the quality of service estimates and enables better assessments of trade-offs between the classical services sensu CICES 5.1 (Bolliger et al., 2007, 2008a, 2011; Steck et al., 2007; Lütolf et al., 2009; Maggini et al., 2014). Simple approaches use look-up tables to link habitat or land use with a specific service. Such look-up tables can either be binary (Kienast et al., 2009; Grêt-Regamey et al., 2012; Huber et al., 2017) or use scaled values (Burkhard et al., 2012; Potschin and Haines-Young, 2013; Sohel Mukul and Burkhard, 2015). An approach that includes additional indicators (e.g., site conditions or socio-economic factors) better captures existing differences between sites compared with look-up tables (Kareiva, 2011). For instance, Chan et al. (2006) investigated opportunities and conflicts between biodiversity conservation and six other ESS. The appropriate approach for assessing ESS depends on the time and data available, as well as the scale and goal of a given study (Kareiva, 2011). ESS assessments are usually trade-offs between accuracy and time invested. Quick links between land use and provided services based on expert knowledge (e.g., Kienast et al., 2009; Helfenstein and Kienast, 2014) provide a good overview assessment, which could and should be improved by including actual indicator data (Burkhard et al., 2012). Complementing links based on land use with more static environmental parameters can improve the accuracy of the links (Chan et al., 2006; Kienast et al., 2009; Gulickx et al., 2013). However, the data necessary for that step are often not available at an appropriate spatial resolution (Burkhard et al., 2012; Gulickx et al., 2013). When analyzing spatial and temporal developments in a LSS based on land use change, it is important to keep in mind that the relationship between a land use type and its provision of a certain service is not necessarily linear (Grêt-Regamey et al., 2012) and can change over time (Bürgi et al., 2015; Maes et al., 2015).

In this study, we use statistical models to quantify the main trends of land use change in Switzerland and forecast the consequences of future changes on LSS. Over the last decades, settlement areas have encroached on agricultural land in the Swiss lowlands, while forests have expanded in the Swiss alpine regions

because of agricultural abandonment (Price et al., 2015). Land use change in Switzerland is under the influence of a set of drivers that can be grouped into five categories: (i) natural/spatial, (ii) technological, (iii) cultural, (iv) political, and (v) economic (Bürgi et al., 2004; Hersperger and Bürgi, 2009). Nevertheless, how land use change will affect future LSS provisioning in the different regions of Switzerland is still unknown, in particular because the classic quantification of services does not consider built-up areas. To provide a more comprehensive picture of how future land use change will reshape LSS provisioning, we consider a more integrative quantification of services. We combine new formulations for the quantification of LSS with land use change models and their drivers. This approach allows us to explore future consequences of land use change in Switzerland with the following expectations:

1. Land use transitions should be largely driven by the landscape state at the starting time point. Therefore, we expect that predictors describing this state, such as the distance to established urban centers or to similar land use types, primarily determine the transition locations for land development or abandonment.
2. Given the considerable heterogeneity of the Swiss landscape, the future dynamics of land use change are likely to be region-specific, with an increase in urban areas in the Swiss lowlands and a continuation of land abandonment in alpine regions.
3. Trade-offs between the LSS provisioning are likely to increase in the future, especially between those LSS based primarily on built-up areas and agricultural services.

Our analysis provides a clearer spatial picture of potential future land use changes across the Swiss landscape and the associated LSS. Linking land use change with its potential consequences provides an information basis for policy interventions (Nelson et al., 2009).

Methods

Study system. We quantified land use change using the Swiss Land Use Statistics provided by the Swiss Federal Statistical Office. The Swiss Land Use Statistics data provide land use information on a 100 m point grid over the entire extent of Switzerland (41,285 km^2), assigning one of 72 specific landscape categories to each grid point based on aerial photographs (Humbel et al., 2014). The complete Swiss Land Use Statistics data sets are available for three flying periods with a periodicity of 12 years: 1979–1985, 1992–1997, and 2004–2009. We aggregated the 72 categories as presented in Table 1.

Modeling landscape transitions. To take into account regional variation we divided the study area into the six biogeographic regions of Switzerland: Jura, Plateau, Northern Prealps, Southern Prealps, Western Central Alps and Eastern Central Alps (Gonseth et al., 2001) and used this as the basis for land use change modeling and quantification of the future LSS (Fig. S1). The biogeographic regions differ in topography, climate and historical context. We opted for a hard regionalization (i.e., region-specific regressions) over a geographically weighted regression approach because: (i) this approach facilitates comparison with other Swiss studies based on the same categories and enables regional interpretation for policy making, and (ii) we assumed that predictors of land use changes differ more between than within the regions.

We considered a set of 22 predictors for the land use change models based on previous studies (Rutherford et al., 2007;

Table 1 Conversion of the original swiss land use statistics landscape categories into land use types

Land use group	Aggregated land use type	Swiss land use statistics SLUS (2004 nomenclature)
Built-up area	Manufacturing and service infrastructure (MSI)	Industrial and commercial buildings, surroundings of industrial and commercial buildings, public buildings, surroundings of public buildings, unspecified buildings, surroundings of unspecified buildings, energy supply plants, waste water treatment plants, other supply or waste treatment plants, dumps, quarries and mines
	Few-family houses (FFH)	One-family and two-family houses, surroundings of one and two family houses, terraced houses, surroundings of terraced houses
	Multi-family houses (MFH)	Blocks of flats, surroundings of blocks of flats
Lowland agriculture	Orchards, vineyards and horticulture (OVH)	Intensive orchards, field fruit trees, vineyards, horticulture
	Arable land (AL)	Arable land
	Grasslands and meadows (G&M)	Meadows, farm pastures, brush meadows, and farm pastures
Alpine agriculture	Alpine agricultural land (AAL)	Alpine meadows, favorable alpine pastures, rocky alpine pastures, brush alpine pastures, sheep pastures, unproductive grass and scrubs
Forest	Forests (FO)	Normal dense forest, forest strips, felling areas, damaged forest areas, groves and hedges, cluster of trees, cluster of trees on agricultural areas, reforestations, open forest on unproductive areas, open forest on agricultural areas, brush forest, scrub vegetation
Stable	Water	Lakes, rivers, flood protection structures, wetlands
	Mountainous area	Rocks, screes and sand, glaciers and perpetual snow
Adapted (cells assigned to dominant aggregated category in direct neighborhood)	Others	Agricultural buildings, surroundings of agricultural buildings, motorways, green motorway environs, roads and paths, green road environs, parking areas, sealed railway areas, green railway environs, airports, airfields green airport environs, construction sites, unexploited urban areas, public parks, sports facilities, golf courses, camping areas, garden allotments, cemeteries, avalanche and rockfall barriers, alpine sports facilities, landscape interventions

Some of the original categories (land use type Others) were assigned the dominant neighboring land use type to remove empty spaces, as not enough data points existed to model them separately

Pellissier et al., 2013; Price et al., 2015). This set includes the most relevant but by no means all potential predictors of land use change in Switzerland. The predictors can be grouped into five categories: twelve predictors are computed directly from the Swiss Land Use Statistics land use types (see Electronic Supplementary Material 1.1.2 (ESM 1.1.2)). Three predictors are assigned to each of the three categories topography (elevation, slope, solar radiation), socio-economics (employee density 1st economic sector, employee density 2nd and 3rd economic sectors, population change), and accessibility (public transportation accessibility, distance to major roads, distance to economic centers). We also considered one climatic predictor (mean annual temperature). For more details on the predictors, their sources, and their temporal development see ESM 1.1. Predictors were selected for each transition individually based on a literature review and logical reasoning. Within each model for individual land use transitions, predictors with high collinearity (Pearson coefficient $r > 0.7$; Dormann et al., 2013) were excluded. We considered 142 different land use change transition models (see Table S1 for details). We used generalized linear models to model the different land use transitions separately, ignoring transitions that happened on fewer than 50 pixels across the whole of Switzerland. We validated the models using an external validation: we calibrated generalized linear models with data from the first transition period of the Swiss Land Use Statistics (1985–1997) and validated them with data from the second transition period (1997–2009). We quantified the model performance using True-Skill-Statistics (Allouche et al., 2006). In addition, True-Skill-Statistics were calculated with the split-sample approach (ratio 70:30), an internal evaluation method. Models of transitions with True-Skill-Statistics < 0.15 were not considered further unless the transition was strongly involved in the past development of a regional landscape and it was reasonable to assume that it happened randomly or would have been better captured with additional unavailable predictors. To check the spatial residuals of the final models, Moran's I statistics were calculated. In addition, we calculated the adjusted deviance of bivariate models with the R package "ecospat" (Broennimann et al., 2016) to analyze the importance of the selected predictors for each transition. To calibrate the final projection models, the separate data sets from both past transitions were combined into one transition data set and considered equally, ignoring their starting time point. For rare transitions, this procedure increased the number of data points, while for frequent transitions samples of equal size were randomly selected from both past transition data sets. All calculations were conducted in R Statistical Software version 3.3.3 (R Core Team, 2013).

Projecting future changes. We projected the land use changes over Switzerland for the next six decades starting from a base map of the period 2004–2009, followed by six future 12-year time steps. For each cell, we forecasted the probability that each land use category would transition into another category using the calibrated generalized linear models. Each cell was thus attributed a set of probabilities of change into other land use types. In addition, we defined the probability that a cell would retain its land use as one minus the maximum transition probability of the cell. For each cell we sampled a single final (projected) transition (1) or stability (0) based on the vector of probabilities. We ran land use change projections separately for each biogeographic region using the regional generalized linear models. At each time step, the projected land use categories from the previous step were used to update the landscape predictors used for the next time step forecast. In order to quantify uncertainties, we ran an ensemble of 100 independent projections.

Quantification of landscape services. We calculated six LSS aligned to the definitions of CICES 5.1 (Table S2). If the required data were not available, we developed formulas adapted to our study. In addition, we considered two non-traditional LSS to expand the research field to services provided by built-up areas, i.e., housing and infrastructure. The formulas for LSS quantification were developed based on a combination of methods from the literature and the available data (Table 2). A detailed description of the calculation of each service, including how the coefficients for the look-up tables were defined, can be found in ESM 1.2. When possible, we validated the quantification of those services using independent data sets. In particular, we combined population numbers (SFSO, 2017a) and living space per person (Häne, 2014; SFSO, 2017b) to validate the quantification of housing space. The spatial quantification of jobs was validated by comparing the Swiss Land Use Statistics with the statistics of the number of people employed in the secondary and tertiary economic sectors (SFSO, 2017c). We validated the quantification of crop production with the cantonal numbers describing total agricultural production (SFSO, 2016). No comparison data were available for the other five services, and thus no validation was conducted. To analyze the development of services over time, we looked at the total value of one service across Switzerland and in each biogeographical region individually. For that, we calculated the service provisions for each cell as described in Table 2 and summed them for each region. As the regions differ significantly in total area, we divided each sum by the area of the respective region to provide an average service provisioning per hectare, which enabled comparison of future trends between the different regions.

Results
Performance and predictors. From the final set of 142 modeled transitions, 17% performed well (TSS > 0.6), while 77% performed in a range acceptable for forecasting use (0.15 < TSS < 0.60; Table S1). We found no spatial auto-correlation in the residuals of the models. The explained deviance of the predictors (D^2) was in the highest quartile of the deviance distribution (5.84–42.45) for 47% of all considered Swiss Land Use Statistics predictors and in the lowest (0–0.53) for only 7%. The climatic and accessibility predictors were prominent in the two middle quartiles, which included 59% and 57% of those predictors, respectively. Topographic and socio-economic predictors explained a smaller amount of the variance in land use transitions, with 57 and 86% of all the considered predictors in these categories falling in the two lowest quartiles of the deviance distribution. Details on the explained deviance of the predictors for individual transitions are provided in Table S1.

Past landscape transition trends. The Swiss Land Use Statistics historical records show that countrywide land use transitions of alpine agricultural land to forests was the most frequent transition in the past 24 years (between 1985 and 2009), occurring on 48,538 ha. Transitions between forests and lower elevation grasslands and meadows also occurred frequently (9727 times for forests to grasslands and 12,243 times for the reverse). Some transitions toward built-up areas were also frequent: from grasslands and meadows to few-family houses (9869 ha) or manufacturing and service infrastructure (5225 ha), and from arable land to few-family houses (4852 ha) or manufacturing and service infrastructure (5988 ha).

Trends in future landscape transitions. As expected, with a few exceptions, the trends observed in the past were projected to continue in the future. However, acceleration and deceleration of

Table 2 Description of the eight modeled landscape services and how their values were calculated for each raster cell

LSS name and description	Quantification equation	Variable description
Housing: provisioning of space for humans to live in	$\text{Housing} = 1 \times \text{FFH} + 6 \times \text{MFH}$	FFH: few-family houses MFH: multi-family houses
Jobs: places that provide jobs in the 2nd and 3rd economic sectors	$\text{Jobs} = \text{MSI}$	MSI: manufacturing and service infrastructure
Crop production: total production of plant-based agricultural products, proportional to the production costs	$\text{Crop production} = (1 \times \text{AL} + 1.04 \times \text{G\&M} + 10 \times \text{OVH}) \times \text{LW factor}$	AL: arable land G&M: grassland and meadows OVH: Orchard, vineyard and horticulture LWfactor: productivity factor based on agricultural zones in Switzerland (FOAG, 2017), Range: 0.4–1
Reared animals: distribution of land use types that can potentially host reared animals or provide fodder for them	$\text{Reared animals} = \text{G\&M} + \text{AAL}$	G&M: grassland and meadows AAL: Alpine agricultural land
Forest products: primarily provisioning of timber, but indirectly a rough indication of carbon sequestration potential	$\text{Forest products} = \text{FO} \times \text{Vol}$	FO: Forests Vol: standing volume per economic region (Abegg et al., 2014), Range: 225–465 m^3
Hazard protection by forests: protection by forests where the risk of a local natural hazard exists and any sort of infrastructure is close by; only where forests are present	$\text{Hazard protection} = \text{Hazard\_risk}$ $\times \sum_{9 \times 9\,\text{cells}} (\text{FFH} + \text{MFH} + \text{MSI} + \text{Transportation})$ $\times \sum_{5 \times 5\,\text{cells}} \text{FO}$	FFH: few-family houses MFH: multi-family houses MSI: manufacturing and service infrastructure Transportation: large transportation routes FO: forests Hazard_risk: presence of local hazard risk derived from the data of the SilvaProtect-CH Project of FOEN (Losey and Wehrli, 2013)
Biodiversity: general biodiversity, including special responsibilities for species with limited spatial distribution	$\text{Biodiversity} =$ $\sum_{9 \times 9\,\text{cells}} \begin{bmatrix} 1 \times (\text{MSI} + \text{FFH} + \text{MFH} + \text{AL}) \\ +2 \times \text{OVH} + 3 \times \text{AAL} \\ +3 \times (\text{G\&M} \cap \text{TWW}) \\ +1 \times (\text{G\&M} \backslash \text{TWW} \times \text{Slope} + 1) \\ +\text{FO} \times \left(1 - \frac{\sum_{9 \times 9\,\text{cells}} \text{FO}}{9 \times 9} + 2\right) \end{bmatrix}$	MSI: manufacturing and service infrastructure FFH: few-family houses MFH: multi-family houses AL: arable land OVH: Orchard, vineyard and horticulture AAL: Alpine agricultural land G&M: grassland and meadows TWW: dry meadows Slope: relative steepness of slope, Range: 0 (flat)–1 (steep) FO: forests
Recreation: available space to perform outdoor activities close to the place of residence on a daily basis; a combination of supply and demand, both normalized to range from 0 to 1.	$\text{Demand} = \sum_{9 \times 9\,\text{cells}} (0.5 \times \text{FFH} + 3 \times \text{MFH})$ $\text{Supply} = \sum_{9 \times 9\,\text{cells}} \begin{bmatrix} 1 \times \text{AL} \\ +2 \times (\text{OVH} + \text{G\&M} + \text{AAL}) \\ +3 \times (\text{FO} + \text{Lakes} + \text{Rivers}) \end{bmatrix}$ $\text{Recreation} = \begin{cases} \text{Supply} - \text{Demand}, & \text{Demand} \geq \text{Supply} \\ \text{Demand}, & \text{Demand} < \text{Supply} \end{cases}$	FFH: few-family houses MFH: multi-family houses AL: arable land OVH: Orchard, vineyard and horticulture G&M: grassland and meadows AAL: Alpine agricultural land FO: forests Lakes: lake present Rivers: river present

Input variables always refer to rasters whose value range is either indicated or binary (1: feature present, 0: feature absent). The sum signs (Σ) indicate a sum neighborhood analysis, where the index below indicates the size of the considered window around the focal cell

specific land use type transitions were observed. Specifically, the rate of grassland to forest transformation was predicted to decrease steadily in the future, with a reduction of 23% in the last 24-year interval (2057–2081). In contrast, changes from grasslands and meadows to few-family houses and from arable land to manufacturing and service infrastructure were projected to continue increasing. The transition from grasslands and meadows to few-family houses was the most extreme projected change: 9869 ha, corresponding to a rate increase of +115%, for 2057–2081. Similarly, but to a lesser extent, transitions from arable land to manufacturing and service infrastructure were predicted to increase by 17% in the latest projected interval.

In general, built-up areas were projected to continue to increase (Fig. 1), with few-family houses being the dominant category and expanding by 115% (~100,000 ha) to reach ~189,000 ha by 2081. On average, multi-family houses and manufacturing and service infrastructure represented ~33,000 ha and ~22,000 ha, respectively, in 2081, which correspond to expansions of 92 and 29%. While grasslands and meadows showed an accelerating decrease, the decrease in arable land, as well as orchards, vineyards and horticulture, decelerating considerably compared with in the past (Fig. S2). Specifically, and most drastically, orchards, vineyards and horticulture were projected to decrease by 52% by 2081, while arable land and grasslands and meadows decreased by 7% and 14%, respectively. Forests, on the other hand, were projected to increase in area (+6%, ~87,000 ha), but with a deceleration of the previous trend. Finally, the past trend of decreasing alpine agricultural land was
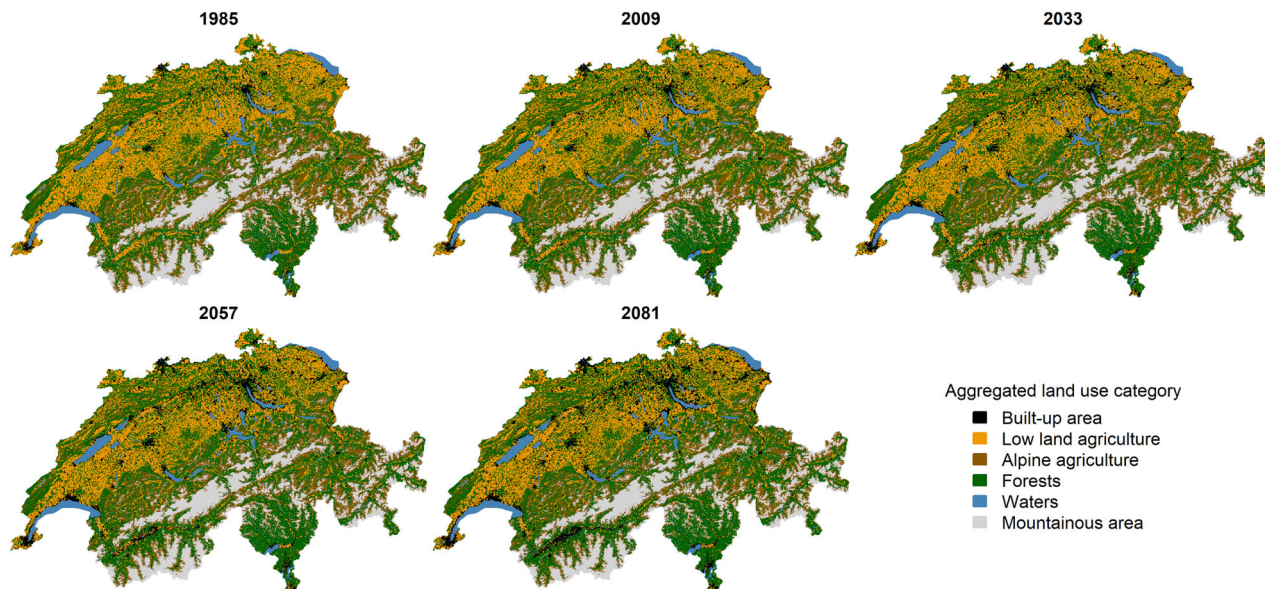
Fig. 1 Spatial arrangement of aggregated land use categories in time steps of 24 years. 1985 and 2009 are the observed land uses for the past, while 2033, 2057, and 2081 are projections from one randomly selected model run. Note the increase in urban area around existing city centers and in the valley bottoms of the Western Alps
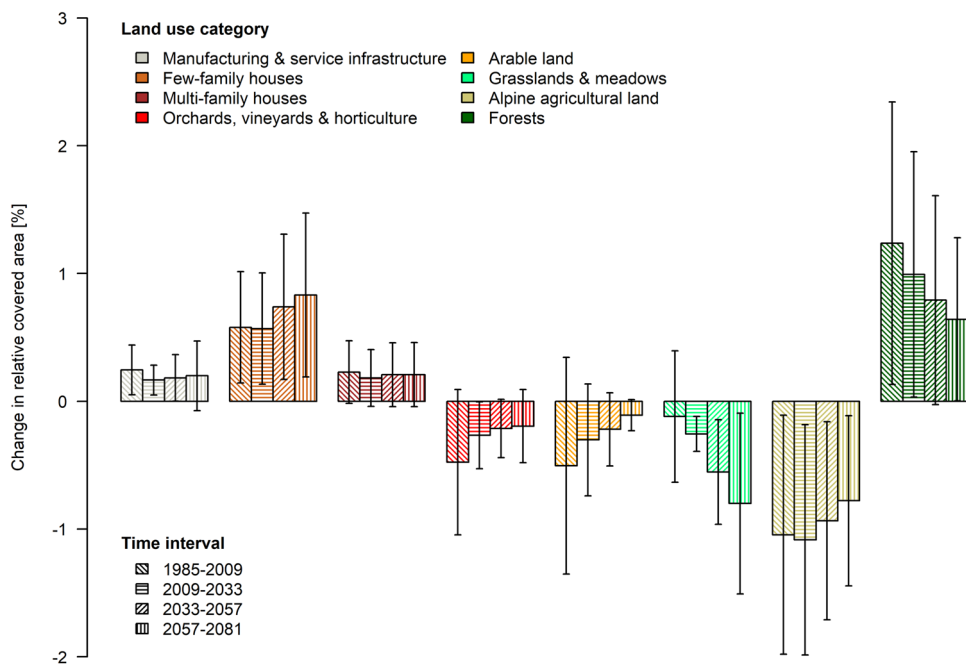

Fig. 2 Average change in relative covered area for each land use category. The changes are for across all six biogeographic regions and all four 24-year time periods. Error bars indicate the standard deviation across the regions

projected to continue in the future at a similar rate: it decreased by ~34,000 ha in the last 24 years and was projected to decrease by ~100,000 ha in the 72-year future period).

Regional effect. Distinct differences in the changes were projected for the individual biogeographic regions (see standard deviations in Fig. 2). The most prominent projected changes happened on the Plateau, where the built-up area was projected to encroach further into the lowland agricultural areas, and in the Western Central Alps, where an immense increase in urban area, largely containing few-family houses and manufacturing and service infrastructure, was projected. Orchards, vineyards and

horticulture were projected to disappear in the Western Central Alps with accelerating speed, while forests were projected to shift upward in elevation (Fig. 1).

Service provision and validation. Clear distinctions between urban and non-urban areas are recognizable in the current distribution of the provisioning of housing, jobs and recreation. Differences are more prominent between the lowland and the alpine regions of Switzerland for biodiversity, reared animals and hazard protection. Crop production occurs mostly in the lowlands. According to our formula, forest patches in the lowlands provide more forest products than those in the alpine regions.
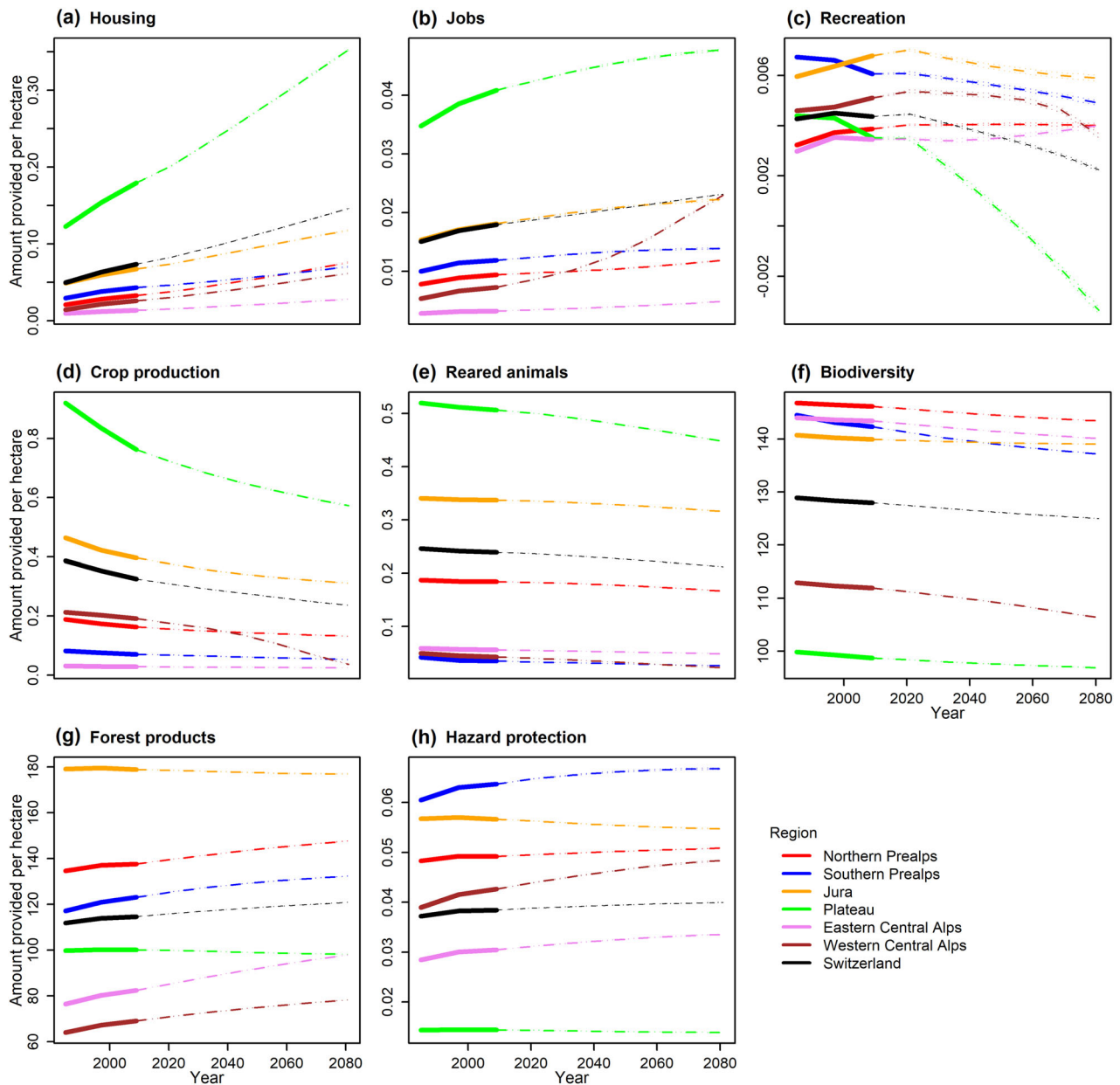
Fig. 3 Development of the provisioning of the modeled landscape services for housing (**a**), jobs (**b**), recreation (**c**), crop production (**d**), reared animals (**e**), biodiversity (**f**), forest products (**g**), hazard protection (**h**). The values are given per hectare for the past (thick solid lines) and projected future (dashed lines). Dotted fine lines represent confidence intervals (quartiles across the 100 independent projection runs). However, as variation was small, these lines are not clearly visible and are mostly relevant for recreation

Thus, as there are more forest patches in some alpine regions, the provisioning per hectare over a region does not show a clear pattern across Switzerland (Fig. 3). The larger alpine valley bottoms are distinctive from the rest of the Alpine regions for all services, as there the services there are distributed in a similar fashion to in the lowlands. Validation of the service calculation showed that for housing and crop production, the ratio of service value to real value changed only marginally between 1985, 1997, and 2009 (Table 3). The ratio of service value to real value for jobs decreased by ~14% in 24 years, implying that manufacturing and service infrastructure cells provide more jobs per spatial unit than in the past. The calculated trend in job provisioning with our formula therefore underestimates the development of actual people employed.

The negative trends observed for biodiversity and reared animals over the past 24 years (−0.75% and −2.85%, respectively,

for all of Switzerland) were projected to continue over the next 72 years (−2.3% and −11.39%, respectively; Fig. 3). While the projection of forest products provisioning across all of Switzerland showed an increase (+5.39%), mainly as a trade-off between agricultural area and rewilding, there was a clear distinction between the two lowland regions (−1.55%) and the four alpine regions (+9.99%) by 2081. Overall change was small for hazard protection by forests but was projected to be positive for all of Switzerland (+5.39%; Fig. 3). However, the spatial distribution of this service is important, and it was projected to decrease in some areas, mainly close to settlements (Fig. 4). The most drastic changes were projected for the provisioning of housing, jobs and crops, especially on the Plateau and in the Western Central Alps (Fig. 3). On the Plateau, the increase in housing was projected to continue linearly to reach a total increase of 97%. The rate of change in job provisioning decelerated over time and only

Table 3 Validating service quantification by calculating ratios between computed service values and related observed data for 1985, 1997, and 2009

LSS	Service metric	SLUS years			Projected (average)		Projected (2009)	
		1985	1997	2009	2045	2081	2045	2081
Housing	Service value	205,495	261,311	303,900	442,091	604,223	442,091	604,223
	Population	6,455,896	7,081,346	7,701,856	**9,766,646**[c]	**11,943,355**	**9,885,957**[c]	**12,089,257**
	Living space per person (m²)	35.5	41.5	45	51[d]	57[d]	51[d]	57[d]
	Total living space (ha)[a]	22,918	29,388	34,658	49,810	68,077	50,418	68,909
	Ratio[b]	**0.00090**	**0.00089**	**0.00088**	0.00089	0.00089	0.00088	0.00088
Jobs	Service value	62,249	69,752	73,978	84,503	95,603	84,503	95,603
	Employees 2nd and 3rd sectors	3,151,000	3,728,000	4,320,000	**4,560,322**	**5,159,349**	**4,934,615**	**5,582,808**
	Ratio	**0.01976**	**0.01871**	**0.01712**	0.01853	0.01853	0.01712	0.01712
Crops	Service value	1,595,337	1,457,210	1,343,982	1,142,210	975,396	1,142,210	975,396
	Total production (1000 CHF)	7,196,551	6,862,180	5,851,815	**5,162,890**	**4,408,876**	**4,973,282**	**4,246,960**
	Ratio	**0.22168**	**0.21235**	**0.22967**	0.22123	0.22123	0.22967	0.22967

For 2045 and 2081, service value quantifications were projected into related actual data with two approaches: (i) with the average ratio of the three Swiss Land Use Statistics (SLUS) years and (ii) with the most recent ratio (2009), rendering slightly different results. Numbers from past observations or values calculated solely based on observations are shown in normal font. Values from modeled projections are in bold and values resulting from a combination of projected and observed data are in italics
[a]Population × Living space per person × 0.0001 ha m^{-2}
[b]Service value/Total living space
[c]Official population estimates for 2045 are: reference scenario = 10.2 million people; high estimate = 11.0; low estimate = 9.4 (SFSO, 2015)
[d]Projected under the assumption that the trend from 2000 to 2012 continues (+2 m² in 12 years; SFSO, 2014)

increased by 17% over 72 years relative to its 2009 level. The opposite trend was observed for crop production projections for the Plateau; the rate of decrease was projected to decelerated over time, mainly owing to agricultural area transformation into built-up area, resulting in a total decrease of 25%. A drastic change was also projected on the Plateau for recreation: a drop by 195% to a negative average amount per hectare. In the Western Central Alps, housing was also projected to increase linearly (+138%), but the particularly drastic changes were predicted for job and crop provisioning. Job provisioning was projected to increase with accelerating speed so that the amount provided in 2081 would be 217% more than that provided in 2009. In contrast, crop production was projected to decrease at an accelerating pace, with a total decrease of 80% by 2081. Recreation in the Central Western Alps increased slightly in the past. Fluctuations in recreation were projected for the future, with an increase in the next 24-year period, followed by a decrease with accelerating speed. These changes in services are associated with the drastic changes projected for the Plateau and the Central Western Alps in the land use categories of built-up areas and lowland agriculture.

Discussion
The assumption that the influence of drivers of land use change modeled for the past will continue identically in the future enables longer forecasts than when detailed scenarios, generally only available for the next two decades, are used. The unusually long-term projection provided by our models makes it possible to provide a picture of possible future Swiss landscapes for the second half of the 21st century and shows extreme urbanization/urban sprawl of the Swiss lowlands beyond 2050, which matches with expected trends of urbanization forecast across IPCC scenarios and UN urbanization studies (UN DESA, 2018). This process is due not only to increasing population but also to an increased demand of living space per person. Urbanization rates are expected to be especially high for fast-developing regions, such as the lowland part of the Valais, and in economically

attractive regions, such as Zürich and the Lemanic coast. The scenarios show also that a high loss of agricultural areas is expected in the form of loss of areas nearby existing cities due to the above described urbanization trends and in the mountains due to forest regrowth. However, as the most recent complete Swiss Land Use Statistics data are almost 10 years old, newer shifts in regulations for landscape development in Switzerland, i.e., toward fostering densification (Weilenmann et al., 2017), were not reflected in the data but are likely to have an effect on future patterns of urbanization. Our projections therefore show a scenario of a possible future trend if these regulations are not implemented strictly or changed, owing to Swiss popular demand.

The projection of land use change and the associated quantification of LSS indicated that there would be specific trade-offs between the provision of LSS in the future. The main beneficiaries of the land use change projections are services from built-up areas, demonstrating the necessity of their inclusion in LSS assessments. A strong expansion of built-up area, in particular few-family houses, provides needed living space in a low-density manner, while the expansion of industrial area facilitates the development of industry associated jobs. Our model projections of housing matched the population projections of the Federal Office of Statistics (2045: our model = 9.9 million people, SFSO (2015) = 9.4–11.0 million people). This widespread urban sprawl, driven by population and per person demand of living space increase, affects several LSS, including recreation and crop production (Fig. 3). However, there are negative effects on other services associated with urban growth, such as soil sealing, increased flooding risk and heat island effects. Densification of built-up areas has been an increasing trend over the past decade (Weilenmann et al., 2017) and could help reduce excessive sprawl of few-family houses and therefore the extreme expansion of urban areas.

The observed decrease in recreational services is mainly due to the lack of (semi-) natural areas close enough to places of residence in growing urban centers, preventing people from experiencing nearby recreational activities. Thus, the decrease in recreational services is especially critical on the Plateau, where
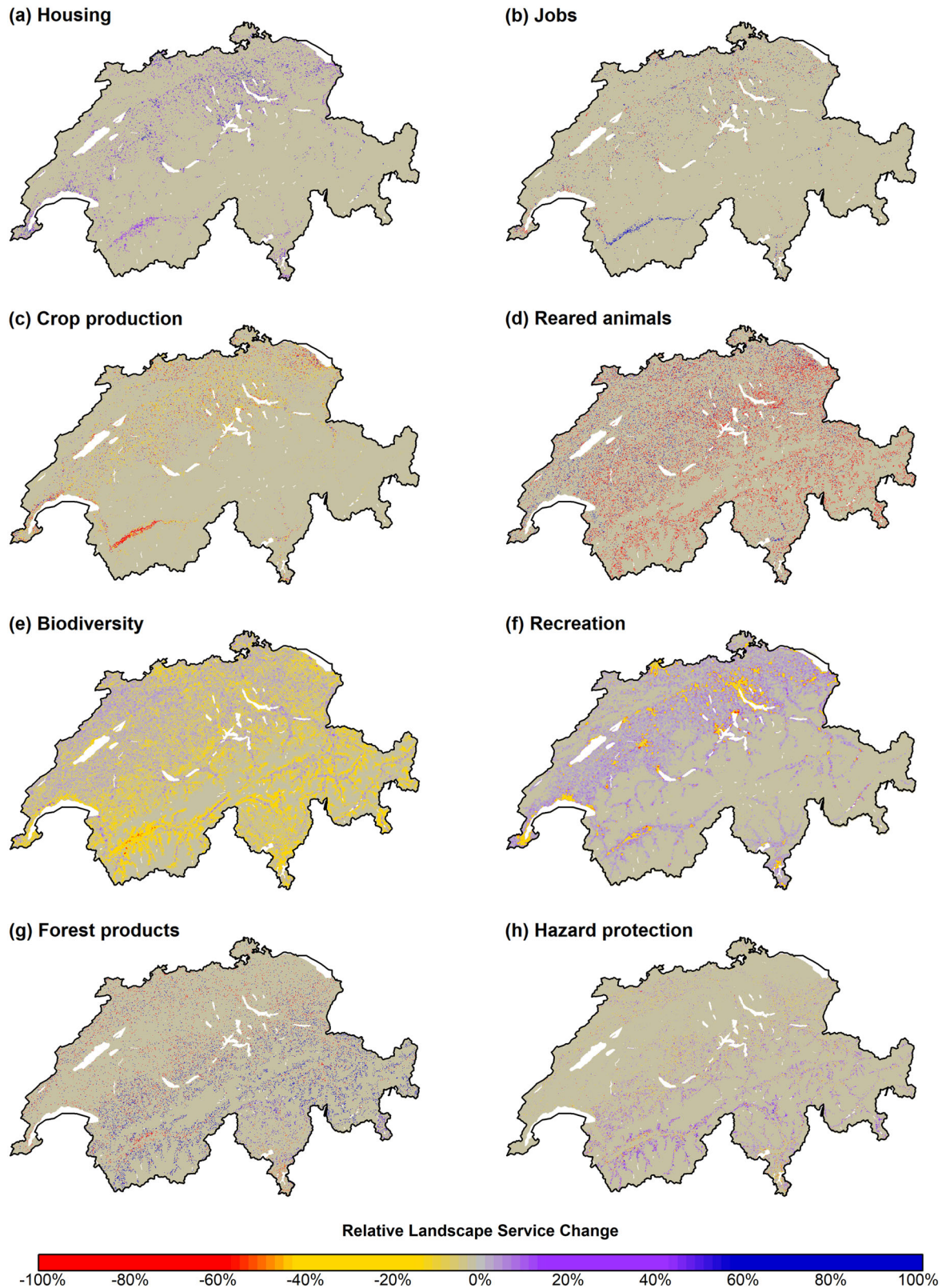
Fig. 4 Relative spatial change of each landscape service between 2009 and 2081 for housing (**a**), jobs (**b**), crop production (**c**), reared animals (**d**), biodiversity (**e**), recreation (**f**), forest products (**g**), hazard protection (**h**). One hundred percent refers to the highest change (increasing or decreasing) that occurred for each service separately. The gray areas indicate that no overall change occurred

urban growth is projected to be most extreme. Providing easy access to nearby forests and other (semi-) natural areas is key in urban areas (Hersperger et al., 2012; Hunziker et al., 2012; Kienast et al., 2012; Morelle et al., 2018). In urbanized areas, efforts to include adequate parks and garden areas are crucial (Hartig et al., 2014; Kabisch et al., 2015). Such areas are already present in many existing urban land use areas, but we were not able to model their transitions because there were not enough data points

available. Therefore, the service provision for recreation is likely to be better than what we have projected with the LSS quantification used in this study. Parks, gardens and other unsealed areas could also reduce negative impacts of urban expansion on biodiversity (FOEN, 2017; Oliveira Hagen et al., 2017). Strategic planning for green infrastructure is a promising approach to address outdoor recreation opportunities and other LSS in urban regions (Grădinaru and Hersperger, 2018).

As a consequence of urban sprawl, and also agricultural land abandonment in alpine regions, crop production is projected to drop considerably from a value of 5.9 billion Swiss francs in 2009 to 4.2 billion Swiss francs in 2081 (Table 3). Animal rearing is also projected to decrease, but not as drastically. In conjunction with the expected population growth, a decrease in agricultural land will further widen the gap between domestic supply and demand (Becker et al., 2014; Kopainsky et al., 2014), increasing the dependency of Switzerland on imported food (FOAG, 2016).

Quantifying the future of biodiversity under global changes depends on how the species-habitat association is modeled (Pereira and Daily, 2006). Overall, only a small decrease in service provisioning for biodiversity is projected using the presented biodiversity-habitat relationship. The decrease is greatest in the alpine regions (Fig. 4) likely related to the spontaneous reforestation of agricultural areas due to land abandonment (Bolliger et al., 2007; Pellissier et al., 2013). In addition to leading to the loss of valuable alpine agricultural land, this change leads to larger forest patches and thus lower biodiversity values according to the formulation. While the two forest-based LSS show little gross change, both exhibit a spatial shift (Fig. 4). This is probably unproblematic for forest products but might be important to consider in more detail for hazard protection.

By extrapolating the past trends of land change into the future, we investigated what would happen to the landscape of Switzerland by 2081 if the land use legislation of 1985–2009 (and its imperfect implementation) were to continue. The feedback loop caused by the step-wise update of the land use related predictors caused either by acceleration or deceleration of the projected frequency of change compared to the past trends. Nevertheless, projections maintain the assumed continuation of the past transition trends. Such business-as-usual projections can form a useful reference for political and planning discussions. Scenarios are often included in assessments of land change analyses to improve the understanding of potential future landscape arrangements (Bolliger et al., 2008b; Lawler et al., 2014; Price et al., 2015). The projection model developed in this paper could be a useful starting point to explore effects of certain Swiss spatial planning policies and potential future socio-economic developments, for example urban growth boundaries (Gennaio et al., 2009; Hersperger et al., 2014; ARE, 2018), tradable development rights (Menghini et al., 2015), local growth management approaches (Rudolf et al., 2018) and quotas for crop land per canton (Mann, 2009). However, the time horizon has to be chosen carefully for such scenarios, as planning policies are normally designed with 15-year (land use policies) to 20-year (strategic spatial planning) horizons in mind (Hersperger et al., 2018).

The largest caveat of our study is related to the quantification of the LSS, which demonstrates many of the issues that scientists have identified as potential causes for the insufficient use of service assessments in sustainable management (De Groot et al., 2002; Wallace, 2007; Bennett et al., 2015; Boerema et al., 2017; Cord et al., 2017; Grêt-Regamey et al., 2017). We adapted the service definitions to suit our requirements (De Groot et al., 2010; Englund et al., 2017) and developed calculation methods fitted to the study what hinders comparisons with other studies and thus making conflicts between services difficult to estimate (De Groot

et al., 2010; Crossman et al., 2013; Cord et al., 2017; Englund et al., 2017). These issues are partly due to the fact that ESS consist of different layers with various names and definitions (Wallace, 2007; Burkhard et al., 2014) that are not used consistently. As each study system is unique, it might also be impossible and even undesirable to standardize ESS assessments fully (Crossman et al., 2013; Gulickx et al., 2013; Helfenstein and Kienast, 2014). Furthermore, the equations for quantification of LSS in our study were based on proxies, analogous to in many other studies (Martínez-Harms and Balvanera, 2012; Crossman et al., 2013; Van der Biest et al., 2015), despite proof that this method is inadequate for detailed assessments (Eigenbrod et al., 2010). Ultimately, it seems necessary that the ESS community further explores the potential to develop a core of generic methods and a set of instructions on how to adapt these methods to regional conditions. This would simplify EES assessments and enhance the much needed comparability of results. A final critical point is that validating the quantification of ESS is widely neglected (Boerema et al., 2017; Englund et al., 2017). This is partially due to a lack of data, but it nevertheless implies that evidence on whether the assumptions and information behind ESS assessments hold true is missing. Therefore, it is not known whether interventions based on ESS assessments actually improve ESS (Carpenter et al., 2009). Our validations indicate that the more complex formulas for quantifying housing and crop production were able to capture the temporal development in these services more effectively than the simple binary link for the provision of jobs. Future studies should use independent data to validate not only the models of land use change but also the methods used to quantify services and their implications for human well-being.

While the benefits from built-up areas are likely quantified by non-ESS research, we believe that there are many advantages to an approach incorporating LSS associated with (semi-) natural and built-up areas within one assessment. Acknowledging that built-up areas do not only have negative effects on the environment, but also provide beneficial services for humankind, is a step toward facilitating the dialog of ESS specialists with actors from other disciplines, such as economics, politics and landscape architecture. Accepting that there is a necessity of built-up area expansion and development, owing to its benefits for society and economy, can be expected to increase the recognition of non-monetary benefits of natural systems by people from other disciplines. A combined assessment of LSS associated with (semi-) natural and built-up areas provides a more comprehensive picture to managers and policy makers. This study thus expands upon recent efforts to incorporate ESS and LSS into planning, for examples see Rall et al. (2015), BenDor et al. (2017) and Schubert et al. (2018). Major changes in LSS are projected for the future in Switzerland, with diverse effects on humans and their environment. Our analysis, applicable to any country under similar process of intense urbanization, can act as a stimulus for discussions about the direction in which society wants to steer future landscapes and associated services.

Conclusions

Our model projections made it possible to pinpoint potential trade-offs between landscape services in a spatially explicit manner, thereby providing information on service provision losses. The integration of services from built-up areas in the LSS assessment proved especially promising in strongly urbanizing Switzerland. While we present future changes as extrapolations of the patterns quantified in the past, future land use policies (ideally informed by such models) likely might be able to address the challenges posed by land change.

Data availability

The datasets and scripts used in the current study are available at the EnviDat repository (https://doi.org/10.16904/envidat.81): https://www.envidat.ch/dataset/swiss_landscape_services_change. The non-public datasets can be obtained under request.

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