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Patterns and drivers of recent agricultural land-use change in Southern Germany

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ABSTRACT

Traditionally, agricultural land-use change (LUC) analyses focus on the conversion of natural land to agriculture especially in developing countries. Studies considering recent agricultural LUC (e.g., to built-up land) for the last two decades in more stable agricultural systems in Western Europe are mostly missing for the regional scale. Major LUC pathways, their drivers and potential counteracting factors such as subsidies or an increasing demand for regional agricultural products should be analyzed.

Using the Metropolitan Region of Nuremberg in Germany, we quantified (i) major pathways of agricultural LUC with a transition matrix, and (ii) spatial patterns of agricultural LUC with optimized hot-spot analyses. (iii) We used boosted regression trees (BRT) to identify factors which foster agricultural LUC towards settlement and forest as well as semi-natural open land. Results for the last 15 years showed a considerable decline of agricultural land due to afforestation (3.1%) and due to settlement and infrastructure development (2.7%), which were the main LUC pathways. Both settlement development and afforestation concentrated at existing hotspots of urban development and in forest-dominated areas. Settlement-driven agricultural LUC was largely dependent on population density and development and independent from agricultural or biophysical parameters. Forest-driven LUC was mostly explained by agricultural parameters (i.e., low land rents and biophysical factors such as high slopes). Governance instruments such as regional planning and payments for maintaining agriculture on marginal land did not seem to maintain a balanced spatial distribution of agricultural land. If not improved, settlement development will considerably outcompete agriculture in prosperous sub-regions. Economic constraints will force farmers to abandon agriculture for forest on marginal locations at the cost of an intact cultural landscape.

1. Introduction

Land-use change (LUC) requires attention due to its major consequences for the environment and human well-being (Plieninger et al., 2016). Quantifying LUC often provides the basis to assess non-monetary impacts (e.g., on ecosystem services such as landscape quality by Schulp et al., 2019). Better insights into LUC equally support the quantification of ecosystem services Estel et al. (2015). The quantified impacts of LUC finally facilitate balancing the cost and benefits of LUC (e.g., cultural and regulating ecosystem services vs. benefits arising from urbanization or agricultural intensification (Plieninger et al., 2016) as main drivers of LUC).

LUC from natural areas to agricultural land (e.g., Geist and Lambin 2002) and from agricultural to settlement or urban areas are often studied (Foley et al., 2005). Globally, meta studies on drivers of LUC emphasize on forests most and consider agriculture less (van Vliet et al., 2016). Meta studies in low- and middle-income countries emphasize on cropland expansion (e.g., Meyfroidt et al., 2014). In Europe and North America, Li and Li (2017) identify considerable farmland abandonment, i.e., a decline of agricultural land. In North America, agricultural land has rather continuously declined. However, other studies for the US show that cropland in the US has been overall rather constant since the 1950s, whereas a decline of cropland was identified at the east coast and an increase at the west coast (Ramankutty et al., 2010).

Europe has even more heterogeneous agricultural LUC patterns. A major study by van Vliet et al. (2015) analyzes more specifically in the European context the two directions of pressure on agricultural land: intensification and extensification. However, extensification and intensification are not equally distributed and present although they might simultaneously arise in one region (Plieninger et al., 2016). The most predominant phenomenon is the loss or the contraction of agricultural land (van Vliet et al., 2015). A major counteracting phenomenon is the decline of agricultural land both due to settlement and infrastructure development and due to afforestation. The increase in grassland in different land-use systems is equally considerable across Europe (Levers et al., 2018a). A European review shows that agricultural expansion and intensification have been more intensively studied (Plieninger et al., 2016). Agricultural abandonment is most prominent in Eastern European countries (especially due to post-socialist transitions) (Levers et al., 2018b) and selected Mediterranean areas (e.g., the Extremadura in Spain) (Plieninger et al., 2013) To some extent, Western European countries are also subject to agricultural land

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abandonment (e.g., McGinlay et al., 2017).

For example, Germany as Western European country shows a considerable decline of agricultural land (Destatis, 2019). The federal state of Bavaria had the highest nominal and relative decline of agricultural land in Germany (383,700 ha) with 10 percent (1992 – 2015) except from the purely urban federal states such as Hamburg (Destatis, 2019). Even federal states in Eastern Germany, which were affected by post-socialist transitions, had lower agricultural LUC rates. In that respect, it is necessary to identify differences in drivers of agricultural land abandonment or agricultural LUC for Western Europe, which is understudied compared with well-studied recent agricultural LUC in Eastern European countries (Müller et al., 2013) or the Mediterranean (Plieninger et al., 2013).

Multiple recent studies analyze agricultural LUC processes at the continental scale such as Levers et al. (2018b), which allow for identifying global trends, but cannot equally well determine relevant patterns at the local or regional scale. Patterns of agricultural LUC differ depending on the regional context (e.g., economic prosperity, population development or labor availability) (van Vliet et al., 2015). In addition, biophysical location-based factors and farm structural parameters are not consistently available at high quality and with sufficient spatial resolution across Europe. Beyond, farming conditions strongly vary across Europe (Neuenfeldt et al., 2018) (e.g., size thresholds for economically viable farms). Therefore, indicators in their regional context may give more reliable insights on agricultural LUC patterns and complement European studies such as Terres et al. (2015) at the rather coarse NUTS2 level (second largest territorial unit for statistics in the EU).

Few studies with comparable agricultural or biophysical structures have been conducted in Germany or Central Europe. If done, the focus was on Eastern Germany with considerably different baseline conditions and dynamics due to the former socialist land consolidation and management (see existing reviews van Vliet et al., 2015; Plieninger et al., 2016). Other studies focus more on historical agricultural LUC patterns for longer time spans (e.g., from 1950 until the late 1990s or even earlier Bender et al., 2005; Hietel et al., 2007; Reger et al., 2007; Früh-Müller et al., 2015). Therefore, studies are needed to close the gap between local-scale studies up to 99 km^2 (c.f. Plieninger et al., 2016 for a review) and continental studies (e.g., Levers et al., 2018b). For a German setting, a sub-national study is especially needed: (i) agricultural LUC is not only occurring at the local scale as new surface sealing in Germany requires ecological compensation (e.g., through upgrading agricultural land to high-nature value farming or forests Ecker and Pröbstl-Haider, 2016). Ecological compensation (e.g., through afforestation) may be conducted in areas with comparable natural habitats outside the original community (Busse et al., 2013). Therefore, impacts on agricultural land as main source of ecological compensation areas are more adequately identified at larger spatial scales. (ii) Land management decisions (especially for agricultural land) are taken at the community level. Aggregated impacts beyond the respective community are likely disregarded by policy makers at community level (Hagenauer and Helbich, 2018) and regional-scale studies likely provide comparative insights across communities.

van Vliet et al. (2015) identified multiple drivers affecting agricultural LUC: demographic, economic, technological, institutional, socio-cultural and location-related factors. Economic, institutional, and biophysical location-based factors are major drivers. Differences in institutional factors occur less likely at the regional scale but rather differ between regions with varying subsidy schemes, land-use planning, and agricultural policies. Regarding technological drivers, comparable levels of mechanization and cultivation are equally likely due to regional competition, similar supplier associations, and farm extension services. Cross-country comparisons such as Bovet et al. (2018) on institutional and overarching economic drivers are likely fruitful.

Different approaches exist to analyze drivers of agricultural LUC (see Levers et al. (2018b) for a discussion of approaches). Conventional regression models are hardly suitable for analyzing multiple non-linear relationships between drivers and LUC (e.g., population density affecting land abandonment Levers et al., 2018b). Therefore, Plieninger et al. (2016) request more reliable methods and approaches to identify the causalities of agricultural LUC. Boosted regression trees (BRT) are proposed to analyze causalities of agricultural land abandonment especially if non-linearity between dependent and independent variables is given (Müller et al., 2013; Levers et al., 2018b). Particularly, thresholds effects such as swift changes in the relationship between dependent and independent variables could be more suitably addressed.

This paper (i) uses a transition matrix to identify major LUC pathways for the Metropolitan Region of Nuremberg for the last 15 years. (ii) We quantify hot and cold spots of agricultural LUC to settlement and to forest and semi-natural open land to understand spatial dynamics and to identify potential failures of current governance. (iii) We use BRT to identify major drivers of agricultural LUC due to settlement and infrastructure development and due to afforestation and nature conservation respectively.

2. Methods

2.1. Study area

The Metropolitan region of Nuremberg comprises approximately 21,800 km^2 and 3.5 million inhabitants and is mainly located in the north-eastern part of the German federal state of Bavaria (EMN, 2018). The urban triangle of the cities Nuremberg-Fuerth-Erlangen is the major agglomeration and the economic and cultural center of the region. This urban triangle well contrasts less prosperous southern as well as north-eastern sub-regions. Agricultural land amounts to 50.4 % (cropland and grassland), and forests to 39.9% of the area in 2018 (Fig. 1). The study area represents major low range mountain areas of Germany. It equally includes a gradient of soil quality with marginal and very fertile production areas.

The analysis focused on the Bavarian part of the Nuremberg Metropolitan region to ensure consistency in data and institutional settings as more likely given within individual federal states for both dependent and independent variables. The share of Bavaria amounts to more than 98 percent of the Metropolitan Region of Nuremberg.

2.2. Time-series and hot-spot analysis

We conducted a LUC analysis for the years 2004 and 2018 based on the land-use datasets (ATKIS-Basis-DLM) from the land survey administration (Bayerische Vermessungsverwaltung, 2018). We used this dataset (scale 1:25,000) due to its higher spatial precision and thematic differentiation in contrast to other available datasets such as CORINE (scale 1:100,000). In contrast to CORINE, ATKIS-Basis-DLM is continuously updated and suitable for regional land management such as the underlying project for this paper. We translated the land-cover classes from 2004 to 2018 with a key provided by the Bavarian Land Surveying Agency. The corresponding land-cover class tables can be found in the supporting information. We combined two fields in the shapefiles to distinguish land-cover classes (KSN and OBJART (2004) (AdV, 2007), KSN and NR (2018) AdV, 2020). We used the first (2004) and the last available year (2018) with comparable data structures. We captured the different transition pathways between major land-use classes given in Fig. 1.

We focused on agricultural LUC and identified hot and cold spots for two major pathways from agricultural land to (i) built-up and (ii) to forest and semi-natural open land. Due to the low share of semi-natural land (Fig. 1), the pathway from agricultural land to forest and semi-natural open land will be only named agricultural land to forest. We performed an optimized hot-spot analysis using ArcGIS Desktop (ESRI, 2015). The optimized hot-spot analysis performs the Getis-Ord Gi*

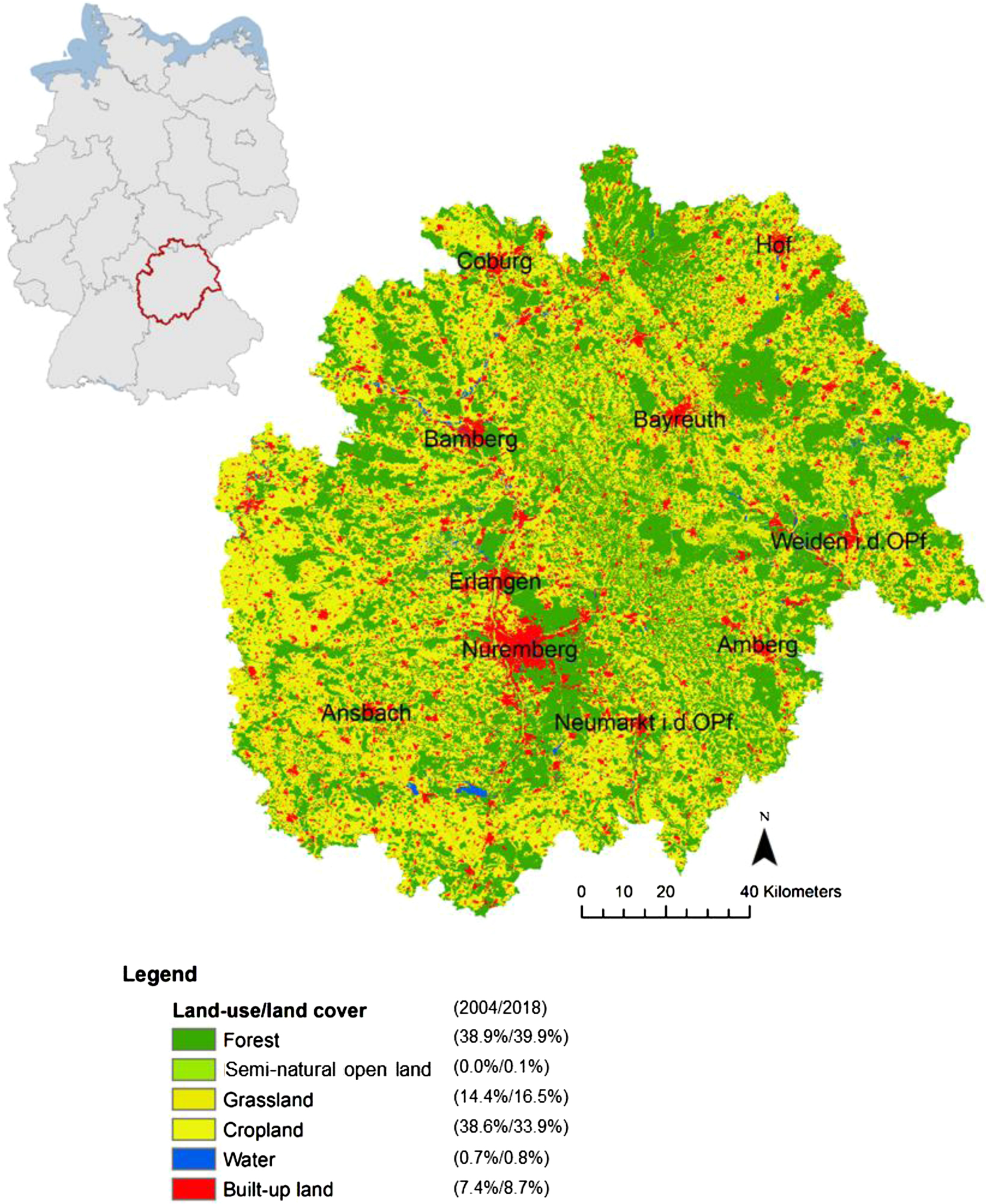

Fig. 1. Land-use/land-cover of the Metropolitan Region of Nuremberg (2018); the shares of the different land-use classes are equally indicated for 2004 and 2018.

statistic (Getis and Ord, 1992) and assesses whether in a neighborhood an incident (e.g., agricultural LUC) occurs considerably more or less frequently compared with a random distribution. We determined hot spots (frequent occurrence of agricultural LUC) or cold spots (scarce occurrence of agricultural LUC) for three different classes or bins of p-values: 0.1, 0.05, and 0.01 (90-99% confidence level). The algorithm automatically decides on the optimal threshold distance up to which an incident is treated as a neighbor (ESRI, 2018). We conducted the optimized hot-spot analysis for two reasons for the entire Metropolitan region of Nuremberg: (i) agricultural LUC occurs not only at the local scale as new surface sealing in Germany requires ecological compensation (e.g., through upgrading agricultural land to high-nature value farmland or forests). Ecological compensation (e.g., through afforestation) is not only conducted in the community with new surface sealing

Table 1
Potential variables explaining major land-use change patterns; the variables are nominal [0, 1], ordinal [1-x] or continuous (unit indicated).

Independent variables	Resolution/ scale	References
Biophysical data		
1 DEM [m] *(derivatives)*	50 m	(Bayerische Vermessungsverwaltung, 2019)
2 Soil Quality Rating	250 m	(ZALF, 2013)
3 Water balance (2004-2009) [mm]	1 km	(DWD Climate Data Center, 2018a)
4 Drought index (2004-2009) [mm °C^{-1}]	1 km	(DWD Climate Data Center, 2018b)
Agricultural data		
5 Livestock density in livestock units (2010) [n ha^{-1}]	community	(BayLfStat, 2019b)
6 Farm size (Agricultural land per farm) (2010) [ha]	community	(BayLfStat, 2019a)
7 Agricultural land rent (2010) [EUR ha^{-1}]	community	(BayLfStat, 2019f)
8 Annual work units per farm (2010) [n]	community	(BayLfStat, 2019e)
9 Farm succession (2010) [0,1]	community	(BayLfStat, 2019g)
10 Land parcel size (2005) [ha]	1:10000	(LfL, 2018)
Socio-economic data		
11 Population density (2017) [n km^2]	community	(BayLfStat, 2019d)
12 Population development (2004-2017) [%]	community	(BayLfStat, 2020)
13 Unemployment rate (2008) [%]	community	(BayLfStat, 2019c)

but also in areas with a comparable natural environment. Therefore, we could identify agricultural LUC due to ecological compensation when considering a larger study area. (ii) Land management decisions (especially for agricultural land) are taken at the community level. Local policy makers as major decision-makers often disregard large-scale impacts beyond their community.

2.3. Drivers of agricultural land-use change

We aimed at explaining the change for two major pathways of agricultural LUC explained in section 2.2: agricultural (cropland and pasture) to built-up as was well as to forest land. We analyzed the Bavarian part of the Metropolitan Region of Nuremberg, which resulted in complete datasets for 568 communities (e.g., most indicators are not available for so-called "community-free areas"). The variables in Table 1 reflect major categories of drivers that are most likely heterogeneous at the local scale. We considered the main categories for agricultural land abandonment and for urban development: biophysical factors (biophysical data), farming characteristics (agricultural data), and economic and demographic factors (socio-economic data) used and collected by van Vliet et al. (2015), Plieninger et al. (2016), and Levers et al. (2018b). We opted for main variables from the mentioned studies available at community level to avoid potentially misleading downscaling. We used mostly aggregated biophysical parameters such as the Soil Quality Rating or the Drought Index to minimize collinearity between variables. The biophysical variables and land-parcel size were aggregated to the arithmetic mean per community based on the listed datasets in Table 1. Other relevant parameters (e.g., the share of organic agriculture) were not available at community level. Institutional factors as additional relevant category were not suitable for the regional-scale case study. Agricultural policy and the regional planning framework were mostly consistently valid and applied across the study region.

We selected BRT to determine major drivers of agricultural LUC in the Metropolitan Region of Nuremberg. We built on the shown suitability of the chosen approach for other studies on agricultural land abandonment (Müller et al., 2013; Levers et al., 2018b). BRT are non-parametric models from the family of machine learning techniques. We chose BRT towards traditional regression approaches since they are not bound to a distribution for both dependent and independent variables (Hothorn et al., 2011; Levers et al., 2018b). BRT build upon the idea of combining multiple simple models, which means that after fitting one model the unexplained variation is targeted by another combination of variables, which could be completely different. This process was repeated iteratively (Breiman, 2001; Elith et al., 2008).

We used the tool *gbm.step* from the package *dismo* (Hijmans et al., 2017) in R (R Development Core Team, 2018) to analyze the data. To avoid a parameter selection bias, we conducted a sensitivity analysis for all combinations of tree complexities (1 to 9) and learning rates (0.00025 to 0.01) and used the 10-fold cross-validated correlation coefficient as quality criterion. We followed Levers et al. (2014) and calculated column and row averages and selected the highest combination for further analysis (see supporting information). We identified the best combination for a learning rate of 0.0025 and a tree complexity of 7 for the settlement- and infrastructure-driven agricultural LUC and for a learning rate of 0.0005 and a tree complexity of 8 for the forest-driven agricultural LUC rate. For each iteration, we split the model into two equally big subsamples of training and test data to avoid overfitting (Dormann et al., 2013). We calculated the relative contribution of each explanatory variable and used partial dependency plots to interpret the impact of individual independent variables on the agricultural LUC rate by holding all other independent variables constant (Friedman, 2001). We smoothed the partial dependency plots and only selected variables with a relative importance above five percent.

3. Results

3.1. Land-use change and hot-spot analysis

We analyzed the LUC between 2004 and 2018 in the Metropolitan Region of Nuremberg. Table 2 indicates the largest nominal changes with a decline in cropland (-12%) and increases in (agricultural) grassland (+15%), in built-up land (+18%), and in forests (+ 3%). Cropland was especially converted to grassland, to built-up land, and to forest. The conversion between the agricultural land-use classes from cropland to grassland allowed a net gain in grassland although grassland was converted to forest (5.3%), to cropland (18.7%), and to built-up land (3.4%). The strong increase of semi-natural open land in relative terms can be explained due to the abandonment and changed classification of former military sites, for example. The water bodies increased due to an increase of perpetually aquiferous ponds and lakes (due to better distinction of ponds from surrounding land cover (e.g., grassland)). All other water bodies stayed mostly constant.

Major LUC was from agricultural land (grassland and cropland) to built-up land (310 km^2) (*red background color*) and to forest (349 km^2) (*green background color*). We conducted a hot-spot analysis for these major LUC pathways (Fig. 2). Agricultural LUC thereby concentrated mainly in the urban triangle Nuremberg – Fuerth – Erlangen and along

Table 2
Land-use change matrix for the Metropolitan region of Nuremberg in km²; the upper table indicates – read row-wise – the land-use change from 2004 to 2018 starting from the land-use composition in 2004 (losses); the land-use composition in 2018 is underlying (gains); the lower table – read column-wise – indicates the relative losses of the land-use composition in 2004.

	km²	2018 Forest	Semi-natural open land	Grassland	Cropland	Water	Built-up land	
2004	**Forest**	8147.4	0.8	61.4	36.0	3.5	37.5	8286.5
	Semi-natural open land	1.1	6.9	0.7	0.1	0.1	0.1	9.0
	Grassland	158.5	6.9	2211.1	572.0	12.0	104.5	3065.0
	Cropland	190.9	1.5	1220.9	6603.4	6.6	205.6	8228.9
	Water	2.3	0.1	5.8	0.8	149.9	1.2	160.2
	Built-up land	17.3	0.1	25.0	12.8	5.1	1514.0	1574.3
		8517.5	16.4	3524.9	7225.2	177.1	1862.9	

		Forest	Semi-natural open land	Grassland	Cropland	Water	Built-up land
2004	**Forest**	98.3%	0.0%	0.7%	0.4%	0.0%	0.5%
	Semi-natural open land	12.0%	76.8%	7.4%	1.2%	1.5%	1.1%
	Grassland	5.2%	0.2%	72.1%	18.7%	0.4%	3.4%
	Cropland	2.3%	0.0%	14.8%	80.2%	0.1%	2.5%
	Water	1.5%	0.1%	3.6%	0.5%	93.6%	0.8%
	Built-up land	1.1%	0.0%	1.6%	0.8%	0.3%	96.2%
	Δ2004-2018	3%	82%	15%	-12%	11%	18%

major train and highway lines between Bamberg and Nuremberg. Cold spots were rare and mainly located in forest-dominated areas of the Frankenwald and the Fichtelgebirge (north and north-west of Bayreuth respectively).

Contrastingly, hot spots of forest-driven agricultural LUC were larger and cold spots were more frequent. Main increase in forest concentrated in the Franconian Swiss between Nuremberg, Bamberg, and Bayreuth. This area is characterized by a landscape mosaic with highly fragmented agricultural land and forests. Cold spots of agricultural LUC were both in intensively used agricultural areas with fertile soils in the western study area as well as in areas with existing large shares of forest in the eastern study area close to Weiden.

The overlap of hot spots of settlement- and infrastructure-driven agricultural LUC and of cold spots of forest-driven agricultural LUC is rather low. In the urban triangle Nuremberg – Fuerth – Erlangen, settlement- and infrastructure-driven agricultural LUC (hot spot)

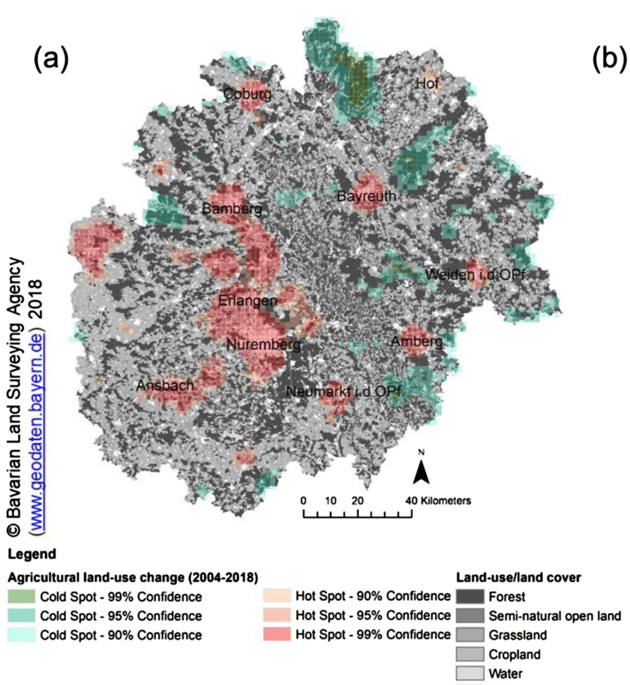

Fig. 2. Hot spots of agricultural land-use change (a) to settlement and infrastructure (2%, 310 km²) and (b) to forest and semi-natural land (4%, 698 km²) in the Metropolitan Region of Nuremberg.

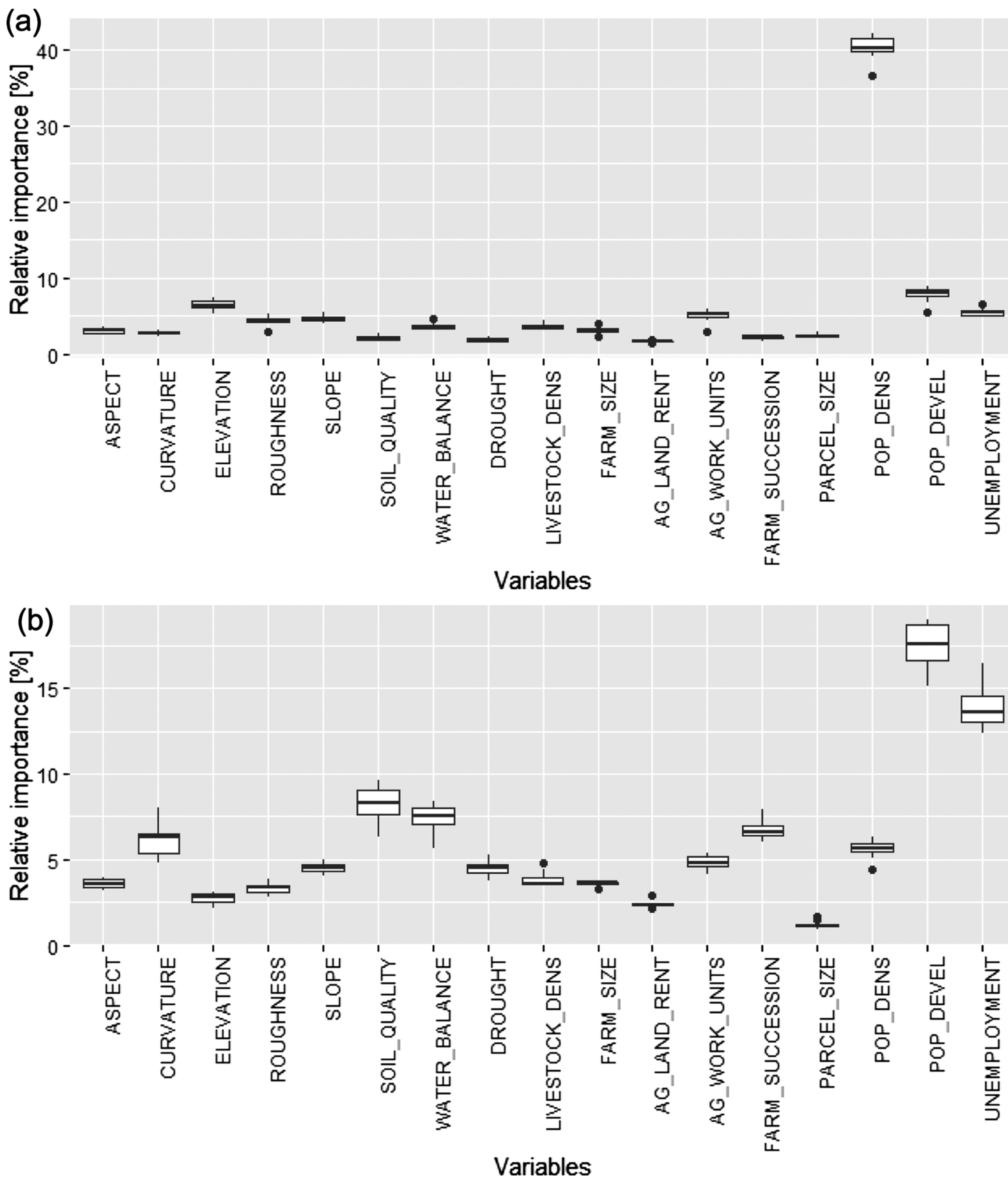

Fig. 3. Relative importance of explanatory variables for agricultural land-use change for (a) by settlement and infrastructure and (b) by forest and semi-natural land (10 folds each).

outcompeted forest-driven agricultural LUC (cold spot).

3.2. Drivers of variation in agricultural land-use change rates

Multiple variables were tested to explain the variation of settlement- and infrastructure-driven agricultural LUC. The BRT model explained 96% of the variation in agricultural LUC rates. The importance of the explanatory predictor variables is shown in Fig. 3. The most important explanatory variable was population density followed by population development.

The partial dependency plots (Fig. 4) show a considerable increase of the agricultural LUC rate up to a maximum of above three percent at a population density between 700 and 800 people per km^2. Interestingly, the population development rate had only an effect on the agricultural LUC rate at a threshold between 2 and 2.3%, and stayed below 2% and above 2.3% rather constant. Variables characterizing the farming system and biophysical properties for farming had a low explanatory power.

The variation of forest-driven agricultural LUC was tested by multiple variables. The BRT model explained 69% of the variation in agricultural LUC rates. Fig. 3 shows the importance of the explanatory predictor variables. The most important explanatory variables were related to the farming system and to biophysical properties. Land rent and plot fragmentation (size of agricultural land units) as well as slope and the soil quality rating were the most important explanatory variables for the variation in agricultural LUC.

The partial dependency plots (Fig. 5) show a considerable decline of the agricultural LUC rate up to the minimal agricultural LUC rate below

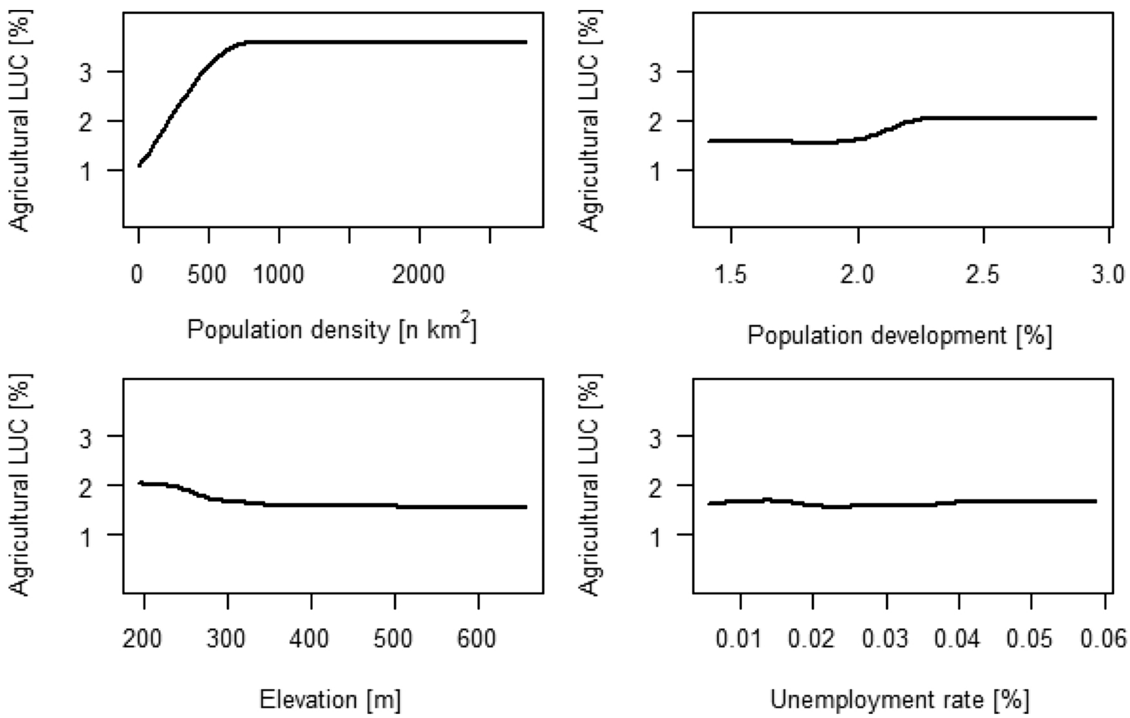

Fig. 4. Partial dependency plots for the four most important explanatory variables (explanation > 5 %) for settlement- and infrastructure-driven agricultural land-use change.

three percent at a land rent slightly above 200 Euro per ha. For higher land rents, agricultural land was converted less to forest. Inversely, the agricultural LUC rate increased up to a slope of 15 percent. Regarding plot fragmentation, the agricultural LUC rate declined up to a parcel size between two and three ha. For the soil quality, the agricultural LUC rate changed at low scores between 30 and 40 as well as at high scores between 60 and 70. Regions with smaller and less intensive (lower livestock density) farms had considerably higher agricultural LUC rates, but were constant above one livestock unit per ha and farm sizes above 50 ha.

4. Discussion

In contrast to existing studies on (agricultural) LUC, we analyzed a rather stable landscape compared with regions under strong political or economic transition (e.g., in Eastern Europe) as a highlighted research gap by Plieninger et al. (2016). Although overall rather stable, the Metropolitan Region of Nuremberg is a typical examples for a region with polarized landscape dynamics (see Primdahl et al., 2013) but comparable institutional and environmental conditions as, e.g., the abandonment of crop- and grassland occurs at one location and the intensification at another location. The chosen medium-scale perspective thereby allows to bridge the gap between European-scale studies with heterogeneous data and small-scale studies with mostly homogenous agricultural LUC patterns. We distinguished between biophysical factors, agricultural, and socio-economic factors to make the polarization tangible. Conceptually, we analyzed major environmental, agricultural, and socio-economic drivers of agricultural LUC in a joined manner and considered their interaction with more robust tools (BRT) beyond previous mostly qualitative assessments of LUC drivers as stated by Plieninger et al. (2016).

Geographically, this study extends existing studies on agricultural LUC in Europe, which are mostly carried out in the Mediterranean, in the Alps, in Eastern Europe, and in Great Britain (van Vliet et al., 2015) and thereby may be representative for major parts of central Europe (especially low mountain ranges of Germany and Austria with mostly medium-sized farming structures).

4.1. Land-use change and hot-spot analysis

The major LUC in the Metropolitan Region of Nuremberg was related to agricultural land. Equally, LUC between agricultural land-use classes from cropland to grassland and vice versa with a nominal gain of grassland became apparent.

The Metropolitan Region of Nuremberg allowed for simultaneous assessment of intensification and extensification of agricultural land (polarized landscape dynamics) as identified by Kuemmerle et al. (2016) (e.g., intensification in western loess areas vs. extensification in northern areas with low soil quality ratings). The current extensification hotspot in the northern study area will be likely intensified in future as shown by multiple scenarios at the European level (Schulp et al., 2019), likely due to global market pressures and changing subsidy schemes. Such overarching perspective was refined and validated at the regional scale. The hot-spot analysis for the two main LUC pathways of agricultural land (to settlement and infrastructure as well as to forest) revealed a concentration of urban development in existing urban areas and an increase in forests in areas with an already high concentration of forest. We have shown a strong spatial concentration of both hot and cold spots for two major pathways of agricultural LUC. Settlement- and infrastructure-driven agricultural LUC is clustered and areas with low agricultural LUC rates, i.e., cold spots, hardly exist. Forest-driven agricultural LUC is spatially spread. These insights extend an existing study at the European scale (Kuemmerle et al., 2016). They mainly address gains and losses from a country's perspective. However, the country's perspective hardly depicts changes in landscape composition and configuration mostly relevant at the regional scale (e.g., analyzed in Meyer et al., 2015). Beyond, Kuemmerle et al. (2016) rather describe patterns and miss the analysis of drivers. Regional analyses of agricultural LUC allow for results with a higher relevance for landscape planning. The spatial concentration of built-up and forest land as well as the above-average decline of agricultural land in Bavaria might hint to weak governance regarding the maintenance or stability of agricultural land and other land uses. For the case study region, a governance instrument is missing: priority areas for agricultural land. This instrument in regional planning is in place for other German federal

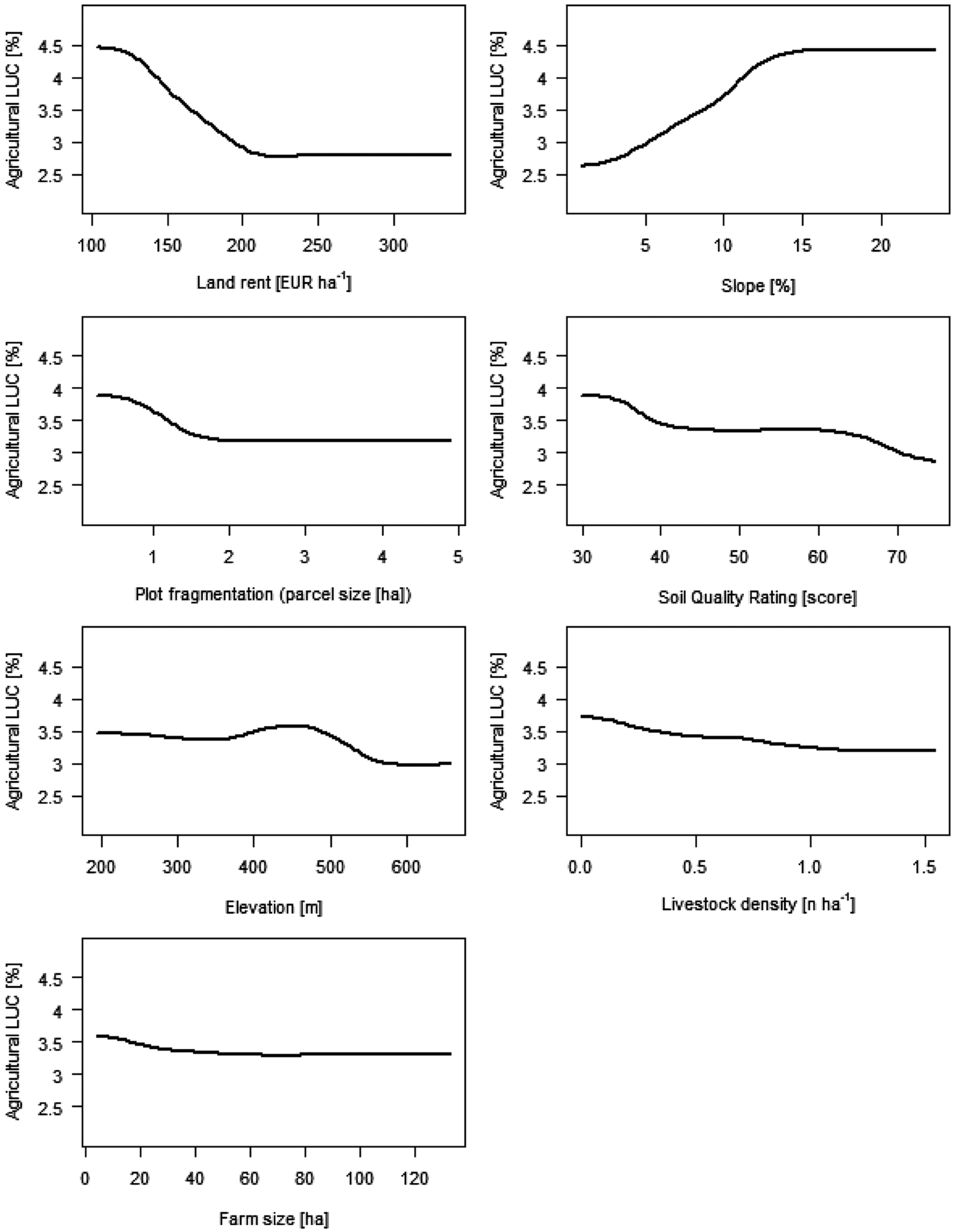

Fig. 5. Partial dependency plots for the seven most important explanatory variables (explanation > 5 %) for agricultural land-use change driven by forest and semi-natural land.

states. Without this instrument, local policymakers have more freedom to convert agricultural land (e.g., for urban development) compared with other German federal states. Equally, compensation payments to maintain agriculture on marginal land from the EU Rural Development fund did not seem to spatially balance the maintenance of agricultural land across the Metropolitan Region of Nuremberg.

Other LUC patterns such as the increase of grassland require further investigation. Permanent grassland stayed rather constant within the last decade (StMELF, 2018). Therefore, the increase in grassland might be attributable to non-permanent grassland driven by policies such as greening measures within the EU agricultural policy (i.e., rotational grassland and other green cover) (e.g., ecological focus areas Zinngrebe et al., 2017). Green cover dominates ecological focus areas in Bavaria. In addition, it needs to be considered that permanent grassland (i.e., grassland for more than five years) must not be converted to cropland. Therefore, farmers will unlikely increase permanent grassland as their land will not be legally convertible to cropland after five years of grassland use anymore and therefore considerably loose value.

The conducted regional LUC and hot-spot analyses are less susceptible to trends at the European scale: the drastic change of the economic and political system in post-socialist Eastern European countries might strongly overlay or hide regionally relevant agricultural LUC patterns as also indicated in the east-west gradient by Kuemmerle et al. (2016) (i.e., the generally higher agricultural LUC rates in Eastern Europe). Therefore, regional analyses in Western Europe like this study with average agricultural conditions might be more representative for a continuous, but stable decline of agriculture as identified in other studies (Kuemmerle et al., 2016; Levers et al., 2018a).

4.2. Drivers of agricultural land-use change

We identified different drivers of agricultural LUC depending on the two major pathways to built-up and to forest and semi-natural open land. The BRT explained major pathways of agricultural LUC better for settlement-driven LUC than for forest-driven LUC. From agricultural land to built-up land, we identified population density, population development, and the unemployment rate as major explanatory variables. The agricultural LUC rate increased with increasing population density and development. The agricultural LUC rate increased with a decreasing unemployment rate. These indicators might reflect the economic prosperity and the need for infrastructure development in more populated areas. This is in line with van Vliet et al. (2015) and Plieninger et al. (2016), who also identified population density as a considerable driver of agricultural LUC. However, their syntheses focus on general patterns of agricultural extensification, which do not distinguish between the analyzed LUC pathways in this study. We confirmed other studies for Western Europe (Plieninger et al., 2016) that biophysical factors and farm characteristics are important for forest-driven agricultural LUC. At lower elevations, agricultural LUC was higher, which might be linked to both preferred urban and infrastructure development in lowlands. The high relevance of agricultural and forest policy highlighted by Plieninger et al. (2016) or of policies bundles by Hersperger and Bürgi (2009) was not tested in this study and should be considered in future research.

In contrast to existing studies at larger scales (Levers et al., 2018b), small-scale processes and locally relevant variables such as the farm succession probability were included as requested by van Vliet et al. (2015). We considered interactions between different factors through BRT to address limitations of previous studies using a linear regression model (e.g., Gellrich et al; Gellrich et al., 2007a, 2007b). The chosen BRT allowed to test biophysical factors (e.g., slope or soil quality) and socio-economic as well as cultural factors (e.g., farm succession, agricultural land rent) jointly in flexible combinations. Although in different categories, biophysical, farming, and socio-economic parameters are partly linked.

The higher forest-driven agricultural LUC rates at high slopes or under low soil quality ratings equally underline the dominance of farm economics: low soil quality land at unfavorable locations (high slope) and inefficient land management (high plot fragmentation) strongly encourage the abandonment of agricultural land. This strong dominance of agricultural parameters explaining agricultural LUC change hints to strong deficiencies of the Common Agricultural Policy. Agricultural LUC due to afforestation, which is mostly associated with parameters closely linked to the farming system, is increasing despite high subsidies from the EU Rural Development Programme to maintain extensive agricultural practices. The rational of globalization and the associated market pressure (van Vliet et al., 2015) lead to lower returns from agricultural products and to higher yield expectations for economic viable farming. This pattern fits to the considerable importance of the land rent for explaining agricultural LUC due to forest expansion. In addition, communities with smaller farms and less intensive livestock production are more likely subject to afforestation. To address this, it would be necessary to improve the impact and effectiveness of the subsidy payments (Früh-Müller et al., 2019). Especially, the non-linear impact of land rent and biophysical parameters has shown that especially subsidy payments or other governance instruments should be more refined by biophysical parameters relevant for agricultural management and agro-ecological effects to maintain a landscape mosaic in the given study area. It would allow to improve subsidy payments especially under a likely declining budget for the EU Common Agricultural Policy in the future funding period and considering the anticipated future result-orientation of subsidy payments (Pe'er et al., 2019).

For the transition from agriculture to built-up land, the negligible explanatory power of farming system variables allows for two recommendations depending on the political aims: i) to maintain agriculture in prosperous regions for food production, it would be necessary to increase compensation payments although likely inefficient from an economic point of view. These compensation payments would also address increasing demand for regional food production (Pinto-Correia et al., 2018). ii) To improve the economic use of public funds, subsidies such as direct payments for farming could be completely abated at urban development hot spots and redirected to environmentally more beneficial farming (e.g., linked to nature conservation or water protection policies Primdahl et al., 2019) or to maintain cultural landscapes through farming.

The abandonment of agriculture on marginal locations in favor of afforestation will considerably change the appearance of highly diverse cultural landscapes: major afforestation hotspots (e.g., Franconian Swiss) in our study have lost and will most likely continuously lose with respect landscape aesthetics and diversity under the given economic constraints for farming and inadequate governance. Therefore, future studies should assess the value added of maintaining agriculture on marginal land instead of forest. One pathway could be to compare the potential beneficial or negative impacts on ecosystem service supply and demand (Meyer et al., 2015) for agricultural cultural landscapes. Ecosystem services likely differ between market-oriented and societal-value oriented land-use systems (Früh-Müller et al., 2016). Studies should identify thresholds for the share and intensity of agriculture that considerably improve or deteriorate regulating and cultural ecosystem services as well as biodiversity.

Agricultural LUC towards built-up land might cause different issues. This process fits to the rational of agricultural extensification due to the change from a rural to an urban society mentioned by van Vliet et al. (2015). Farm characteristics seem completely unimportant for agricultural LUC driven by urbanization. Here, the urbanization trend was manifested and seemed to overrule all farm characteristics and biophysical parameters. Only a small share of ecosystem services is provided in cities (Gómez-Baggethun and Barton, 2013). Not only ecosystem services between different ecosystems but also other major basic human needs such as living space, working opportunities, and traffic infrastructure compete with provisioning ecosystem service (especially food production) as also considered in the concept of peri-urban agriculture (Zasada, 2011). How this exchange could be quantified, needs to be tested. Urban stakeholders often consider provisioning ecosystem services from agricultural land less important up to now. Cultural or regulating ecosystem services are often more important for multiple reasons as shown for urban ecosystem service assessments (Gómez-Baggethun and Barton, 2013; Meyer and Schulz, 2017). In that respect, it will be necessary to identify whether ecosystem services of locally sourced agricultural products (provisioning ecosystem services and local food security) can be aligned with those provided by other urban green spaces such as forests with a generally high provision of cultural and regulating ecosystem services (Meyer et al., 2019).

4.3. Limitations

Conceptually, this study combined spatially explicit datasets and census data. As the latter was only available at community level, we conducted the BRT analyses at community level as further disaggregation would have created an artificial homogeneity of census data. In addition, we could not link farmers and their practices to actual plots for data protection purposes. Future research should be supported by a modified data protection policy of the EU: farmers could be asked to reveal major farm characteristics and biophysical parameters in an anonymized manner in addition to already published subsidies (Früh-Müller et al., 2019) as given in the Farm Accountancy Data Network at NUTS2 level (Terres et al., 2015). Such improvement would also reduce mostly missing time-series data on farming characteristics, which impedes to analyze LUC patterns at a higher temporal resolution. The chosen period of 15 years was due to missing high-resolution land-cover data for earlier periods. However, most existing studies looked at longer time-frames beyond a 20-year timeframe (Plieninger et al., 2016). Therefore, our study looking at short-term and recent dynamics is rather complementary to existing research.

Methodologically, we used BRT to allow for flexible combinations of parameters and to capture non-linear relationships in contrast to linear regression techniques (Dormann et al., 2013; Levers et al., 2014). However, it was necessary to consider potential collinearity in predictor variables for the interpretation of the results, which may still prevail to a limited extent (e.g., soil quality rating and land rent, which are likely negatively correlated).

The chosen medium-scale study may provide less an overview of Europe compared with other studies (e.g., Levers et al., 2018b), but allows to consider potentially explanatory variables for agricultural LUC that are not consistently available across Europe (e.g., farm succession or land parcel size) at sufficiently high resolution (e.g., in Terres et al., 2015). In addition, the spatial data heterogeneity is much lower and mostly limited to smaller conceptual changes (e.g., better quantification of water bodies).

5. Conclusions

The shown LUC dynamics linked to agricultural land highlight the need for improved mechanisms to maintain diverse and equally distributed multifunctional cultural landscapes. The further development processes and the current growth of the population in urban regions will reinforce the trend of increased spatial separation of agricultural production and urban development. The opposite pathway from agricultural land to forest is equally challenging: the strong growth of forest land in highly fragmented cultural landscapes (e.g., the Franconian Swiss) will likely affect multiple ecosystem services (e.g., landscape aesthetics) and biodiversity due to changes in landscape composition and configuration.

The analysis of drivers of agricultural LUC has shown that two major issues need to be addressed if agricultural LUC should be governed more efficiently at the regional scale: spatial planning needs to address priorities of agricultural land, also in urbanizing regions. Otherwise, population development and space consuming business development will mostly outcompete agricultural production. We would recommend functioning governance mechanisms, for example, through regional planning. Other options could be mandatory fiscal impact assessments for new built-up land (i.e., assessing the long-term financial benefits at community level) or even a market for land consumption certificates (Langer and Korzhenevych, 2018) if governed better than GHG certificates. Although the decline of agricultural land will unlikely affect food security, a higher demand for regional agricultural products will be less likely met if the trend of agricultural LUC continues.

The decline of agricultural land due to afforestation was explained by biophysical parameters affecting farming such as the slope and by combined biophysical and farming parameters such as the land rent. Existing subsidies to maintain agriculture for marginal arable land within the EU Rural Development Programme do not seem to ensure the maintenance of agricultural land. However, we equally miss knowledge on the extent of agricultural LUC without these subsidies.

Future research should assess the impact of changed governance mechanisms, especially under a new Common Agricultural Policy. In addition, the relevance of different development pathways for agricultural production should be evaluated regarding the opportunity costs of agricultural land. Studies should test how alternative production pathways such as agricultural products targeted for a regional market or organic agriculture perform not only compared with conventional agriculture but also compared with alternative land uses such as built-up land or other (urban) ecosystems.

CRediT authorship contribution statement

Markus A. Meyer: Conceptualization, Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Funding acquisition. **Andrea Früh-Müller:** Conceptualization, Data curation, Writing - review & editing.

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Appendix A. Supplementary data

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