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ORIGINAL ARTICLE

Spatio-temporal dynamics of grassland use intensity in Switzerland

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Abstract
Land use intensity determines the provision of multiple important ecosystem services of agriculture. In Switzerland, agricultural policy developments have aimed and still aim to extensify agricultural systems and especially grassland use. We here provide a spatial and temporal analysis of changes in grassland use intensity and discuss them in the context of agricultural policy developments to assess potential policy impacts. We use farm-level census data over a period of 19 years. Spatio-temporal patterns of in- and extensification are investigated visually and by global and local Moran's *I* measures. We find that while average changes in grassland use intensity are small, there is a substantial increase in the heterogeneity of grassland use intensity strategies over time, as indicated by increasing interquantile ranges of yearly boxplots. Our results suggest that both in- and extensification are profitable strategies for farmers within the given policy framework. Furthermore, Moran's *I* measures show the emergence of regional clusters of in- and extensification. These intensification clusters possibly amplify environmental problems. Our analysis therefore highlights the need for spatial assessments of agricultural policies, i.e. local adverse environmental effects of intensive grassland use should be targeted by spatially tailored policy measures.

Keywords Land use intensity change · Spatial autocorrelation · Agricultural policy · Swiss case study · Farm-level census data

Introduction

Grasslands cover the largest proportion of agricultural area and provide multiple ecosystem services, contributing to food security, carbon sequestration, habitat provision and cultural services (Harrison et al. 2010; Allan et al. 2015; Le Clec'h et al. 2019). The intensity of grassland use determines the provision of these services and the associated trade-offs (Le Clec'h et al. 2019; Baronti et al. 2022). Policy measures, economic and climatic boundary conditions as well as structural change affect the provision of these services over space and time (Brookfield 2001; Hecht et al. 2016; Brunner et al. 2017; Malek et al. 2019). However, the link between policy changes and land use changes over both time and space is not often considered (Tappeiner et al. 2003; Hinojosa et al. 2019; Bruley et al. 2021).

Grasslands are a key to ecosystem service provision in agriculture, and land use intensification is an important threat to this provision (Allan et al. 2015; Schils et al. 2022). Therefore, a variety of public, policy-based and private, market-based measures aim to internalise these positive and negative externalities of intensive land use by promoting an extensification of production (Lehmann and Hediger 2004; Jones et al. 2015; Mack et al. 2019). At the same time, farmers receive general food supply security payments that aim for a high domestic self-sufficiency and do not require changes in land use intensity (Möhring and Mann 2020), and liberalisation steps (Chavaz 2010) further encourage intensive land use. Within this framework, farmers decide on how to use their land. This decision is an essential part of a farmer's production strategy: farmers are expected to choose a strategy to maximise their private utility, balancing between

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profits from fodder production and payments for providing other ecosystem services, while taking into account farm-specific constraints.

To some extent, land use intensification leads to increased yield and increased quality of yield (Beckmann et al. 2019), and can result in higher profit as long as additional marginal cost of production does not exceed additional marginal income. Land use extensification, on the other hand, can be a profitable strategy if the financial compensation of these public and private agri-environmental programmes is higher than the farmers' compliance costs (Daniel and Kilkenny 2009). Indeed, heterogeneous developments were also identified for Swiss agriculture (Mann 2005). Understanding the link between changing framework conditions and changing land use intensity may be crucial in order to understand the partial inefficacy of well-intentioned policy measures.

Heterogeneous developments often have a spatial dimension. Spatial patterns, i.e. clusters of production strategies, may emerge due to inherent reasons such as climate and soil, or economical and social reasons: Farmers choose their production strategy in accordance with their individual production constraints (Burel et al. 2013). Important economic agglomeration drivers are economies of scale and up- and downstream linkages to industries, such as fodder and other agricultural inputs industry, slaughterhouses or dairy plants (Gruber and Soci 2010). Social networks among farmers within their socio-cultural environment are important determinants of land use strategies and land use change (Celio and Grêt-Regamey 2016). Previous research highlighted the importance of the spatial allocation of ecosystem service provision and land use decisions. Optimal land use intensity and resulting ecosystem service provision differ in space even under similar management due to structural differences across or within parcels (e.g. soil types, elevation, climatic conditions) (Le Clec'h et al. 2019). Finally, the (economic and societal) value placed on ecosystem services (i.e. willingness to pay) differs substantially across regions (Brunner et al. 2017; Huber and Finger 2020; Huber et al. 2022). Yet, previous studies addressing spatial aspects of policy changes were often restricted to spatial dimensions higher than the single farm, such as municipalities or regions (Daniel and Kilkenny 2009; Schmidtner et al. 2012; Teillard et al. 2012; van der Sluis et al. 2016; Ye et al. 2020). Furthermore, existing studies have often disregarded the fact that specific spatial land use dynamics are a potential response to policy changes.

This paper contributes to filling this gap by thoroughly investigating spatial and temporal dynamics of grassland use intensity using spatially explicit farm-level census data. This data allows to observe land use intensity decisions of each single farmer, and how this decision is embedded in these farmers' neighbourhood. We are able to derive farm-specific indicators on grassland use, animal production and intensity (animal stocking rates), and to quantify developments in heterogeneity across farms. We use data for the period 2000 to 2018 (a total of 1,344,307 observations) to depict dynamics of grassland use intensification and extensification. Moreover, we investigate the spatial patterns of in- and extensification developments as well as spatial autocorrelations of these developments. We embed our empirical analysis in a framework of agricultural policy developments and general agricultural policy discussions. Our highly disaggregated data of a whole farm population allows us to investigate the spatial autocorrelation of in- and extensification developments using global and local Moran's I (Moran 1948; Cliff and Ord 1981; Chen 2013). We highlight spatial patterns of development using time series and heat maps. Our analysis aims to identify blind spots in policy-making. Our results therefore allow better spatial targeting of incentive-based agri-environmental programmes.

We use Switzerland as a case study for two reasons: first, grasslands account for 70% of agricultural area (Federal Office for Agriculture FOAG 2019) and are therefore said to form the backbone of agricultural production and other ecosystem services (Mack and Huber 2017; Huber and Finger 2020). Second, there have been significant, ambitious changes in agricultural policies within the past 20 years, from market support to direct payments linked to minimum environmental and animal welfare standards (Mann and Lanz 2013). While participation in policy programmes in countries such as Switzerland is usually quite high (Steiger et al. 2016; Mack et al. 2017), efficacy and efficiency may differ substantially across policies and space (e.g. farmers joining voluntary programmes for convenience, see Mack and Kohler 2019). Different policy goals are often also strongly interdependent, e.g. food supply security payments may have an effect on biodiversity in some regions (see Huber et al. 2017). As a result, the actual additional ecosystem service provision arising from policy interventions is often lower than desired outcomes in regard to biodiversity, landscape, soil, water and climate (BAFU and BLW 2016; Riedel et al. 2019). For example, biodiversity monitoring in Swiss grasslands over recent decades shows that some locations enjoyed improvement, while others suffered even more loss (Fischer et al. 2015).

Swiss agricultural policy developments and spatial implications

The Article 104 of the Swiss Federal constitution defines the multifunctionality of the agricultural sector in Switzerland. Next to feeding the population, these functions include the decentralised settlement of the land as well as the conservation of production potential, soil, biodiversity and landscape through sustainable use (Flury and Huber 2008). Since 1998, Swiss farmers need to fulfil cross-compliance requirements (proof of ecological performance) that guarantee minimum environmental and animal welfare standards to receive direct payments. The shift from market and price support to farm-level direct payments was intended to comply with international requirements and meet demands from citizens and farmers alike, namely for more environmentally and animal-friendly production and a secure income. This policy shift also led to a redistribution of financial support among production systems and regions. More precisely, two different time periods of policy development can be distinguished (Mann and Lanz 2013), with corresponding consequences for grassland use intensity and spatial implications.

During the first period of policy development (1999–2013), price and sales guarantees were abolished, and farmers had to comply with environmental standards to qualify for direct payments. For grassland farmers, these cross-compliance obligations are (a) to reach an even nitrogen balance that restricts the animal density or mineral fertiliser input to the natural factor endowment on the farm and (b) to set aside at least 7% of the total farmland as ecological compensation area. However, in spite of an even nitrogen balance in the cross-compliance obligations, the average nitrogen surplus is still twice the world average (OECD 2019). With regard to grassland, farmers can use two types of meadow and pasture as ecological compensation area: less intensive and extensive (Jeangros and Thomet 2004). According to the Direct Payments Ordinance, the first (mandatory) cut of both less intensive and extensive meadows is restricted to be not before a certain calendar date (June 15 for the plain and hill zone, July 1 for mountain zones I and II, July 15 for mountain zones III and IV) that should approximate the time of flowering. Less intensive meadows and pasture differ from extensive ones as they allow for a small amount of liquid manure (30 kg available Nitrogen per ha). Both the decoupling of payments from production and prices and the introduction of cross-compliance standards are intended to de-intensify agricultural production. Almost 80% of the total direct payment budget went into general measures to maintain the landscape and preserve food security, i.e. ensuring farmers to have a secure income (Möhring and Mann 2020). Only 20% went into voluntary agro-environmental measures (e.g. ecological programmes providing additional direct payments to farmers on a voluntary basis). Farmers in hill and mountain regions continued to be compensated with additional payments for adverse production conditions. Furthermore, deregulation aimed to increase the competitiveness of the agricultural sector. With regard to market support, the Swiss milk market was liberalised gradually. In 1999, government-guaranteed milk prices were abolished and replaced by payments for milk processed into cheese and silage-free milk production (Finger et al. 2017). A free trade agreement on cheese with the European Union followed in 2007. The abolishment of the milk quota system in 2009 (announced in 2007) enabled farmers to intensify milk production (Chavaz 2010).

The second period of policy development started in 2014 with the introduction of a new direct payment system (Mann and Lanz 2013). It was characterised by a budget redistribution towards agri-environmental measures. A further decoupling of support from production by replacing animal-based payments with area-based direct payments led to a shift of support from animal-intensive farms in the plains region towards land-intensive farms in the hill and mountain region (Zimmermann et al. 2011; Mann and Lanz 2013). Single payment schemes now target specific policy goals. Two schemes are considered most relevant for grassland use extensification. First, the voluntary grassland-based meat and milk production programme aims to decrease adverse environmental effects in favour of locally adapted grassland production systems by restricting farmers' concentrate and maize silage use (Mack et al. 2017; Mack and Kohler 2019). Second, payments for measures promoting biodiversity (biodiversity quality levels now being differentiated) were significantly increased with this reform in order to counter the evident biodiversity loss in the past (Fischer et al. 2015). The Swiss government redesigned the biodiversity payment scheme in 2014 by integrating payments from the Ecological Quality Ordinance into the Direct Payments Ordinance (Direktzahlungsverordnung, DZV, SR 910.13). In addition, direct payment rates for result- and multi-actor-oriented payments were substantially increased (Mack et al. 2020; Wuepper and Huber 2022).

Data, definitions and methods

The following two sub-sections describe our data and methods as well as our baseline assumptions and definitions. We present definitions for grassland use intensity, neighbourhood relations and spatial autocorrelation. In a third sub-section, we describe a series of tests carried out to check the robustness of our results.

Data and definition of grassland use intensity

For this analysis, we used census data from the Farm Structure Survey conducted annually by the Swiss Federal Office of Agriculture and the Swiss Federal Statistical Office (Bundesamt für Statistik 2016). This database comprises the years 2000–2018 and all farms in Switzerland meeting the definition of "farm", i.e. fulfil at least one of the following criteria: more than 1-ha total agricultural land; more than 0.3-ha specialised crops; more than 0.1-ha greenhouse crops; more than 8 sows; more than 80 piglets and more than 300 hens. Over the period 2000–2018, there are on average 70,753 farms per year in this database. This survey contains detailed information on land use and animal production, allowing us to derive indicators of production intensity. Furthermore, the coordinates of each farm's main building are available, allowing us to assess farm neighbourhoods. For our analysis, we considered farms that cultivate a minimum of 1-ha grassland area (*gAREA*) and possess a minimum of 1 ruminant livestock unit (*rLSU*). Furthermore, some farms (on average 323 per year) were excluded from this study due to missing or implausible farm coordinates This led to an average of 46,789 farm observations per year. However, this reduced set of observations still represents more than 99% of the total grassland area.

At farm level, the database allows us to differentiate between three categories of meadow (intensive, less intensive and extensive), two categories of pasture (intensive and extensive), several other categories such as wood pastures or low meadows (meadows along watercourses) and temporary grasslands. Even though temporary grasslands are officially categorised as arable crops, their forage production role has a major impact on possible land use intensity (LUI). If they are omitted, LUI is greatly overestimated. In order to indicate hectares of *gAREA*, we aggregated all available categories of grassland.

As grassland use in Switzerland is bound to ruminant production, the extent of roughage-eating livestock per farm must also be determined. For this, we aggregated livestock units per available category of cattle, goat, sheep and other roughage-eating livestock (*rLSU*). Livestock units are defined for each livestock type and age group according to Swiss legislation (Schweizerischer Bundesrat 1998) in order to ensure comparability. Examples are as follows: cow = 1 LSU, dairy goat = 0.2 LSU, dairy sheep = 0.25 LSU.

Grassland use intensity (abbreviated as *gLUI*) was then defined as the animal stocking rate for each farm i in year t:

$$gLUI_{i,t} = \frac{rLSU_{i,t}}{gAREA_{i,t}} \tag{1}$$

gLUI depends heavily on local production conditions. Therefore, a comparison of absolute values of *gLUI* between farms in different regions is largely a comparison of production conditions (e.g. grassland use intensity is lower in mountain and hill regions than in plains regions) rather than management decisions. We overcome this by looking at (absolute) changes $\Delta gLUI$ with respect to the year 2000:

$$\Delta gLUI_{i,t} = gLUI_{i,t} - gLUI_{i,2000} \tag{2}$$

Summary statistics of our data and variables of interest are shown in Table 1. The decrease in number of farms per year represents the known structural change within the agricultural sector in Switzerland. This goes hand in hand with increasing farm sizes, in terms of both average grassland area (average *gAREA*) and ruminant livestock units (average *rLSU*) per farm. The average grassland use intensity (in terms of stocking density *gLUI*) decreased over the years.

Table 1 Number of farm-level observations and averages per year for the variables of interest

Year	Number of observations	Average grassland area (*gAREA*)	Average ruminant livestock units)	Average stocking density (*gLUI*)
2000	54,799	13.1	18.8	1.62
2001	53,411	13.6	20.0	1.68
2002	52,314	13.9	19.9	1.61
2003	51,206	14.2	20.1	1.57
2004	50,258	14.4	20.1	1.55
2005	49,306	14.4	20.4	1.57
2006	48,427	14.6	21.0	1.58
2007	47,474	15.0	21.4	1.57
2008	47,767	15.8	22.3	1.58
2009	46,889	16.2	22.3	1.54
2010	46,399	16.5	22.5	1.53
2011	45,383	16.8	22.9	1.53
2012	44,484	17.0	23.2	1.53
2013	43,606	17.3	23.8	1.53
2014	42,698	17.9	24.9	1.57
2015	42,112	18.0	25.1	1.56
2016	41,456	18.2	25.4	1.56
2017	40,832	18.3	25.6	1.55
2018	40,179	18.5	26.0	1.56

This table comprises all observations from farms cultivating a minimum of 1-ha grassland area *gAREA* and possessing a minimum of 1 ruminant livestock unit *rLSU*

Moran's I measures

In order to identify and describe spatial clusters of land use strategies, we are interested in spatial autocorrelation, i.e. the correlation of a farmer's strategy with the strategy of neighbouring farms. We used Moran's *I* measure (Moran 1948; Cliff and Ord 1981) as an indicator for the global existence of clusters in space. We choose Moran's *I* over other cluster-based entropy measures because our spatially explicit data allows us to define spatial relations between observations (Kopczewska et al. 2017). Furthermore, we choose Moran's *I* over Geary's c as we have data on the whole population; the latter is more suitable for sample observations (Chen 2013). The global Moran's *I* is defined by:

$$I = \frac{N}{W} \frac{\sum_i \sum_j w_{ij} \left(x_i - \bar{x}\right)\left(x_j - \bar{x}\right)}{\sum_i \left(x_i - \bar{x}\right)^2} \tag{3}$$

where x_i, x_j denote the variable of interest of farm i and its neighbouring farm j, respectively. In our case, the analysis is done for $\Delta gLUI$ (see (2)), and the two indices i and j run over all farms in the subset. Accordingly, $\bar{x}$ are yearly means of x, the $\Delta gLUI$. The spatial weights matrix w_{ij} encloses the (binary) information of whether or not a farm j is considered as a neighbour and possibly a weight of connectedness to this neighbour. As exact information on neighbourhood relations does not exist, the definition of w_{ij} usually relies on assumptions. We followed the approach taken by previous authors (Roe et al. 2002; Läpple and Kelley 2015) and assumed that influential neighbours live within a certain (eucledian) distance. Other approaches suggest for example that very successful peers are important (e.g. Skevas et al. 2021) or that specific networks matter for farmers' decisions (e.g. Blasch et al. 2020). Indeed, neighbouring farmers can actually have opposite effects on a farmer's behaviour (Storm et al. 2015), which would result in negative Moran's I measures. In the small-scale Swiss agricultural landscape, a distance of 5 km is sufficient to represent a large number of neighbouring farms. Furthermore, we assumed the same weight of connectedness of each assigned neighbour. Finally, the fraction indicating spatial autocorrelation is multiplied by the factor $\frac{N}{W}$, which is the number of farms N, divided by the sum of all w_{ij}, denoted as W. As Moran's I measures tend towards zero with high numbers of observations, we expect low values for our case of $N = 46{,}789$ farm observations per year.

Accordingly, local Moran's I were calculated for each farm by decomposing the global indicator into the contribution of each individual observation (Anselin 1995):

$$I_i = N\left(x_i - \bar{x}\right)\frac{\sum_j w_{ij}\left(x_j - \bar{x}\right)}{\sum_i\left(x_i - \bar{x}\right)^2} \quad (4)$$

In contrast to the global Moran's I, local measures are able to show clusters of high and low autocorrelation, and thus allow detection of spatial heterogeneity.

Finally, Moran test statistics assessed the significance of spatial aggregation. These tests compare calculated global and local Moran's I against corresponding measures, calculated under the assumption that there is no spatial autocorrelation, i.e. the H_0 hypothesis would imply that all non-diagonal elements of w_{ij} are zero. We used expected values and standard normal deviates as defined by Cliff and Ord (1981). Global and local Moran's I, as well as test statistics, were calculated using R statistical software and the "spdep" package (Bivand and Wong 2018). Appendix A.5 contains the R-codes for calculating yearly global and local Moran's I. Local Moran's I allow us to visualise clusters by the means of maps. We identified clusters of in- and extensification through density-based clustering (Ester et al. 1996). To avoid clusters that are built on outliers, we chose a Reachability minimum of 30 points and a Reachability distance of 0.25.

Robustness checks

Our analysis is based on a series of definitions and assumptions, which are varied in order to investigate the robustness of our findings. First, we conducted analyses not only for Switzerland in total, but also separately for the plain/hill region and the mountain region (Appendix A.1, Fig. A.1–A.2) to analyse whether our decision of pooling all regions was correct. These regions are defined to reflect different agricultural production conditions. Second, we vary our definition of land use intensity, to analyse the robustness of our results: We consider not only grassland categories, but also arable land used for fodder production (maize silage, fodder beet and others), including when calculating the stocking density of ruminant livestock (Appendix A.1, Fig. A.3; Appendices A.2 and A.4). Third, we also vary the definition of our neighbourhood matrix (Appendices A.2–A.3), as different definitions can be found in literature (Vroege et al. 2020). Still assuming that neighbours live within a certain distance, we vary this distance from 1 to 10 km. We also consider a definition where a certain number of closest neighbours define a neighbourhood and vary this number of neighbours from 5 to 50.

Results

Developments of the indicators rLSU, gAREA and gLUI over time

A first assessment of the development of livestock units per farm $rLSU$, grassland area per farm $gAREA$ and livestock stocking density $gLUI$ as well as their heterogeneity are given by means of yearly boxplots from 2000 to 2018 (see Fig. 1). For both $rLSU$ and $gAREA$, the yearly median of all observation increases (overall trend and ± standard deviation are indicated in each plot). For $gLUI$, a slight decrease can be observed. Furthermore, we observe a divergence of the 10% and 90% percentiles for all three indicators $rLSU$, $gAREA$ and $gLUI$, already shows a clearly visible increase in heterogeneity and thus a divergence of land use intensity strategies. Interquartile and 10–90% interquantile ranges support this result. These plots can be found in Appendix A.1 (Fig. A.1). For both $rLSU$ and $gAREA$, the gap between large-scale and small-scale farms steadily increases. For $gLUI$, changes in the interquartile range are smaller. For a short period around 2004, strategies even converged. After 2010, the heterogeneity also steadily increases.

Development in space

Yearly global Moran's I of $\Delta gLUI$ give a first impression on heterogeneity in space, as shown in Fig. 2. The year 2000 serves as the baseline and $\Delta gLUI$ is the absolute change with respect to this year. Therefore, $\Delta gLUI$ is equal to zero for all farms in 2000, and no clusters in space can be expected. Straight from year 2001, Moran's I test statistics show

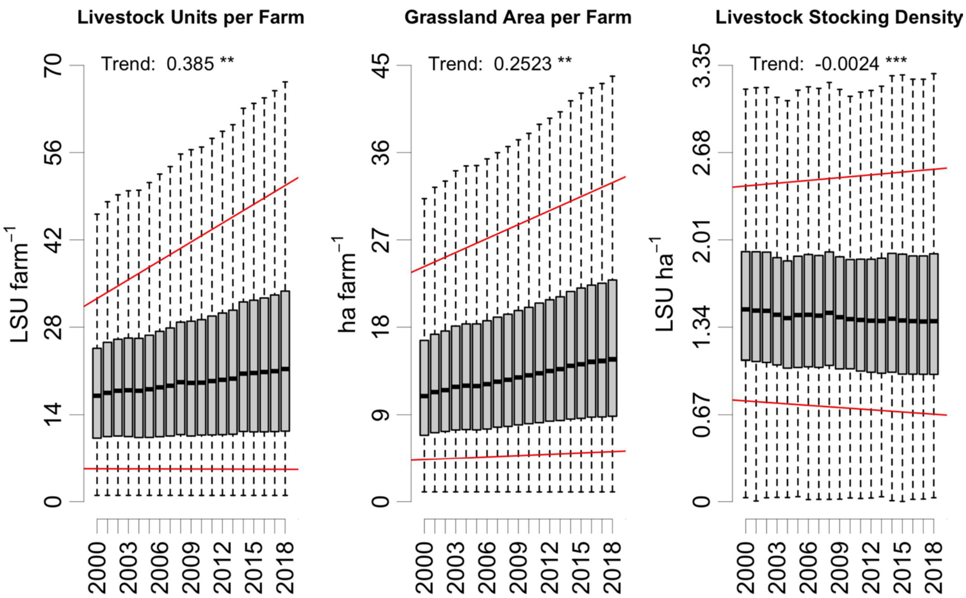

Fig. 1 Delevopments of livestock units and grassland area per farm as well as livestock stocking density of farms in yearly boxplots and interquantile ranges. The graphs show the distribution of livestock units per farm, grassland area per farm and livestock stocking density by means of yearly (2000–2018) boxplots. The black line in the middle of each boxplot indicates the yearly median, while the lower and upper limit of each box is set at the 25% and 75% percentile, respectively. The boxplot whiskers end at the data limit or 1.5 times the interquartile. Outliers are not drawn. The overall trend ± standard deviation is indicated at the top of each plot, showing an increase for livestock units and grassland area per farm as well as a slight decrease in livestock stocking density per farm. The red lines indicate the 10% and 90% percentiles. These lines show a clear increase in heterogeneity and thus a divergence of livestock units per farm, grassland area per farm and livestock stocking density. Separate figures for different agricultural areas (plains/hill and mountain area) and different definitions of land use intensity can be found in Appendix A.1. Graphs in the Appendix also include a second row of graphs, containing Interquartile and 10–90% interquantile ranges of these yearly distributions. For both livestock units per farm and grassland area per farm, these ranges steadily increase. Phases of convergence exist for stocking density, but heterogeneity increases steadily again after 2010

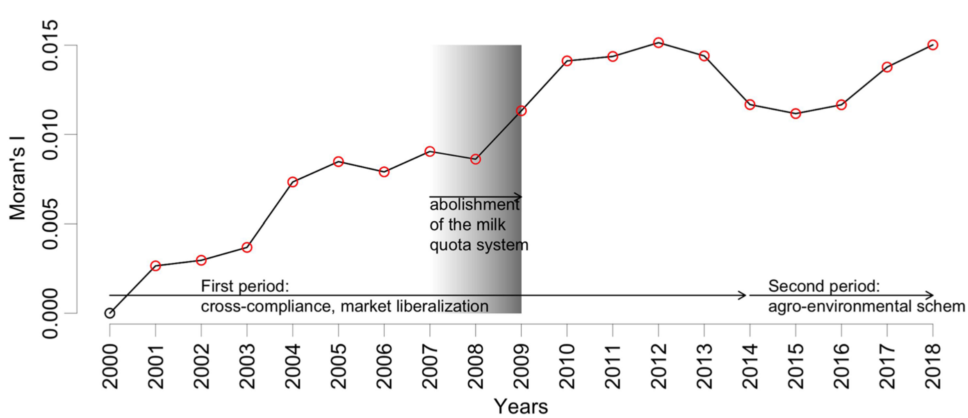

Fig. 2 Yearly global Moran's I of changes in land use intensity $\Delta gLUI$. The neighbourhood matrix w_{ij} defines influencing neighbours as living within 5 km. Red circles show that Moran's I test statistics are significant on the 10% level. The arrows at the bottom indicate the two periods in Swiss agricultural policy-making (as described in Swiss Agricultural Policy Developments and Spatial Implications). In the first period, subsidies were replaced by direct payments conditional upon ecological cross-compliance. Market liberalisation steps included the abolishment of the milk quota system, first announced in 2007 and completely implemented by 2009. The second period saw the introduction of a new direct payment system in which payments were strongly linked to agri-environmental schemes. The development of Moran's I over the years while considering different definitions of w_{ij} as well as land use intensity is displayed in Appendix A.2

significant differences from a H_0 hypothesis (H_0 assumes no neighbourhood effects). The positive Moran's I values show that similar values attract similar values, i.e. there is spatial clustering. The overall upward trend indicates a spatial divergence of strategies (and thus stronger clustering). However, two phases of pause or convergence occur from 2005–2008 and 2013–2015. These phases coincide with two major stages in Swiss agricultural policy-making: the abolishment of the milk quota system between 2007 and 2009 (shadowed grey in Fig. 2), and the introduction of the new direct payment system in 2014 (marked with an arrow at the bottom of Fig. 2.

Local Moran's I and test statistics of $\Delta gLUI$ were also calculated for each individual farm. Figure 3 shows the spatio-temporal development of $\Delta gLUI$, i.e. the changes in grassland use intensity, over the years 2002, 2006, 2010, 2014 and 2018 as heat maps. Only points of farms with significant spatial autocorrelation (significant local Moran's I test statistics on the 5% level) are displayed with solid colours; other points received a transparency of 20%. This highlights areas where either intensification or extensification strategies concentrate. We observe the emergence of two clusters of intensification and five clusters of extensification, indicated in Fig. 3 by numbers 1–2 and 3–7, respectively. A visual assessment shows that the clusters agree reasonably well with the administrative borders of some cantons (NUTS 3 regions of Switzerland, drawn with grey lines for orientation). Intensification occurred in the plains of the cantons Lucerne (1) and Thurgau (2). The intensification clusters show remarkable dynamics: The Lucerne cluster continuously increases in size and density. The Thurgau cluster first spreads over the whole canton, then concentrates in the south-eastern part. Extensification can be observed in the plains of the canton Vaud and Fribourg (3), as well as in Bern (4), the southern plains of Solothurn (5), parts of Aargau (6) and the northern part of Zurich (7).

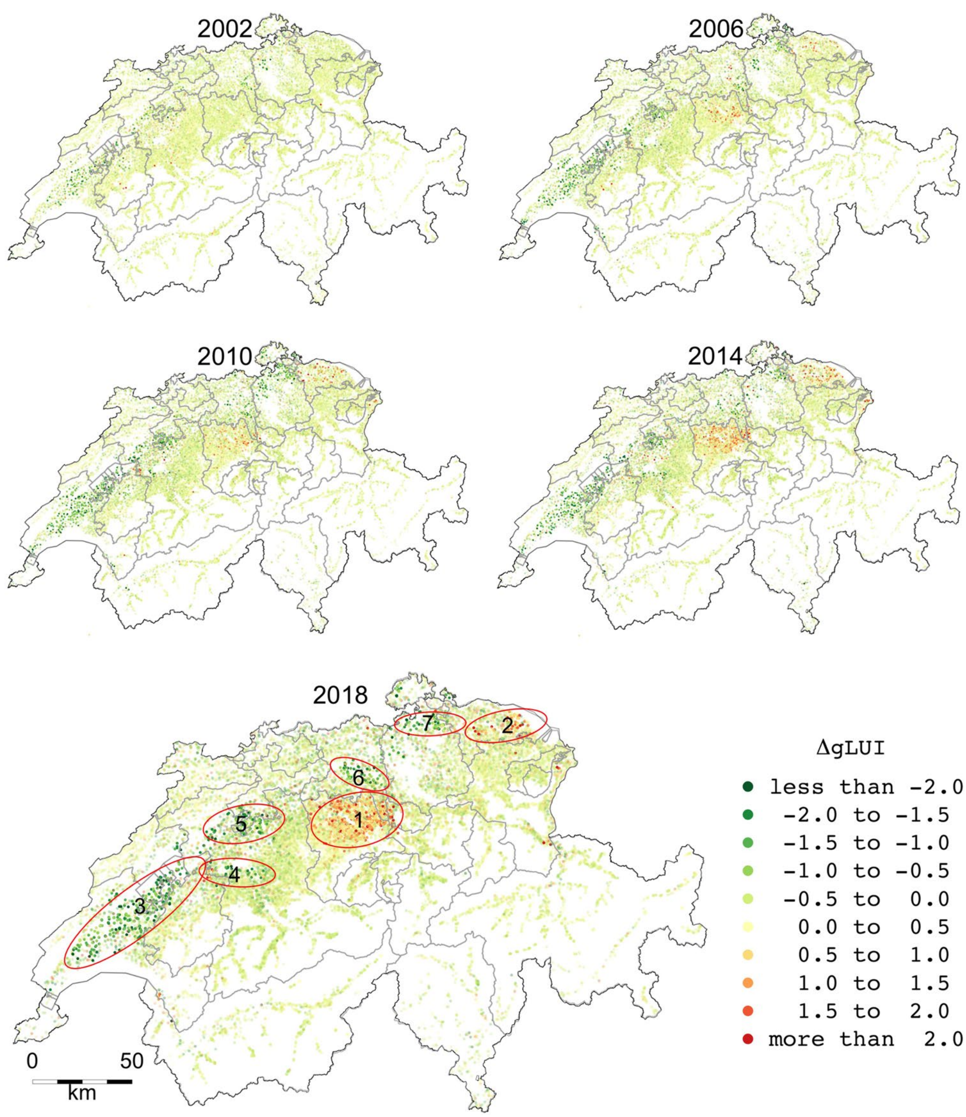

Fig. 3 Spatio-temporal development of changes in grassland use intensity $\Delta gLUI$ (grassland use intensity change in relation to 2000). Colours towards red indicate intensification, while colours towards green show areas of extensification. Solid colours indicate significant local Moran's I test statistics on the 5% level. This allows us to point out areas where either intensifying or extensifying strategies prevail. Density-based clustering (Ester et al. 1996) revealed two clusters of intensification (1–2) and five clusters of intensification (3–7). Red ellipses indicate the 95% confidence ellipses around these clusters. Versions of these maps, once without different transparency levels (only showing changes in land use intensity $\Delta gLUI$), once showing absolute land use intensity $gLUI$, can be found in Appendix A.3, Figure A.9 and A.10. Maps showing results for 2018 and different definitions of neighbourhood and/or land use intensity are drawn in Appendix A.4, Figure A.11 and A.12

Most extensification clusters emerge early and do not change much after 2006. Some dynamics can be observed for the Zurich cluster (7): after a peak in 2010, there is another decrease. The Bern cluster (4) on the other hand does not manifest before 2014. No clusters can be found in the alpine regions.

Robustness checks

We conducted our analysis of the development of farms (Fig. 1) separately for different agricultural regions (Appendix A.1), namely for the plains and hill regions (Fig. A.2) and the mountain regions (Fig. A.3). Both figures show a clear increase in heterogeneity and thus a divergence in livestock units per farm, grassland area per farm and livestock stocking density. However, the effect is much more pronounced in the plains and hill regions than in the mountain regions. When calculating the stocking density of ruminant livestock, considering an alternative definition of land use intensity, i.e. not only grassland categories, but also arable land used for fodder production, does not affect our results (Fig. A.4).

Appendix A.2 contains versions of Fig. 2, with varying (1 to 10 km) maximum distance to neighbours (Fig. A.5) and an alternative definition of neighbourhood based on a number (varied from 5 to 50) of closest neighbours (Fig. A.6). Overall, variations in the neighbourhood definition do not change the key messages presented in the "Development in space" section. The key findings are also unaltered when using the alternative definition of land use intensity (Fig. A.7 and A.8).

Finally, the emerging clusters of in- and extensification were drawn with varying definitions of neighbourhood and land use intensity (Appendix A.4, Fig. A.10 and A.11). Again, the key messages presented in the "Development in space" section remain unaltered, although clusters are not as pronounced with low maximum distance to neighbours or low number of closest neighbours.

Discussion

Developments in Swiss agricultural policy and socio-economic conditions in the last 20 years have left visible marks on farmers' grassland use intensity strategies. Deregulation measures in Swiss agricultural policy such as market liberalisation, the abolishment of the milk quota and the cheese free trade agreement with the European Union provided producers with more room for strategic decision-making, making less intensive but also more intensive production more attractive for some farmers (Lips and Rieder 2005). At the same time, cross-compliance obligations and incentive-based ecological programmes aim to extensify grassland use. To some extent, this policy framework shows conflicting priorities that are brought to light by our results on diverging grassland use strategies.

Our assessment of the temporal dynamics of grassland use intensity changes in Switzerland showed (on average) small, but slowly decreasing intensities, which would confirm the extensification aims of Swiss agricultural policies in the reforms since 1999. However, the results also show a high and increasing heterogeneity of grassland use intensities among farmers. Thus, assuming that farmers aim to maximise their private utility, both intensification and extensification are potential strategies within the given framework of regulations and incentive-based policies. Seeing farmer reacting differently to common policies has important implications for further assessment of policy effects as well advices to policy makers. This finding goes beyond the scope of our investigation of policy effects on Swiss grasslands, but emerges as an important aspect in other countries as well (e.g. Daniel and Kilkenny 2009; Teillard et al. 2012; Lakes et al. 2020; Wolff et al. 2021). Furthermore, we found significant and increasing spatial autocorrelation of ex- and intensification processes, expressed as global Moran's *I*. Slight drops in that process, visibly around years with significant agricultural policy changes (the abolishment of the milk quota in 2009 and the introduction of a new direct payment system in 2014) imply that such national external factors can cause some temporal homogenisation. However, forces of economic agglomeration such as economies of scale and the proximity to up- and downstream linkages to industries (Gruber and Soci 2010) as well as social networks (Celio and Grêt-Regamey 2016) lead to a continuing spatial divergence of strategies.

Local Moran's *I* allowed us to identify two intensification and four extensification clusters. These are all restricted to the plains and bound by administrative borders of cantons. Why do we find clusters only in the plains? Natural production conditions in the plains are generally less constraining on farmers' production strategies than conditions in the hill or mountain regions. Farmers are therefore more likely to base their intensification or extensification strategies on social networks and behavioural aspects (Burton and Wilson 2006) and/or economies of scale and backward/forward linkages, rather than on national policies, and are also less constrained by natural production conditions. In fact, direct payments make up a much smaller proportion of farm incomes in the plains than in the hill and mountain regions (16% versus 24% and 41%, respectively) (Federal Office for Agriculture FOAG 2019). Thus, farmers' individual strategic decision-making has a significant impact on their success. Why are clusters bound by administrative borders? Cantons do have some competences in agricultural policy-making and even receive some budget transfers from the national agricultural budget, but their monetary power to steer policies seems to be small (Binder and Mann 2019). Yet, cantons have large leverage potentials in education, extension services and the development of cantonal-level programmes that can strongly affect farm-level decisions (e.g. Krämer and Wätzold 2018; Wuepper et al. 2021). For example, the canton of Vaud supports several regional development projects that could lead to the observable extensification cluster. The canton of Thurgau, on the other hand, receives the lowest financial transfer per hectare. Thus, drivers other than agricultural policies might be the reason for this intensification cluster. This is also true of the canton of Lucerne, which is recognised as having the highest livestock stocking rates in Switzerland but actually emphasises incentive-based extensification measures in its current local agricultural policy strategy (Canton Lucerne 2018). However, the responsibility for agricultural basic and further education and training, as well as for agricultural advisory services, lies in the hands of cantonal administrations. The explanatory power of cantons on heterogeneity in the uptake of agri-environmental schemes in Switzerland has already been illustrated by previous studies (Mack et al. 2020).

Conclusion

From a policy perspective, our results allow a more nuanced picture in assessing policy effects. Overall, the target to reduce intensification of roughage-eating livestock production was not achieved. Food supply security payments may be high enough to have preserved a status quo (i.e. reducing farmers' incentives to adopt voluntary schemes for extensification), but deregulation measures also left more room for intensification strategies. The observable heterogeneous responses to policy incentives and changing market conditions show that in- and extensification of grassland use are farm and region specific. Spatially explicit data and methods allowed the detection of regional clusters and their development over time. With regard to future agricultural policies, spatially tailored measures should target possible blind spots in past policy-making. Such measures will also be useful for agricultural policies in other countries, as spatial dimensions of policy effects are often overlooked. Our results imply that cross-compliance-based agri-environmental direct payments cannot prevent intensification. Especially in regions that suffer most from adverse environmental effects of agricultural production, farmers seem to react much more to market signals than to incentive-based agricultural policy measures. While increasing the competitiveness of agriculture is another goal of agricultural policy (Art. 104 of the federal constitution of the Swiss confederation), more regionally targeted and tailored policies are needed to reduce adverse environmental effects.

From a research perspective, our analysis and findings highlight the need for more spatio-temporal dynamic assessments of policy effects on land use changes. Further research should look at possible mechanisms of cluster development. We expect driving forces other than agricultural policies, e.g. forces of economic agglomeration such as economic backward/forward linkages, and social networks, to have a significant impact on local grassland use intensity decisions. Further research may also consider analyses on plot level if data availability allows for such analyses.

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Declarations

Disclaimer The content of this article does not reflect the official opinion of the European Union. Responsibility for the information and views expressed herein lies entirely with the authors.

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