

Nineteenth-century land-use legacies affect contemporary land abandonment in the Carpathians

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Abstract Historical land use may shape landscapes for centuries into the future, but it remains unclear how much land-use legacies affect contemporary land use. Knowing for how long and how strongly land-use legacies affect agricultural systems is important for contemporary land-use planning and conservation. We assessed the effect of nineteenth-century agricultural legacies for contemporary agricultural abandonment by integrating historic maps and satellite imagery in the Carpathian region. We modeled the choice of agricultural land, and the legacies of Habsburg and Socialist regimes, while controlling for agro-

ecological, accessibility and sociopolitical variation. Farming during the Habsburg era was concentrated in agro-ecologically suitable areas, but socialist agricultural expansion occurred mostly in less suitable areas, leading to subsequent abandonment. In addition, our results showed that historic land use affected abandonment even 100 years later. Although legacies diminished over time, their effects were amplified when political transformations occurred, likely due to land tenure systems, land owner attitudes, cultural values and differences in land improvement over time. Taken together, land-use legacies and shifts in political systems can constrain current land management and possible future land-use options, suggesting that contemporary land-use decisions can affect future land use for decades and even centuries.

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Introduction

Contemporary global environmental change reflects centuries of socio-ecological interactions. One of the major components of global change is land-use change (Fuchs et al. 2015; Hurtt et al. 2006; Schelhaas et al. 2003), which is the result of complex forces such as environmental conditions, accessibility and markets (Lambin and Meyfroidt 2011; Meyfroidt 2015; Plieninger et al. 2016). In addition to these proximate and underlying drivers, historical land uses can affect ecosystem structure and functioning for centuries (Foster et al. 2003; Perring et al. 2016; Plue et al. 2009), yet the effects of land-use legacies on environmental change remain poorly understood (Perring et al. 2016).

Worldwide, many landscapes bear marks of historical land use (DeFries et al. 2004; Foley et al. 2011). From an ecological perspective, land-use legacies affect soils, water content, seed source, vegetation composition, and species establishment and dispersal (Brudvig et al. 2013; Ficitola et al. 2010; Foster et al. 2003). Land-use legacies include, for example, the chemical and biological alterations imposed on soils by past agricultural activity, as far back as the Roman Empire (Montgomery 2012; Plue et al. 2008). The reason why such legacies can persist for centuries is that changes in soil structure favor non-native species (Ficitola et al. 2010), constrain vegetation succession and productivity (Foster et al. 2003), and change seed bank, seed dispersal and soil nutrients (Plue et al. 2009, 2008). Agricultural legacies also affect beta-diversity in forest understory and hence ecosystem functioning (Mattingly et al. 2015), but past land-use decisions often cause biodiversity loss with a time lag (Dullinger et al. 2013; Essl et al. 2015).

From a land-use perspective, land-use patterns and change are path-dependent processes (Lambin and Geist 2006; Meyfroidt 2015) affected by historical land uses (Munteanu et al. 2015). Path dependency is prominent in urban dynamics (Lambin and Geist 2006; Seto et al. 2012), but all types of land use may exhibit path dependencies (Meyfroidt 2015; Verburg et al. 2004). For instance, areas that were historically non-forested had a 50% higher chance of contemporary harvests and natural disturbances compared to areas that were historically forested (Munteanu et al. 2015). In swidden-fallow systems, path dependence shapes farmers' land-use choices (Coomes et al. 2011) and agricultural intensification is also path dependent and self-reinforcing (Börjeson 2007). However,

while there is empirical evidence of path dependency, effects of long-term land-use legacies on recent land change have rarely been quantified.

Land-use theory explains land-use choices and subsequent land changes based on environmental, social, political, economic, technological and cultural context (Geist and Lambin 2002; Meyfroidt 2015). Immediate land-use choices depend on spatial characteristics such as environmental suitability or accessibility (Müller et al. 2013; Nagendra et al. 2003). Based on land rent theory, agricultural land with the most favorable environmental conditions will be preferentially farmed (Ricardo 1821), and after land-use specialization, marginal land will be abandoned (Müller et al. 2013). However, if indeed path dependencies and land-use history affect contemporary land change; then, even after accounting for the spatial determinants, legacies are also important predictors of change.

The effect of land-use legacies on contemporary land change should be most obvious during times of rapid and widespread land-use change stemming from shifts in social, political, economic, technological or cultural factors (Geist and Lambin 2002; Meyfroidt 2015). For instance, agricultural expansion during the Soviet Virgin Lands Campaign in Northern Kazakhstan affects contemporary land abandonment (Kraemer et al. 2015). In socialist Romania, war repayments to the Soviet Union led to institutionalized overexploitation of forests (Munteanu et al. 2016). The transition of former Soviet states to market economies led to widespread land abandonment across Europe and Asia (Alcantara et al. 2013; Prishchepov et al. 2012). Similarly, Eastern Europe had many shifts in political and institutional regimes that caused changes in land management and affected land-use patterns, providing a great 'natural experiment' to study legacies.

Agricultural abandonment is widespread throughout both temperate and tropical biomes (Munroe et al. 2013) and well suited to study legacy effects, because post-agricultural landscapes can bear the marks of historical land-uses for decades (Plieninger 2014; Plieninger et al. 2010). There are several processes that can result in contemporary abandonment. For example, environmental conditions and intensive agricultural practices may make soils unsuitability for agriculture (Matteucci et al. 2016). Similarly, the removal of subsidies can lead to rapid abandonment (Brain 2010; Jepsen et al. 2015; Kraemer et al. 2015). Indeed in Europe, the drivers of recent land abandonment include environmental, financial and socioeconomic factors (Estel et al. 2015; MacDonald et al. 2000; Prishchepov et al. 2012), and due to the collapse of socialism, much of the European land abandonment in past decades was concentrated in the former Eastern Bloc (Griffiths et al. 2013; Munteanu et al. 2014), making this regions well suited to

study the effects of land-use legacies on contemporary abandonment.

Our overarching goal was to assess the role of century-long land-use legacies on contemporary agricultural land use in the Carpathian region. We define land-use legacies as the effects of historical land use on contemporary agricultural abandonment, especially the transition between tilled annual or perennial crops to any other land cover type. Our research questions were:

1. How did agricultural land use change in the Carpathians since 1860, and to what extent do agro-ecological conditions explain agricultural land-use during each of the major political regimes?
2. Were there land-use legacies after controlling for agro-ecological variation, and how did the persistence of the legacy effect change over time?
3. Did the strength of the legacy effects differ for the distinct historical political regimes?

We expected to observe agricultural expansion, followed by abandonment after the collapse of the Soviet Union, and that agro-ecological conditions would explain well the choice of arable land, particularly in historical periods. We expected to observe land-use legacies of multiple historic time periods and expected that their effect would diminish over time.

Methods

Study area

We studied an area of approximately 265,000 km² covering the Carpathians and adjacent parts of the Pannonian Plains. The study region includes all of Slovakia and parts of Hungary, Romania, Czech Republic, Poland and Ukraine (Fig. 1). We measured agricultural land use at six points in time: Habsburg era (1860), Interwar (1930), socialism (1960, 1985) and post-socialism (2000, 2010, Table 1). Contemporary land cover is a mix of agricultural fields, grasslands and forests at higher elevation and predominantly agricultural fields and grasslands at lower elevations (Kozak et al. 2013b; Munteanu et al. 2017). Agricultural land covered 23% of the region in 2010 (Griffiths et al. 2013) (Fig. 1).

Land was largely owned by nobles during the Habsburg Empire (Berger 2006). During socialism, most land was under collective state management, with the exception of Poland and some isolated mountainous areas (Kozak et al. 2013a; Lerman et al. 2004). Following the collapse of the Soviet Union, land ownership was distributed to the rural population or restituted to historical owners and

contemporary farms range from small subsistence family farms to large private landholdings (Griffiths et al. 2013).

During the Habsburg Empire, agriculture expanded. During socialism, however, despite policies fostering agricultural expansion and intensification, agricultural abandonment was already widespread (Jepsen et al. 2015; Munteanu et al. 2014). After the collapse of the Soviet Union, rapid abandonment continued. Approximately 24% of the total cropland in 1985 was abandoned by 2000 and another 9% by 2010 (Griffiths et al. 2013; Munteanu et al. 2014).

Datasets

We reconstructed agricultural land use from 1860 to 2010 (Table 1 and Supplementary Material 1). Here, we define agricultural land as tilled areas used for crops according to historic maps or satellite classification and do not include pastures and grasslands (Table 1). We considered an area to have experienced land abandonment, if its land use changed from agriculture to any other land-cover type (including to grasslands or pastures). We classified land use for a regular 2 × 2 km point sampling grid (Gallego and Delincé 2010; Munteanu et al. 2015).

Our study area included 70,947 points. For 1860, 1930 and 1960, we assigned binary land-use classes (agriculture or non-agriculture) to each point (Supplementary Material 3). The most recent maps (1960) had positional errors less than 10 m, but for the oldest maps (1860s), errors ranged from 11 to 200 m (Kaim et al. 2014; Mackovčín 2014; Pavelková et al. 2016; Timár 2004). Because in some cases, we could not assess the positional errors of the maps themselves, we ensured the consistency of point locations across map sets, by using a back-dating approach in which the location of the digitized point was verified for subsequent dates relative to nearby landmarks (Kaim et al. 2016). This approach allowed us to avoid false land use changes induced by potential positional errors. This approach was employed for all points in Slovakia, Czech Republic and Poland. Overall, uncertainties induced by positional accuracies when using point-grid analyses did not greatly affect land change assessments in the Polish Carpathians (Kaim et al. 2014). For 3409 points in Romania and Hungary, we could not clearly distinguish agriculture from grasslands in 1860 and assigned the land-use class according to the subsequent map dataset (1930). We checked for errors by running the subsequent analysis with and without these points, but our results did not change substantially, so we retained the points in the analysis. For 1985, 2000 and 2010, we extracted land use from 30-m resolution Landsat TM/ETM + image classification. The overall accuracy of the remotely sensed land

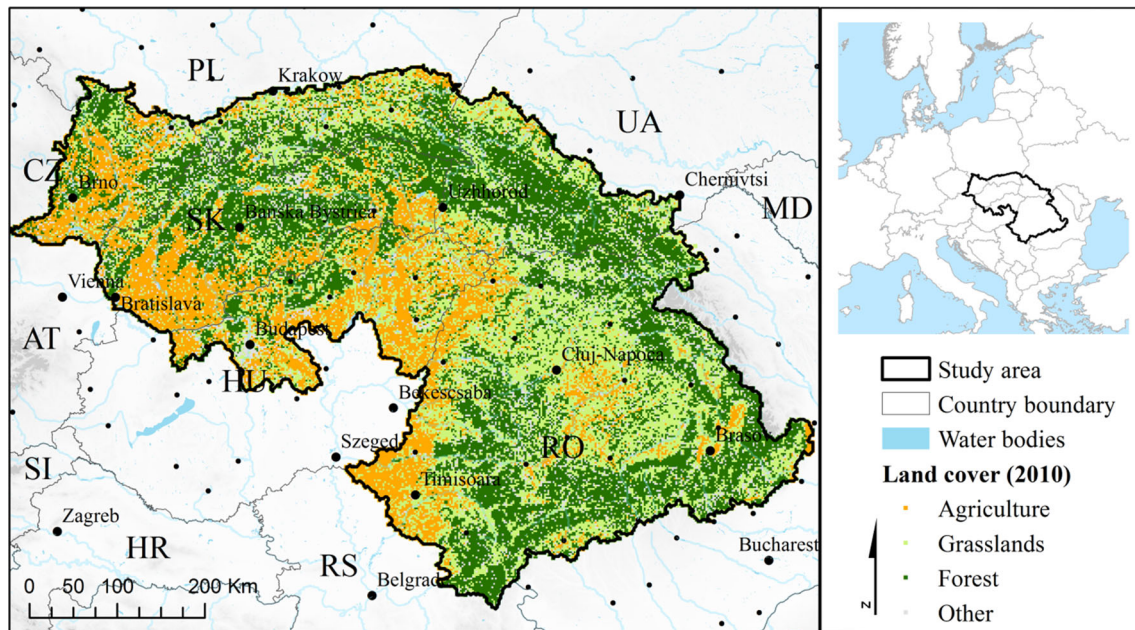


Fig. 1 Study area. Country codes: *CZ* Czech Republic, *HU* Hungary, *PL* Poland, *RO* Romania, *SK* Slovakia, *UA* Ukraine

Table 1 Paper terminology

Agricultural land	We define agricultural land here as tilled areas, covered by annual or perennial crops. Our definition of agricultural land does not include pastures or grasslands
Habsburg era	In this manuscript, the time from 1800s to 1914, during which most of the study area was part of the Habsburg Empire (except the southern ridge of the Carpathian Mountains in Romania). We refer to early Habsburg as the period before 1860 and to late Habsburg thereafter ^a
Interwar era	1914–1945, time of major political transformations due to the two World Wars, and the Great Depression. The period is marked at both ends by the Habsburg and the Socialist political regimes
Socialist era	In this manuscript, 1945–1985, during which all countries in the study area were influenced by Moscow politics. We refer to early socialist as the period before the 1960s and to late socialist thereafter ^a
Post-socialist era	In this manuscript, 1985–2010, during which most countries in the study region changed to market economies and joined the EU (except Ukraine) ^a
Socialist abandonment ^b	Land abandonment that occurred between the 1960s and 1985, mapped using military topographic maps (1960s) and Landsat image composites (1985). Note that this does not capture the entire Socialist era, but a period of 25 years, to ensure comparability with post-socialist abandonment
Post-socialist abandonment ^b	Land abandonment that occurred between 1985 and 2010, mapped using Landsat images for 1985, 2000 and 2010 ^a
Land-use legacy	The effects of historical land uses and land-use decisions on contemporary land-use change, once other spatial determinants of change are accounted for
Habsburg legacy	The effect of whether or not land was farmed prior to 1860 on subsequent agricultural abandonment. This legacy captures the effect of early versus late Habsburg agriculture on abandonment
Habsburg versus Socialist legacy	The effect of the whether or not land was farmed prior to 1930 on subsequent abandonment. This legacy captures the differences between land farmed during the Habsburg era and agricultural expansion during the socialist era ^c
Socialist legacy	The effect of whether or not land was farmed prior to the 1960s on subsequent abandonment. This legacy captures the effect of early versus late socialist agricultural expansion on abandonment

^a We note that the historical periods are not fully captured by our analysis period. We use the same names for simplification

^b We define land abandonment to represent land-use transitions between tilled annual or perennial crops to any other land cover type (including grasslands and pastures)

^c The Interwar era represented a time of major political and socioeconomic changes with largely stable agricultural dynamics throughout the period (Munteanu et al. 2014). We use this point in time to capture effects of two major land management systems that mark the Interwar period: Habsburg and Socialist

use classifications was over 80% (Griffiths et al. 2013, Supplementary Material 1).

Based on the binary classifications (agriculture versus non-agriculture), we mapped socialist abandonment (1960–1985) and post-socialist abandonment (1985–2010) (Table 1) as all points that transitioned from agriculture to non-agriculture in any of the two periods. Socialist abandonment represented 20,501 points that were in agriculture in 1960 and either abandoned or still in agriculture by 1985. Post-socialist abandonment (between 1985 and 2010) represented 13,419 points that were agriculture in 1985 and either abandoned or not by 2010.

Data analysis

Agricultural dynamics and agro-ecological conditions

To quantify agricultural change in relation to agro-ecological conditions (Objective 1), we compared change trajectories between binary agriculture versus non-agriculture classes for six time periods (Supplementary Material 1). To understand the spatial determinants of agricultural dynamics in different time periods, we selected from the total sample (70,947 points) only those points that were either (a) used for agriculture during the Habsburg era (i.e., 1860, 31,106 points), (b) converted to agriculture from other land uses during the Socialist era (i.e., 1960, 6488 points) or (c) used for agriculture during the post-socialist era (i.e., 2010, 15,722 points). Because we were interested to what extent land-use decisions during Habsburg and Socialist eras were based on agro-ecological conditions, we modeled agriculture as a function of seven agro-ecological variables: elevation, slope, distance to nearest river, average annual temperature, average annual precipitation, crop suitability index and length of the growing season (Table 2, Supplementary Material 4) using multiple logistic regression models (Hosmer et al. 2013). We evaluated model performance using the area under the receiver operating curve (AUC Freeman and Moisen, 200).

Persistence of land-use legacies

To quantify the persistence of land-use legacies over time, i.e., for how long effects of historic uses can still be evident on the landscape (Objective 2), we compared the effect of Habsburg land-use on socialist (1960–1985) and post-socialist abandonment (1985–2010) (Supplementary Material 2). We fitted multiple logistic regression models (Hosmer and Lemeshow 1980). Our models included 20,501 points for the socialist abandonment models and 13,419 points for post-socialist abandonment (Supplementary Material 5). In addition to the agro-ecological variables used in Objective 1 (7 variables), we controlled for accessibility to markets

and ease of transport (6 variables) and sociopolitical variation (2 variables) (Table 2). We estimated the effect of Habsburg legacy (Table 1) via the odds ratio, which represents the exponential values of the model coefficients (Hosmer et al. 2013). For each of the two abandonment time periods, we fitted one overall model for the Carpathian region and six country-specific models (Müller et al. 2009). In total, we fitted fourteen models, seven for each abandonment period (Supplementary Material 5).

We performed best-subsets variable selection using an exhaustive search (Hosmer et al. 2013) based on the Akaike Information Criterion (AIC). To ensure model parsimony, we restricted the maximum number of variables per model to six for the country models and seven for the overall model (including a country dummy). We always retained the best-performing model, and in cases where the best-performing model did not include the land-use legacy (4 of 14 models), we refitted the best-performing model adding the land-use legacies, because we were interested in estimating their effect.

We calculated the relative rates of agricultural abandonment in areas that were not farmed in 1860 (i.e., late Habsburg) comparing to areas that were already farmed then (i.e., early Habsburg) based on the odds ratio. We transformed the odds ratio to percentage points, where values higher than 0 indicated how much more likely abandonment is in areas that were not farmed historically versus areas farmed then. For the remaining variables, we interpreted the sign of model coefficients, to understand how agro-ecological conditions and accessibility influenced agricultural abandonment. We did not calculate significance levels or confidence intervals in our analysis because our data represent a full census of historical and recent land cover and because our estimate of the effect that we observed is independent of sample size (Lohr 2010; Munteanu et al. 2015). AUC values varied between 0.79 for the overall socialist abandonment model and 0.82 for the overall post-socialist abandonment model. We checked the degree of spatial autocorrelation of the dependent variable using semivariograms of model residuals (Curran 1988; Griffith 2003) and did not find significant spatial autocorrelation.

Strength of land-use legacies

The strength of land-use legacies refers to the effect size of different historic land uses on contemporary abandonment. To assess the strength of land-use legacies, we compared the effect of legacies from three historic time periods (Habsburg era, Interwar era, Socialist era) for post-socialist agricultural abandonment (Objective 3, Supplementary Material 2). We modeled post-socialist abandonment using multiple logistic regression models (Hosmer and

Table 2 List of predictors used in logistic regression models, including land use legacies, agro-ecological conditions, accessibility and sociopolitical variables

	Description	Source	Unit	Spatial resolution
Response	Agricultural abandonment between 1960 and 1985	Mapped, Griffiths et al. (2013)	Yes/No	30 m
	Agricultural abandonment between 1985 and 2010	Griffiths et al. (2013)	Yes/No	30 m
Historic land use	Habsburg agriculture (1860)	Mapped	Yes/No	Vector
	Interwar agriculture (1930)	Mapped	Yes/No	Vector
	Socialist agriculture (1960)	Mapped	Yes/No	Vector
Agro-ecological*	Elevation	Farr et al. (2007)	m	90 m
	Slope	Farr et al. (2007)	°	90 m
	Annual mean temperature	Hijmans et al. (2005)	C° × 10	~ 1 km
	Annual precipitation in mm	Hijmans et al. (2005)	mm	~ 1 km
	Crop suitability index	FAO (GAEZ) (2014)	%	~ 8 km
	Length of growing season	FAO (GAEZ) (2014)	days	~ 8 km
	Accessibility	Travel time to the nearest town with 50,000 inhabitants	Nelson (2008)	minutes
Distance to nearest major city		ESRI (2008)	km	Vector
Distance to nearest settlement		EEA (2013)	km	Vector
Distance to nearest road		CIESIN and ITOS (2013)	km	Vector
Distance to nearest current border		Calculated	km	Vector
Distance to nearest railroad		ESRI (2008)	km	Vector
Distance to nearest main river		Vogt et al. (2007)	km	Vector
Sociopolitical	Country	ESRI (2008)	N/A	Vector
	Population count 1990	CIESIN, FAO and CIAT (2005)	No	~ 5 km

For studying how agro-environmental conditions affect the choice of farmed land during different time periods, we only used explanatory variables marked with * in our models

Lemesbow 1980) that controlled for agro-ecological, accessibility and sociopolitical variation (same 15 variables as in Objective 2, Table 2). We applied same model selection criteria as in Objective 2, retained the best-performing models, and, in cases where the best-performing model did not include the land-use legacy (8 of 21 models), refitted the best-performing model after adding land-use legacies and interpreted the odds ratios to estimate legacy effects. The legacy of the Habsburg era (hereafter Habsburg legacy, Table 1) captures differences in abandonment between land already farmed prior to 1860 (early Habsburg) compared to land farmed after 1860 (late Habsburg). The legacy of the Socialist era (hereafter Socialist legacy, Table 1) captures differences in abandonment between land expanded for agriculture in the Socialist era prior to 1960 (early socialist), compared to after 1960 (late socialist). Finally, the legacy of the Interwar era (hereafter Habsburg versus Socialist legacy, Table 1) captures differences between land farmed already during the Habsburg era and land expanded during the Socialist era.

In total, we fitted twenty-one models (one overall and six country-specific models for each of the three periods). Sample size varied from 3424 for the Socialist legacy model to 16,843 for Habsburg versus Socialist model

(Supplementary Material 6). For overall models, AUC values ranged from 0.80 (socialist legacy) to 0.83 (Habsburg vs. Socialist legacy). For the country models, AUC was lowest for Ukraine in the Habsburg versus Socialist model (AUC = 0.64) and highest for Poland in the Socialist legacy model (AUC = 0.91) (Supplementary Material 7).

Results

We found strong land-use legacy effects on land abandonment in the Carpathians. As expected, the strength of the legacies diminished with time, but differences in land abandonment were greatest in areas farmed under different political regimes. Agricultural land expanded until 1960, but after 1930, this expansion was to a large extent in less environmentally suitable areas. Abandonment was already strong during socialism and continued during post-socialism. The effect of Habsburg land-use legacies was stronger on socialist than on post-socialist abandonment, but we found the strongest legacies for post-socialist abandonment when comparing areas farmed during the Habsburg versus the Socialist era.

Agricultural dynamics and their drivers

Agricultural use peaked in 1960, when agricultural land covered 38% of the Carpathians (Fig. 2). In 1860, roughly 31% of the study area was arable, and this area increased during the late Habsburg era. Romania and Ukraine had the highest percentage of land in agriculture in 1960 with 32 and 25% of their territory, respectively. By 2010, only 20% of the study region was in agriculture (Fig. 2).

Agricultural abandonment started during the late Socialist era, when 34% of the agricultural land was abandoned, and continued throughout the post-socialist period, when 30% of the remaining agricultural land was abandoned. Between 1960 and 1985, abandonment was most rapid in the Polish Carpathians and the Southern

Romanian Carpathians. Between 1985 and 2010, the most rapid abandonment occurred in Ukraine and Romania. In Poland, abandonment was substantially higher during socialism (68%) than during post-socialism (33%, Fig. 2).

Socialist agricultural expansion occurred predominantly in less suitable areas, while both Habsburg agriculture and the post-socialist agriculture were concentrated where agro-ecological conditions were favorable (AUC = 0.82 and 0.89, respectively) (Fig. 3a, c). Areas at low elevations, flatter slopes, closer to rivers, and with higher precipitation and better crop suitability were more likely to be farmed in the Habsburg era. Conversely, areas of new agriculture during socialism, i.e., points converted to agriculture by either 1960 or 1985, were less well explained by agro-ecological conditions (AUC = 0.69) (Fig. 3b), and agricultural

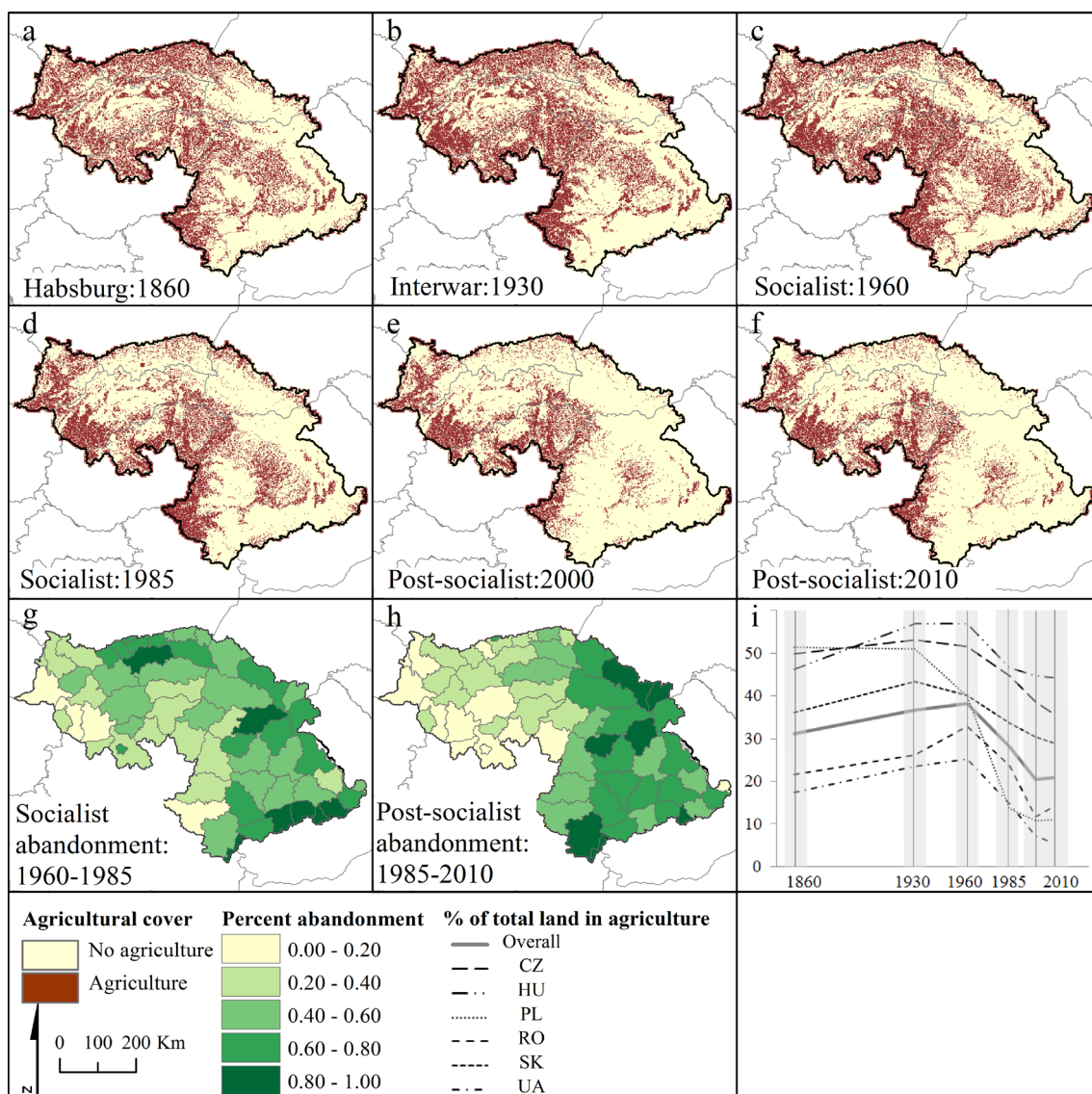


Fig. 2 a–f Agricultural land between 1860 and 2010, g–h socialist and post-socialist land abandonment in the Carpathian region and i change in percent of total land in agriculture by country (see Table 1 for definitions)

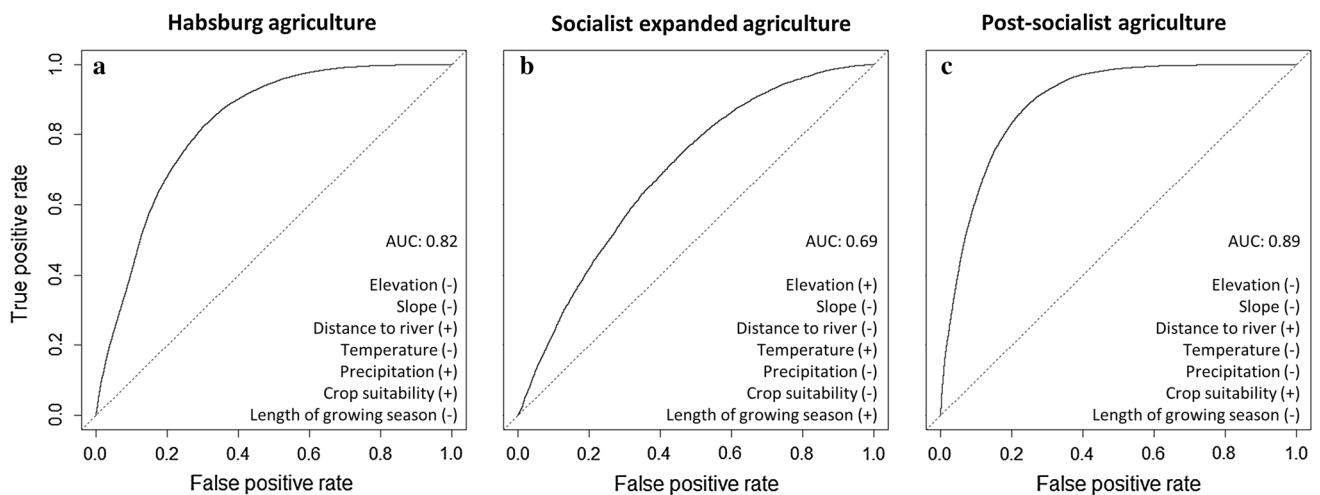


Fig. 3 Model performance for distribution of agricultural land as a function of environmental variables during the Habsburg (a), Socialist (b) and post-socialist eras (c). Socialist expanded agriculture refers

expansion happened mostly at higher elevations and in areas with lower crop suitability. Finally, the occurrence of agriculture in both 2000 and 2010 was well explained by agro-ecological factors (AUC 0.89) (Fig. 3c).

Persistence of legacies

Clearly, agro-ecological conditions and accessibility are important spatial determinants of agricultural land-use patterns. Furthermore, the same spatial determinants affected both historical and recent land use, which means that using only historical land use to predict current land use patterns would greatly overestimate legacy effects. However, we found that even after controlling for agro-ecological, accessibility and sociopolitical variation, the effect of land-use legacies was clearly evident and persisted for as long as a century. Indeed, Habsburg legacies affected both socialist abandonment and post-socialist abandonment. The odds of socialist abandonment were 65% higher in areas converted to agriculture by Habsburgs after 1860, compared to areas farmed before 1860, and the relationship was strong across all countries. The legacy effect was, however, smaller for post-socialist abandonment (46% higher odds). In Poland (163%) and the Czech Republic (104%), the odds of socialist abandonment were especially high if land was farmed after 1860, but in Slovakia, the odds were weaker (39%, Fig. 4a). Aside from legacy effects, we found that socialist abandonment was concentrated near settlement, on steeper slopes and in areas with low crop suitability (Supplementary Material 8).

Comparing the Habsburg legacy for socialist abandonment (65% higher odds) with that for post-socialist abandonment (46%) showed that land-use legacies diminished over time. The Habsburg legacy on post-socialist abandonment was

only to agricultural land expanded during the Socialist time period (b). Model performance is measured as AUC, where values close to 1 indicate high model performance

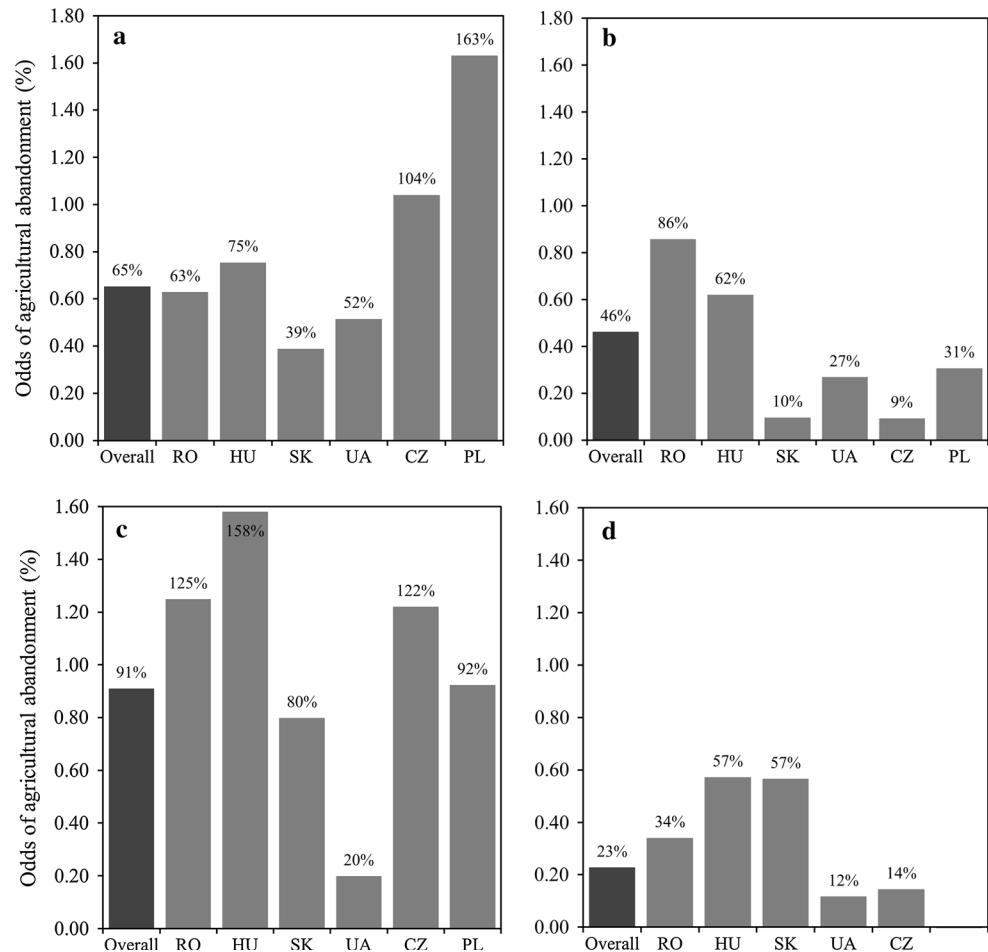
strong in Romania (86%) and Hungary (62%), but practically absent in Slovakia and Czech Republic (10 and 9%, respectively, Fig. 4b). In addition to the legacy effects, our models showed that post-socialist abandonment was concentrated in areas with steep slopes, high precipitation and low crop suitability (Supplementary Material 8). Overall, our results showed that even when accounting for agro-ecological and accessibility variation, legacy effects were strong, but their effect diminished over time.

Strength of land-use legacies

We compared the post-socialist legacy effect of three historic periods: the Habsburg, the Interwar and the socialist era. Overall, we found that areas that were later converted to agriculture had higher odds of abandonment than areas farmed earlier. Of all the areas abandoned by 2010, most were on land farmed by the Habsburgs (before 1930), but new socialist agriculture was abandoned at higher rate than Habsburg agriculture (Supplementary Material 6). Legacy effects were strong even when accounting for agro-ecological, accessibility and sociopolitical factors. All models were consistent in their variable selection: abandonment occurred predominantly on steeper slopes and in areas with less suitable soils and more precipitation. The socialist legacy models also indicated higher chance of abandonment in more accessible areas and closer to rivers (Supplementary Material 9).

When comparing the legacy effects among the three time periods (Habsburg, Interwar and socialist), we found greatest differences for the Habsburg versus Socialist legacy (Fig. 4). Land farmed during socialism was 91% more likely to be abandoned compared to land farmed during the Habsburg era. This pattern was strong for all

Fig. 4 a, b Persistence of Habsburg land use legacies. Odds of **a** socialist and **b** post-socialist abandonment (in %) in areas that were not farmed by the Habsburgs in 1860, compared to areas farmed then. The odds of abandonment on land not farmed in 1860 were higher, and the relationship was consistent across countries. For example, in Hungary, the odds of socialist abandonment were 75% higher in areas farmed in 1860, compared to areas not farmed then (**a**) and the odds of post-socialist abandonment were 62% higher (**b**). **b, c, d** Strength of land use legacies. Odds of abandonment (in %) in areas that were not farmed in a given historic period (**b** Habsburg, **c** Interwar, **d** Socialist), compared to areas farmed then



countries, and the odds of abandonment were more than double for Hungary (158%), Romania (125%) and Czech Republic (122%), but weak in Ukraine (20%).

The legacy of differences between early and late Habsburg land-use patterns on post-socialist abandonment (the Habsburg legacy) was stronger than that between early and late socialism (the socialist legacy). Land converted to agriculture late in the Habsburg era, i.e., after 1860, was 46% more likely to be abandoned than land farmed prior to 1860 (Objective 1, Fig. 4b–d). In contrast, land converted to agriculture late during socialism was only 23% more likely to be abandoned. The odds of abandonment were high in Slovakia and Hungary (57% higher) and weak in Ukraine (12%) and the Czech Republic (14%), and in Poland, the sample size was too small to parameterize the model (43 observations).

Discussion

Our results showed that strong agricultural land-use legacies occurred in the study region, but their effect diminished over time and their strength differed between

historical political regimes. The long land-use history and multiple institutional transformations in the Carpathians strongly affected the rates of contemporary agricultural abandonment after accounting for spatial determinants of change. Our findings support the assertion that land-use legacies can shape important aspects of global environmental change (Foster et al. 2003; MacDonald et al. 2012; Perring et al. 2016). We show that historical land uses can add explanatory power to land change models, and we highlight the importance of century-long effects of human–environment interactions for contemporary environmental change. Most importantly, our results highlight the need of making farsighted land management and conservation decisions because they may affect environmental change for centuries into the future.

Agricultural dynamics and their drivers

As expected, we found that historically the choice of which land to farm was based on agro-ecological suitability and economic profitability, in line with Ricardo's land rent theory (Ricardo 1821). Furthermore, environmental conditions explained well the distribution of the remaining

agricultural land in the post-socialist era, likely a result of agricultural specialization, increasing land-use efficiency, and displacement of land use to areas outside Europe (Foley et al. 2011; Kastner et al. 2014; Meyfroidt et al. 2010).

However, when modeling agricultural expansion of the Socialist era, we found that the explanatory power of agro-ecological conditions was low and that agricultural expansion was concentrated in more marginal locations, characterized by high elevations, low soil suitability and away from rivers, thereby ignoring fundamental principles of the economics of land use stipulated by Ricardo and von Thünen. These results support prior studies that found socialist agricultural expansion was driven by political goals and disregarded environmental conditions (Bičík et al. 2001; Štych et al. 2012). The high rates of post-socialist abandonment were in turn largely due to the spatial patterns of socialist agricultural expansion on marginal land for crops (Baumann et al. 2011; Munteanu et al. 2015) because these areas have low land rents. Overall, spatial reorganization of agriculture on suitable lands is a key in explaining land abandonment across other parts of Europe and the former Eastern Bloc (Jepsen et al. 2015).

Our results confirm regional trends that were previously only documented in local case studies from eastern and central European countries (Gerard et al. 2010; Kozak 2003; Mojses and Petrovič 2013). In the Carpathians, agricultural land expanded until the Second World War (WW II), and abandonment was widespread during the Socialist and the post-socialist eras. During the socialist era, we observed particularly high abandonment rates in southern Poland, a process likely related to forced depopulation (Woś 2005). Abandonment rates were also high in the Southern Romanian Carpathians, where forced industrialization policies of the Ceausescu regime displaced farmers to industrial centers (Ban 2012). Between 1985 and 2010, about 0.8% of the cultivated land was abandoned annually in the Carpathians, compared to 0.7% across Europe for 2001–2012 (Estel et al. 2015). The widespread abandonment during the post-socialist period is likely linked to institutional changes and restructuring of property rights following the collapse of the Soviet Union in 1990 (Estel et al. 2015; Jepsen et al. 2015; Levers et al. 2014). Overall, national institutions likely played an important role in shaping agricultural dynamics across the Carpathians.

Our results represent the first long-term cross-border assessment of agricultural dynamics in the Carpathians and provide evidence for an ‘agricultural transition,’ with the region as a whole experiencing the highest point in agricultural cover during the Socialist era. This transition point coincides well with the forest transition in the region, which occurred during the Interwar period (Munteanu et al.

2014, 2015) because the forest cover on former agricultural lands reestablishes only after a time lag.

Persistence of legacies

When modeling agricultural abandonment as function of historical land uses and environmental factors, we found that even after controlling for other spatial determinants of land change, historical land-use patterns had strong explanatory power in our land abandonment models. Agricultural legacies persisted for as long as a century, but their effect generally diminished over time, with the exception of Romania, where it is likely that policy factors (not captured in our analysis) diminished the legacy effect for socialist abandonment. Overall, we provide quantitative evidence for path dependency in agricultural systems, suggesting that agricultural land use is more likely in areas that were used for agriculture in the past. Our result is consistent with prior finding on path dependency showing that once a land-use type is established, land change is less likely (Coomes et al. 2011; Seto et al. 2011; Verburg et al. 2004). Our finding that land farmed for a longer time had a smaller likelihood of abandonment also supports the idea that cultural landscapes are persistent in some areas due to the collective memory of communities (Brierley 2010; Stobbelaar and Pedroli 2011).

Strength of land-use legacies

Political and socioeconomic conditions, which varied considerably between the Habsburg and the Socialist eras, affected the land-use changes in the respective periods, allowing us to observe their contemporary legacies. We found highest differences in the odds of abandonment when comparing areas farmed during the Habsburg period with agricultural areas established during socialism (91% higher odds of abandonment on Socialist agriculture versus Habsburg agriculture), even when controlling for agro-ecological and accessibility variables. This legacy effect may be related to a) differences in land ownership and land owner attitudes during the two periods and b) differences in agricultural land improvement over time. We examine these two causes in more detail below.

In the Habsburg period, in addition to agriculture being concentrated in agro-ecologically suitable areas (Objective 1), agriculture was dominated by large private land holdings (Good 1984). Land was in possession of the same families for long time periods, which likely carried on responsibility for the land. However, socialist nationalization and collectivization led to abolishment of land rights and fostered state ownership. Under policies of agricultural expansion, heavy subsidies and intense use of machinery and fertilizers (Bičík et al. 2001; Lerman et al. 2004),

agricultural area expanded forcefully. However, following the collapse of the socialist regime, land was returned to private ownership, under various policies varying from distribution to restitution (Hartvigsen 2014). Although land ownership data are not available to allow us to conduct statistical tests, the differences in the strength of legacies observed between countries that implemented land restitution policies (Czech Republic and Slovakia) and countries where agricultural land reforms were based on the distribution of land (Ukraine) may support this argument (Hartvigsen 2014).

Land-use legacies were also present when comparing the odds of abandonment on late and early Habsburg agriculture and when comparing late and early socialist agriculture. We suggest that in addition to land tenure, areas farmed later within a period were more likely to be abandoned than areas farmed earlier because of differences in land improvement and land management. Because stable land tenure is associated with increasing investment in land improvements such as soil amelioration, irrigation or drainage (Abdulai et al. 2011; Myyrä et al. 2007), we suggest that agricultural land within the same type of ownership for a longer time may have been more likely to be improved and hence less susceptible to abandonment. Furthermore, long-term agricultural areas might be more likely to be improved, partly due to traditions and stronger customary claims. Our explanation is supported by the fact that the Habsburg legacy effects were strongest in Hungary and Romania, the two countries where agricultural improvements peaked only in the late Habsburg period, following the 1850s removal of taxes for agricultural products from Eastern Empire provinces (Alix-Garcia et al. 2016).

We did not see strong differences in the odds of abandonment on early versus late socialist agriculture. Following WW II, most countries adopted the agrarian philosophy of the Soviet Union (Bezák and Mitchley 2014; Lerman et al. 2004; Nelson 1993), but abandonment occurred equally on land expanded before and after 1960, likely because socialist agricultural expansion on other land uses was ecologically and economically unfeasible and led to subsequent abandonment, regardless of when it was expanded.

We caution that our analysis is based on binary agricultural data and our definition of agriculture excludes grassland dynamics. We therefore abstracted from different definition of abandonment that include cropland–grassland transitions. Moreover, the length of the study periods differed, which may have confounded the duration of the legacy eras. The nature of the data used to map socialist abandonment did not allow us to separate the abandonment between 1985 and 1990, so that our estimation of ‘socialist abandonment’ might be conservative because it excluded abandonment just before the collapse of socialism. We suspect that the weak legacy effect for the socialist period

is partly related to the short period of socialist agricultural expansion (1930–1985) considered here compared to the Habsburg period.

Our study confirmed and reinforced the importance of land-use legacies for contemporary and future land change. In a scientific context, the consideration of past land uses as spatial determinants of change could enhance the performance of land-use models at regional and global scale and can improve the prediction of future land changes. In a land management context, we stress the importance of considering the effects of contemporary land-use decisions on centuries to come and highlight the environmental responsibility for future generations when making land management and political decisions.

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