Long-term land use trends and their legacies in the Carpathian Region of Eastern Europe

by

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Abstract

Land change is a major contributor to contemporary global change, affecting climate, biodiversity and livelihoods. Yet, the long-term consequences of historic land uses (hereafter land use legacies) are still poorly understood, leading to potentially ill-informed land management and conservation decisions. My goal was to understand if and how land use legacies affect contemporary land change, and what the implications are for conservation. I studied over a century of forest and agricultural change in Eastern Europe and found that forest transition occurred during the Interwar period, followed by agricultural abandonment during socialism and thereafter. I found that legacies affected contemporary forest disturbance and agricultural abandonment and that legacy effects persisted for over 150 years. Although legacy effects diminished over time, political and socio-economic shocks strengthened legacy effects. Contemporary forest disturbance was higher in areas that were not forested in 1860 and contemporary agricultural abandonment was higher in areas not farmed then. Furthermore, legacies also affected subtle changes within land cover types. For instance, forest management in Romania during the 19th century caused an increase in spruce cover, and a loss of old forests, with potential implications for conservation. Taken together, these results show that land-use legacies and shifts in political systems may constrain future land management and that we carry great environmental responsibility for generations to come. Finally, based on century long habitat dynamics and the conservation responsibility of the Carpathian region, I developed conservation recommendations for the protection of bird habitat. The Carpathians carry high conservation responsibility for forest and grassland bird species, and available habitat increased over the past century for these species. Because the region has no conservation responsibility for agricultural species, subsidies for maintaining row crops may not be justified in this region.

Conservation efforts should support forest recovery, low-intensity grassland management and promote forest structure and diversity because they will benefit species at the European level. Overall, these findings advance land system science by integrating legacies in land change modelling and highlight the need for making farsighted land management and conservation decisions because their effects will persist for centuries into the future.

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Introduction

"Brothers, what we do in life, echoes in eternity!"

- Russell Crowe, *Gladiator (2000)*

We all have a choice between leaving a positive or negative legacy for generations to come. As individuals, we often make this decision consciously, for example, by securing the future of our children. But as a society, we rarely consider the responsibility that we carry for generations ahead. This may be partly because we do not fully understand how our ancestor's legacies affect our lives and our environment today. My dissertation is looking at a special type of legacies – land use legacies from a century ago – and how they affect contemporary land change and conservation. I ask if and how land use legacies affect current land change, and what is our environmental responsibility for future generations? To answer these questions, I turn to land system science and the tools of scientific inquiry that this emerging discipline provides.

The mosaic of land covers and land uses, both drives and responds to global environmental change (Foley et al., 2005; Turner et al., 2013; Verburg et al., 2013). Land use change is one of the largest contributors to changes in climate, biodiversity, ecosystem services and economies, which in turn cause further land change (Gibbs and Herold, 2007; Ojima et al., 1994; Verburg et al., 2013). Land management and conservation efforts are often focused on changing the magnitude or even reversing the direction of land changes that negatively affect the environment (Ferretti-Gallon and Busch, 2014). Usually this requires a shift in the underlying driving forces (such as economic incentives, policies or nature protection) across a range of spatio-temporal scales (Verburg et al., 2013). Most drivers of recent land transitions are well understood (Bürgi et al., 2005; Geist and Lambin, 2002; Lambin et al., 2001) and could be adjusted to accommodate our future land plans. However, one aspect of land change that remains poorly understood and largely unquantified is the role of historic land uses in driving land change. This is unfortunate, because disregarding legacies may lead to misinterpretation of land change patterns and to ill-informed land use decisions.

Over long time periods, land-use transition theories predict gradual changes among land covers (such as from cropland to forest), primarily as a function of demographic and economic factors (DeFries et al., 2004; Foley et al., 2005; Lambin and Meyfroidt, 2010). A leading theoretical example is the forest transition theory, which postulates that gradual economic and demographic change lead initially to deforestation, but then to agricultural specialization and reforestation of marginal lands. The forest transition itself is the shift from decreasing forest area in a given country or region to increasing forest area (Barbier et al., 2010; Mather, 1992). A regions' socio-economic context and socio-ecological feedbacks may lead to differences in timing and extent of the forest transition (Foley et al., 2005; Lambin and Meyfroidt, 2010; Meyfroidt and Lambin, 2011). Regions where socio-economic and political changes occur at relatively short intervals are particularly interesting in this respect, because they allow comparisons between different socio-economic, political and demographic components of the land change process. Eastern Europe represents a great study case for transition theories, because "the region reinvented itself every half century" in terms of its economies and politics (Good, 1994).

Land use transitions are explained by a series of causal mechanism, i.e., a set of complex factors involved in causing land change (Lambin and Meyfroidt, 2010; Meyfroidt, 2015). The immediate human activities that affect the environment act at local scales and are the proximate causes of land change; they are in turn driven by underlying forces, or complex social, political, economic, technological, and cultural factors (Geist and Lambin, 2001; Meyfroidt, 2015). For example, the establishment of a new type of land use is constrained by local and national markets or policies, with magnitudes of change being attenuated or amplified by global forces (Lambin et al., 2001). Deforestation in Vietnam was directly driven by coffee expansion which was in turn a result of increasing global coffee demand (Meyfroidt, 2015). The agricultural expansion in Kazakhstan in the 1950s was driven by the increasing demand for agricultural products in the Soviet Union, which in turn resulted from poor policies (Kraemer et al., 2015). One potential shortcoming of current land use theory is that, despite acknowledging path dependency, and the fact that ecosystems may respond to past changes for decades in the future (Foster et al., 2003; Wallin et al., 1994), land use histories and the legacies they create are rarely quantified in land change models (Perring et al., 2016). In Eastern Europe, the factors causing land change after the collapse of the Soviet Union are well understood (Baumann et al., 2011; Kuemmerle et al., 2007; Müller et al., 2013a), but historical land use dynamics remain widely unexplored, despite potential lingering effects of historical events (Good, 1994).

Land change has been an active process for millennia, with forest and agricultural land use experiencing substantial changes in the past century at unprecedented rates (Gibbs et al., 2010; Hansen et al., 2010): more than 3% forest was lost from 2000 to 2005 across the globe (Hansen et al., 2010) while agriculture expanded by 3% from 1985 to 2005 (Foley et al., 2011). Highlighting that land use changes are complex, though, agricultural land of the size of France was also abandoned globally between 1995 and 2005, mostly in the former Soviet Union and Latin America (Munroe et al., 2013). In Europe alone, an area the size of Spain was abandoned since 2001, most of it in the Former Eastern Bloc (Estel et al., 2015). In parts of the World where long term land use transitions are punctuated by political and socio-economic shifts, the changes in land use can be abrupt and transformations between land uses can succeed at faster pace under economic or institutional pressures. The history of Eastern Europe since the mid 19th century represent in this respect a great 'natural experiment' for investigating the effects of different socio-economic and political contexts on long term land change processes.

Despite acknowledging the magnitude of land changes under political transformations, longitudinal studies addressing questions of the legacies they produce are scarce. Legacies and path dependencies have mostly focused on urban systems (Lambin and Geist, 2006; Seto et al., 2012) although scattered evidence suggests legacies exist in forest and agricultural systems (Börjeson, 2007; Coomes et al., 2011; Radeloff et al., 2001). More evidence on legacies is provided in ecology, where legacies of past land uses are shown to linger in the ecosystems for decades or even centuries, affecting carbon storage, soil structure and vegetation composition (Brudvig et al., 2013; Ficetola et al., 2010; Foster et al., 2003). Long term changes in land use and habitat, can have cascading effects for species abundance (Pidgeon et al., 2011), and may cause extinctions or spread of invasive species (Dullinger et al., 2013; Essl et al., 2011; Tilman et al., 1994). This is why land management and conservation planning need to take into account historic and recent land use changes, if they are to provide sustainable solutions for the future environment.

Long term land use trends are important not just for improving our understanding of contemporary land change, but also for devising appropriate conservation measures. Globally, two strategies are considered when aiming to balance food production and nature conservation. Areas of low intensity farming are considered ideal for implementing a land sharing strategy where both agricultural production and nature conservation coexist (Fischer et al., 2012; Mikulcak et al., 2013). Alternatively, under a land sparing scenario, high yield farming in some places, could free up land for wild nature in others (Fischer et al., 2014; Grau et al., 2013; Phalan et al., 2011). The Carpathian Mountains of Eastern Europe, have been devised as an ideal place for retaining wildlife friendly farming due to the long history of human-environment interactions and high levels of biodiversity in low-intensity landscapes (Fischer et al., 2012; Hartel et al., 2013). On the other hand, the region has also been a primary target for rewilding due to the high rate of agricultural abandonment, contiguous forest ecosystems, and unique presence of large carnivore and herbivore species (Ceaușu et al., 2015b; Kuemmerle et al., 2010; Navarro and Pereira, 2012). Despite the existence of empirical evidence about which species could benefit under each of these conservation strategies, an integrated view on the conservation responsibility of the Carpathians in light of the historical land use changes is still missing. This is unfortunate, because conservation efforts could be miss-directed at species or habitats whose conservation could bring only minor benefits at European or global level.

The overarching goal of my dissertation was to understand the role of land use legacies for contemporary land use dynamics and for conservation action. I investigated forest and agricultural land use transitions over the past two centuries in Eastern Europe, in the context of the rise and the collapse of several political systems and explored their implications for conservation. My specific objectives were to:

1) Identify and quantify long-term forest and agricultural change patterns and their main driving forces in times of socio-economic and political change.
2) Assess if and how much land-use legacies affect contemporary forest disturbance and the abundance of forest types
3) Explore potential cause-effect relationships between historic forest characteristics and contemporary forest patterns

4) Assess the role of land use legacies of different historic time periods on contemporary agricultural land use abandonment
5) Provide conservation recommendations, based on historic and recent bird habitat evolution for species of highest conservation responsibility at European level

To address these goals, I studied land use dynamics since the 18th century in the Carpathian region using a combination of historical land use maps, remote sensing data and statistical records, as well as species range maps for birds whose range at least partly cover my study region. Eastern Europe represents a great 'natural experiment' for the study of century long term land use dynamics because it experienced multiple political and land management systems which caused drastic land cover changes over a relatively short time span. The substantial changes that occurred in forest and agricultural management over the past centuries in the Carpathians allow me to analyze legacy effects of multiple historic periods at broad spatial scales. Another advantage of the regions is that under the influence of major political regimes, land use was thoroughly documented in form of historical cartographic and statistical material, allowing me to spatially reconstruct over a century of land use history. Although well documented, the extensive land cover changes of the last decades remain poorly understood in the context of historical changes in policies and land use patterns. Furthermore, despite being considered a conservation hotspot in Europe (Hartel et al., 2013; Knorn et al., 2012a), it remains unknown for which species the Carpathians carry highest conservation responsibility at European level. The five chapters of my dissertation examine specific questions related to long term land use dynamics in the Carpathians.

Chapter summaries

Chapter 1. Forest and agricultural land change in the Carpathian region – a meta-analysis of long-term patterns and drivers of change

Despite the availability of many small scale land change studies in the Carpathians, the overall land use transitions and their drivers remain broadly unknown. Furthermore, differences induced by shifts in socio-economic and institutional transformations remain largely unexplored at trans-Carpathian scale.

In Chapter 1, I examined land use transition trajectories (such as the forest transition) in the Carpathians over the past 250 years and the relation to underlying drivers of land change. I conducted a meta-analysis of 66 publications describing 102 case study locations and quantified the main forest and agricultural changes in the Carpathian region since the 18th century. I assessed the heterogeneity of the local-scale studies across the region and identified the importance of the different drivers of land-use change for individual forest and agricultural dynamic processes. The case studies captured gradual changes since the peak of the Austro-Hungarian Empire up to the accession to the European Union of most of the formerly socialist countries in the study region. Agricultural land-use increased during the Austro-Hungarian Empire in 70% of the case studies, but dropped sharply during and especially after the collapse of the Socialism (over 70% of the cases). The Carpathian region experienced forest transition during the Interwar period (93% of the cases), and the forest expansion trend persisted after the collapse of Socialism (70% of the cases). In terms of the drivers, institutional and economic factors were most influential in shaping deforestation and agricultural expansion, while socio-demographics and institutional shifts were the key drivers of land abandonment. My study highlights the drastic effects that socio-economic and institutional changes can have on land-use and land-cover change, and the value of longitudinal studies of land change to uncover these effects.

Related manuscript: Munteanu C, Kuemmerle T, Boltiziar M, Butsic V, Gimmi U, Halada L, Kaim D, Király G, KonkolyGyuró E, Kozak J, Lieskovsky J, Mojses M, Müller D, Ostafin K, Ostapowicz K, Shandra O, Štych P, Walker S, Radeloff VC (2014) Forest and agricultural land change in the Carpathian region—A metaanalysis of long-term patterns and drivers of change. Land Use Policy 38:685–697

Chapter 2. Legacies of 19th century land use shape contemporary forest cover.

Although long-term persistence of legacies for ecosystem structure and composition is relatively well understood in ecology, it remains unclear if land use legacies can shape the extent and pattern of current environmental change, affecting management and conservation decisions. In Chapter 2, I assessed if and how much land-use legacies affect contemporary forest disturbance. Specifically I quantified (1) the magnitude of contemporary forest disturbance in relation to historic land uses, (2) the relation to spatial determinants of forest disturbance, and (3) changes in main forest types. I modeled contemporary forest disturbance (based on satellite image analysis from 1985 to 2010) as a function of historic land use (based on digitized topographic maps from 1860 and 1960). Contemporary forest disturbance was strongly related to historic land use even when controlling for environmental, accessibility and socio-political variation. Across the Carpathian region, the odds of forest disturbance were about 50% higher in areas that were not forested in 1860 (new forests) compared to areas that were forested then (old forests). These legacies may be explained by extensive plantations outside forest ranges, predominantly spruce, poplar, and black locust, which are prone to natural disturbances. Furthermore, as plantations reach harvestable age of about 70 years for pulp and 120 year for saw-timber, these are likely to be clear-cut, producing the observed legacy effects. Across the Carpathians, forest types shifted towards less coniferous cover in 2010 compared to the 1860s and 1960s likely due to extensive historic conifer harvest, and to recent natural disturbance events and clear-cuts of forest plantations. My results underscore the importance of land-use legacies, and show that past land uses can greatly affect subsequent forest disturbance for centuries. Given rapid land use changes worldwide, it is important to understand how past legacies affect current management and what the impact of current land management decisions may be for future land use.

Related manuscript: Munteanu C, Kuemmerle T, Keuler NS, Müller D, Balázs P, Dobosz M, Griffiths P, Halada L, Kaim D, Király G, Konkoly-Gyuró E, Kozak J, Lieskovsky J, Ostafin K, Ostapowicz K, Sandra O, Radeloff VC (2015) Legacies of 19th century land use shape contemporary forest cover. Global Environmental Change, 34: 83-94

Chapter 3. Historical forest management in Romania is imposing strong legacies on contemporary forests and their management

Historical forest management can heavily affect contemporary forest management and conservation. Yet, relatively little is known about century-long changes in forest composition, structure, ownership and management, and that limits the understanding of how past management and land tenure relate to current forestry practice and forest conservation.

In Chapter 3, I examined the relationship between historical forest management (as depicted by historical forest cover, species composition, age structure and harvesting data) and contemporary forest patterns. I used the case study of Romania, the country with the largest share of the Carpathian region, because detailed data on historic forest management was available at multiple spatial scales, allowing me to explore the relationship between past and current management. I reviewed forestry literature and statistics since the 19th century and reconstructed a time-series of forest cover, composition, disturbance patterns, and ownership patterns, and interpreted these data in light of institutional changes. I also assessed changes in forest cover, forest harvest, species composition and age structure between two points in time (1920s and 2010s) at the county level and for three case studies for which stand- forest management data was available. I found that forest area increased in Romania since 1924 by 5% and that the annual rate of forest harvest between 2000 and 2013 was half of the annual rate between 1912 and 1922, which indicates high potential for forest biodiversity conservation. However, the composition, distribution, and age structure of contemporary forests is also substantially different from historical forests. I found an overall increase in coniferous species and several deciduous species (such as Tilia, Populus, Betula, Alnus sp), a spatial homogenization of species composition, and more even-aged stands. I also found a drop from 14% to 9% in the relative abundance of old forests (>100 years). Spikes in forest harvests coincided with times of widespread forest privatization, and drastic institutional changes, such as agrarian reforms, or the onset and collapse of the Soviet Regime. Overall, my results suggest that effects of past management, land ownership and institutional changes can persist for a long time, and affect forest ecosystem composition, health and structure. My findings are scientifically important because they provide evidence for legacies of past management and for the effects of forest privatization on harvesting rates. My findings are also relevant to forest management and conservation practice, because they highlight that environmentally sound management over long time periods is essential for sustainable forestry and old-growth forest protection in Europe and elsewhere.

Related manuscript: Munteanu C, Nita M-D, Abrudan I V., Radeloff VC (2016) Forest history is repeating itself, imposing strong legacies for Romanian forests and forestry. Forest Ecology and Management, 361: 179-193

Chapter 4: 19th century land-use legacies affect contemporary land abandonment in the Carpathians.

Land-use legacies can shape landscapes for centuries into the future, affecting their structure and function - but for how long legacies may persist and whether they differ with historical political and socio-economic regimes remains unclear.

In Chapter 4, I assessed the effect of land use legacies for contemporary agricultural abandonment and studied the legacy effects of different political regimes after environmental variation was controlled for. The specific research questions were (1) to what extent agro-ecological conditions explained farming choices during major political regimes, (2) if legacy effects existed once agro-ecological variation was controlled for, and whether their effect diminished with time and (3) how legacies differed during different political and institutional regimes? To answer these questions, I modeled the choice of agricultural land, and the legacies of Habsburg and Socialist regimes, while controlling for agro-ecological, accessibility and socio-political 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, my 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. As globally land change is happening at ever faster rates, my study stresses the importance of considering our land use responsibility for future generation when making land use decisions.

Related manuscript: Munteanu C, Kuemmerle T, Boltiziar M, Halada L, Kaim D, Király G, Konkoly-Gyuró E, Kozak J, Lieskovsky J, Mojses M, Müller D, Ostafin K, Ostapowicz K, Radeloff VC (in review): 19th century land-use legacies affect contemporary land abandonment in the Carpathians. Regional Environmental Change.

Chapter 5: Bird conservation recommendations for the Carpathian Ecoregion in light of long-term land use trends and conservation responsibility

Bird populations in Europe are declining and conservation action is needed to protect species and their habitats. Suggested conservation strategies include both wildlife friendly farming and rewilding. Despite the existence of empirical evidence on which species could benefit under each of these conservation strategies, the historical landscape context and the conservation responsibility of the Carpathians for different bird species remain largely unexplored, potentially leading to miss-directed conservation efforts.

In Chapter 5, I provide conservation recommendations for the Carpathian Mountains, based on historic and recent habitat evolution for species of highest conservation responsibility at European level. My specific research questions were: 1) How did habitat for different bird species change in the Carpathian Mountains over the past 150 years? 2) For which of the bird species do the Carpathians carry the highest conservation responsibility at the European level? 3) What bird conservation strategies should be pursued, and what future land use trends would be most desirable for conservation, given the major threats to different species, their past habitat trends and the conservation responsibility of the Carpathians?

To address these questions, I analyzed long term land use trends since 1860 in relation to species range maps for 252 bird species whose European ranges at least partially cover the Carpathian ecoregion. I analyzed the major habitat and their changes in the Carpathians over the past 150 years, for all species present in the Carpathians, and evaluated for which ones the region carries highest conservation responsibility at the European level. Finally, based on observed habitat changes, conservation responsibility and species life history, I discussed conservation strategies and land management.

I found that forest and grassland available habitat increased substantially since 1860 within the ranges of all Carpathian species, and that agricultural habitat declined. Overall, the Carpathians carry high conservation responsibility for species that use forests and grasslands as their major habitat and only low conservation responsibility for birds that rely on agricultural fields. Furthermore, the habitat requirements of species of high conservation responsibility indicated that several species would benefit from a mosaic of forest and grassland landscapes. The main concerns at European level for the survival of species of high conservation responsibility were agricultural intensification and natural system modification. Because I found that agricultural land declined substantially in our study region since the 1960s, I suggest that that the Carpathians have high potential for conservation of forest and grassland species. I identified a list of 29 species for which the Carpathian ecoregion could become a conservation hotspot and suggest that land management is focused on providing suitable habitat for these species, such as supporting forest recovery, low-intensity grassland management and promoting forest structure and diversity.

Related manuscript: Munteanu C, Pidgeon A, Radeloff V C (in preparation) Bird conservation recommendations for the Carpathian Ecoregion in light of long-term land use trends and conservation responsibility (to be submitted: Conservation Biology)

Related publications

Aside from this dissertation, I authored and co-authored several other papers related to the larger topic of long term land change in the Carpathian Region:

Munteanu C, Radeloff V, Griffiths P, et al. (2016) Land change in the Carpathian Region before and after major institutional changes. In: Gutman G, Radeloff VC (eds) Land Use and Land Cover Change in Eastern Europe after the Collapse of Socialism. Springer (in press)

In this book chapter, we synthesized the long term drivers of land change and their land-use outcomes in the Carpathian region, with a particular focus on forests, agriculture and grasslands. We provided evidence on how ecosystems respond to political shocks using examples of alternative stable states, time-lags and land-use legacies.

Butsic V, **Munteanu** C, Griffiths P, Knorn J, Radeloff V C, Lieskovský J, Müller D, Kuemmerle T (in review) The impact of protected areas on forest disturbance in the Carpathian Mountains 1985-2010. Conservation Biology

Here, we estimated the effectiveness of protected areas over time and space using forest disturbance data for 1985-2010, matching statistics and a fixed effects estimator. We found heterogeneous results in terms of protection effectiveness and suggest that the strength of institutions, the differences in forest privatization and management and the timing of accession to the EU may provide explanations for these differences.

Feurdean A, **Munteanu C,** Kuemmerle T, Nielsen AB, Hutchinson SM, Ruprecht E, Persoiu A, Parr K, Hickler T (in review) Effects of socio-political transformations on semi-natural

grasslands in Transilvania (CE Europe), based on pollen and historical land survey. Regional Environmental Change

For a study case in Transylvania, we analyzed land cover from historical maps in conjunction with a pollen record, in order to assess changes in grassland persistence and diversity over time. We found that although grassland extent increased over time, grassland persistence was low and diversity varied over time, likely in relation to land management policies of different political regimes. Our results suggest recent positive changes in grassland extent and diversity and the need for conservation action to maintain these landscapes.

Kaim D, Kozak J, Kolecka N, Ziółkowska E, Ostafin K, Ostapowicz K, Gimmi U, **Munteanu C**, Radeloff V (2016): Broad scale forest cover reconstruction from historical topographic maps. Applied Geography, 67: 39-48

In this paper we compare two methods for reconstructing forest cover based on historical maps: a classical wall-to-wall polygon digitizing approach and a regular sampling grid approach, similar to the one used in my dissertation. We found that the point-based reconstruction captured forest cover dynamics with a comparable accuracy to the wall-to-wall mapping, yet was much more time efficient. Our findings demonstrate that historic land change can be effectively assessed over larger areas much further back in time than commonly done.

Griffiths P, Kuemmerle T, Baumann M, Radeloff, VC, Abrudan, IV, Lieskovsky, J, **Munteanu C**, Ostapowicz K, Hostert P (2014) Forest disturbances, forest recover, and changes in forest types across the Carpathian ecoregion from 1985 to 2010 based on Landsat image composites. Remote Sensing of Environment 151:72–88.

In this paper, we analyzed changes in forest cover, forest disturbance and forest types for the Carpathian region, based on Landsat image 5-year composites between 1985 and 2010. We found that forest cover increased in the Carpathians by 4.4% and that forest composition shifted towards more deciduous. We also found a time-lag in the timing of disturbance, with Romania, Poland and Czech Republic experiencing disturbance later than other countries in the region.

Significance and implications

With an increasing world population and ever shifting dynamics in global economic and socio-political contexts, the effects of land use decisions for future land change become of increasing land management and conservation concern (Perring et al., 2016). My dissertation addresses broad questions on the role of land use legacies for subsequent land change and conservation, with particular focus on periods of political and socio-economic change. My research is – broadly speaking – relevant to land change science and land management and has wide implications for conservation. The Carpathian region represents the ideal 'natural experiment' for investigating effects of land use legacies, socio-political shifts, and the implications for conservation at broad spatial and temporal scales. But the results of my research are relevant to many landscapes with long history of human use and good land use records, such as the Eastern US or Sub-Saharan Africa. Similarly, my methods are straightforward, and can be applied to other regions and extrapolated to continental or global scales.

In this dissertation, I shed new light on the long term land changes and their drivers in the Carpathians, quantify land use legacies and provide conservation recommendations for bird species in light of their habitat changes. I showed that forest transition occurred in the Interwar period, and that contemporary forest cover is higher than historically. Similarly, an agricultural transition from increasing to decreasing cropland occurred in the 1960s and land abandonment was strong since. Historic land uses did affect rates of forest disturbance and agricultural abandonment, even after accounting for the classical determinants of land change. I found strongest legacy effects when comparing land abandonment on land farmed under different political regimes. Last but not least, I showed that decreasing land use intensity provides great conservation opportunities in the Carpathians – specifically for species of high conservation responsibility that require forest and grassland for their survival and for which habitat increased in the last century.

Scientifically, my work makes a major contribution to land change science, by quantifying the role of land use history and of path dependency for contemporary land change. By modeling change over long time periods, I advance the scientific and theoretical understanding of land use legacies as driving forces of land use change that may in turn be affected by underlying forces such as political regimes. Furthermore, the finding that the longer a given land use persisted, the less likely it was to transition to a different state (Chapters 2 and 4) bridges the gap between the theoretical concept of path dependency and the quantitative measure of land use legacy in contemporary landscapes. The concept of path dependency has been mostly tested in urban systems, and my research extends evidence of path dependency to forest and agricultural systems. Furthermore, I show that all else being equal, legacies may diminish over time, as expected from ecological succession theory (Chapter 2 and Chapter 4). However, legacy effects can be stronger when comparing land change between political and institutional regimes which may abruptly affect historical land use decisions (Chapter 4). My results highlight the importance interactions between environmental and anthropogenic drivers of land use change at various spatial and temporal scales (Chapter 3).

In addition to elucidating legacies, my results verified the applicability of forest transition theory in an area that experienced multiple socio-economic and political shifts and showed that the timing of transition can vary between countries due to local and national differences in policies and institutional transitions (Chapters 1 and 2). My results are important to land change science, because they show that in parallel to forest transition, a 'mirrored agricultural transition' occurred in the Carpathians – agricultural expansion peaked with a delay compared to the forest transition point and continued throughout the contemporary period (Chapter 4).

Last but not least, because Eastern Europe has "reinvented itself every half century" in terms of politics and socio-economics (Good, 1994), my findings from the Carpathians can contribute more broadly to the understanding of land change dynamics of regions affected by multiple socio-economic and socio-ecological changes. My findings on accelerated rates of change in relation to political shifts are relevant to many regions that are currently hot-spots of human pressure on the environment due to wars, political unrest (e.g., the Middle East) or large development projects (e.g., China). For the Carpathian region specifically, this work represents the first comprehensive land change assessment over broad temporal and spatial scales, integrating and synthesizing most of the previous knowledge on the region.

From a methodological perspective, my work utilized straightforward approaches to answer broad questions relevant to land change science. The meta-analytical approach I used in Chapter 1 allows for harmonization and comparability of historical land use data from different sources. In Chapters 2 and 4, I used a novel approach to quantify and model historic land uses. Because the efficiency in analyzing historical data has been a major barrier to broad-scale historical analysis so far, I employed a point grid approach for mapping land use, which proved to be more time-efficient and equally reliable to traditional approaches (Kaim et al., 2016). This approach could be used at different scales and for any type of spatial datasets. Having at hand a method to assess historic land change based on this point-grid approach provides great new opportunities for scientific inquiry related to historic land use across a large part of the world for which historical spatial data is available. The straightforward methods I applied in Chapter 5 to assess conservation responsibility and outline conservation goals can be easily adapted to other species or eco-regions because they rely on comparable, globally available data.

In addition to new mapping and spatial analysis methods, I developed statistical models that quantified the role of historic land use for recent land change and explored their relation to other drivers of change (Chapter 2, Chapter 4). My models are easily applicable to any area for which spatially explicit long term datasets of land cover are available and can be used to reveal the relative importance of past uses for recent changes. Areas where the implementation of my models would be particularly interesting include regions which underwent multiple land use transitions in the past, driven by changes of political, socio-demographic, economic or environmental pressures such as the Midwestern U.S., the Middle and Far East, and South-Central and Eastern European countries.

Last but not least, my results are relevant in the context of land management and conservation. Three broad management and conservation messages emerge from my work. First the changes in contemporary landscapes are affected by land use history, and thus historic landscape conditions, should be considered when making contemporary land use and conservation decisions. For instance, prioritizing areas for conservation might consider constraints imposed by historic land use. In turn, knowing the constraints on a specific landscape can help mitigate the legacy effects when making land management decisions. Second, my results highlight the need for making farsighted land management and conservation decisions, because we bear great land use responsibility for generations to come. Furthermore, because land use legacies may not affect just rates of land change into the future, but also species population dynamics (e.g. extinction debt), considering the cascading effects of contemporary land use decision is of utmost importance for land management and conservation. Third, providing conservation goals based on long term habitat dynamics and the conservation responsibility of specific regions, may enhance conservation outcomes. My results suggest that decreasing land use intensity provides great opportunities for conservation, as long as appropriate conservation policies are implemented.

For the Carpathian region, my datasets are directly relevant for management and planning because they represents the first a spatially explicit and cross-border account of land change for the past century. These datasets can inform forestry and agricultural planning and highlight areas suitable for conservation, such as protected areas. In terms of conservation action, my analysis of habitat dynamics for birds of high conservation responsibility suggests that conservation should focus on forest and grassland bird species, for which habitat has been increasing over the last century. Because the Carpathians do not carry conservation responsibility for cropland bird species, we suggest that allowing the remaining agricultural lands to convert to grasslands would benefit biodiversity at European level more than maintaining low intensity farming on the landscape. Last but not least, my study provides an important basis for the emerging cross-border conservation and management efforts in the Carpathians, because it is consistent and comparable across six countries.

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Chapter 1. Forest and agricultural land change in the Carpathian region – a meta-analysis of long-term patterns and drivers of change

Introduction

Land-cover change is a main component of global environmental change (Foley et al., 2005), affecting climate, biodiversity and ecosystem services, which in turn, affect land-use decisions (Ojima et al., 1994). Humans have altered land cover for centuries, but recent rates of change are higher than ever (Foley et al., 2005; Goldewijk, 2001; Hansen et al., 2010). The temporal dimension of change is particularly interesting because land-use legacies may persist for centuries (Foster et al., 2003). Over long time periods though, land-use transition theories predict gradual changes, primarily as a function of demographic and economic factors (DeFries et al., 2004; Foley et al., 2005). For example, forest transition theory postulates that gradual economic and demographic change leads to agricultural specialization and reforestation of marginal lands, and defines the transition point as the time of the lowest forest cover in a given country or region (Mather, 1992; Meyfroidt and Lambin, 2011). Different regions may experience these transitions at different points in time, depending on economic, political or institutional condition (Meyfroidt and Lambin, 2011) or go through multiple transition phases (Yeo and Huang, 2013), as land systems respond to institutional and economic changes (Lambin et al., 2001). Shifts in political systems, and the related socio-economic adaptations, such as those following the collapse of the Soviet Union, greatly affect land trends (Hostert et al., 2011). The question is though first, how land cover changes over long time periods, and how these changes vary depending on economic, institutional and social factors. Regional land change patterns are the combined result of changes at much finer scale, that are driven by complex economic, policy and institutional, demographic and market forces (Lambin and Meyfroidt, 2010; Verburg et al., 2009). These localized changes, in turn, are constrained by interacting broad- and local-scale driving forces, especially in crisis situations (Cioroianu, 2007). While, the local-scale drivers of land-use change can be understood from case-studies (Foley et al., 2005), the variation of these drivers across regions can only be understood from a broader perspective.

Capturing land change under successive distinct economic periods and documenting change processes over large areas and long time periods (e.g., centuries) is often impossible due to the lack of consistent, broad-scale and long-term data. When that is the case, a meta-analysis can be a valuable tool for synthesizing knowledge and extracting broader scale patterns and drivers of change (Poteete and Ostrom, 2008; Rudel, 2008). Meta-analyses have been applied to assess, for example, long-term urban growth across the globe (Seto et al., 2011), desertification (Geist and Lambin, 2004), deforestation (Geist and Lambin, 2002), and tropical agriculture (Keys and McConnell, 2005). In regard to forest change, such a meta-analysis showed that tropical deforestation is a result of interacting proximate causes and underlying driving forces, which vary geographically and with historical context (Geist and Lambin 2002). Another meta-analysis focusing on forest cover in Mexico showed that cattle ranching and outmigration cause deforestation in lowland areas, while highland regions with outmigration experience forest cover increase (Rudel, 2008). Dryland degradation globally has been attributed to the combined effects of climate, economies and institutions which drive cropland expansion, overgrazing and infrastructure development (Geist and Lambin, 2004). In Central Eastern Europe, Kozak (2010) analyzed land change across a number of local case studies to describe forest transition in the Polish Carpathian Mountains as occurring between the two World Wars (WW). However, while most meta-analyses examined broad spatial extents and explain spatial variation, their temporal scale has been limited to decades, which limits the ability to isolate effects and legacies of major socio-economic shifts across time and space. Furthermore, most meta-analyses of land change processes included only case studies that were published in English (Geist and Lambin, 2004; McConnell and Keys, 2005; Seto et al., 2011), thus not including local research and knowledge. Broad scale, long term comparative studies across countries of Eastern Europe are still lacking (Björnsen-Gurung et al., 2009), despite the availability of a high number of local, regionally published studies. Given its long land-use history and multiple social, political and economic shocks, the Carpathian region represents a "natural experiment" (Gehlbach and Malesky, 2011) to examine long-term land-use change and to develop a broader synthesis of land-use histories. Our overall goal was to identify and quantify broad-scale and long-term land change patterns and processes during times of shocks, and the main driving forces of these changes. To do so, we conducted a meta-analysis of historical land change studies for the Carpathian region, reaching as far back as 1790s.

Specifically, our objectives were to:

1. Assess and quantify the main forest and agricultural changes in the Carpathian region for politically and economically distinct time periods over the past 250 years;
2. Assess the heterogeneity of the local-scale studies across the region;
3. Identify the main drivers of long-term land-use change and the impact of major socio-economic shocks on forest and agricultural change.

Methods

Study area

We studied the 350,000 km^2 Carpathian region in Eastern Europe, which comprises two major eco-regions: the Carpathian Mountains and the Pannonian Plains. The study area includes parts of the Czech Republic, Poland, Ukraine and Romania, and all of Hungary and Slovakia (Figure 1.1), has a temperate climate, and landscapes consisting mostly of a mosaic of forests, pastures, and agricultural fields. The region harbors some of the largest contiguous temperate forests in Europe (Knorn et al., 2009; Kuemmerle et al., 2007) alongside high nature conservation value farmland (Paracchini et al., 2008). The Pannonian plains also represent one of the most fertile regions in Europe (Schiller et al., 2010). The Carpathian eco-region is a global biodiversity hotspot, particularly regarding plant diversity, and harbors rare old-growth and alpine meadow ecosystems and many wildlife species of conservation concern (e.g., brown bear, wolf, lynx, European bison, Salvatori et al., 2002).

The region has a long land-use history, with centuries of agricultural and forest land use being influenced by changes in political, economic and demographic dynamics (Verburg et al., 2009). Land-cover changes during recent decades (since 1980s), have been captured by remote sensing analyses of the entire region, and showed overall increases in forest cover and agricultural abandonment (Griffiths et al., 2014; Kuemmerle et al., 2008). However, our understanding of long-term land-use trends remains scattered across numerous local-scale case-studies dispersed across the region (e.g., Feranec and Oťahel, 2009; Kaim, 2009; Ostafin, 2009) and a synthesis of these studies is lacking.

Theoretical land change predictions

In order to understand land-use trends in the region, we examined agricultural and forest change during five historical periods with distinctive socio-economic, political, technological and cultural characteristics, that were demarcated by several large-scale shocks: (1) the Habsburg and Austro-Hungarian Empires (K.u.K. Monarchy), a time of agricultural modernization and the beginning of the industrial revolution, which ended with World War I (WWI), (2) the Interwar period, characterized by the emergence of several nation-states, industrialization and intensification up to World War II (WWII), (3) the Socialist period, defined by intensification, centrally planned economies and land reforms leading to nationalization and collectivization, which ended around 1990 in the Carpathian countries, (4) the Transition when countries established market economies and land reforms took place, which lasted roughly until 2000, and lastly (5) the Accession of most countries to the EU in either 2004 and 2007 (except Ukraine), a period influenced by EU's trade, agricultural, and economic policies. We considered this last time period to start in 2000 because that is when most countries already adjusted their regulations and legislation according to European standards.

We formulated a set of expected land change trends for each period, based on overall socio-economic and technological trends during the respective time periods. Specifically, we predicted that the expansion of the Austro-Hungarian Empire, and the industrial revolution, led to homogenization and specialization of land use practices (Bičík et al., 2001), manifested as an increase in agricultural lands and a decrease in forest cover up to WWII. Under socialism, natural resource use intensified (Cioroianu, 2007), and we hypothesized that agricultural expansion, intensification and in some countries collectivization, led to an increase of agricultural land, especially in lowland areas, while abandonment of marginal lands allowed for forest recovery. We expected that the collapse of socialism, followed by the changes in ownership structure and the establishment of market economies led to a decrease in agricultural lands due to abandonment and forest re-growth during the Transition period (Baumann et al., 2011; Kuemmerle et al., 2009a, 2009d; Prishchepov et al., 2013). We also expected that the effects of the EU macro-economic policies would result in the increase of agricultural lands due to subsidies (Björnsen-Gurung et al., 2009) and continued forest transition (Lambin and Meyfroidt, 2010).We hypothesized thus increases in both agricultural lands (over previously abandoned fields) and forest cover after 2000 (Csaki and Jambor, 2009). For a summary of these expected trends, see Table 1.1.

Data

We collected case study information on forest and agricultural change both from peer-reviewed articles and grey literature. We used Google Scholar and regional scientific databases using combinations of "historic", "land-use/ land-cover change", and "maps" in English and the regional languages (Romanian, Slovakian, and Ukrainian) and complemented this information with traditional library research in the respective countries plus references from local experts in the Czech Republic, Hungary, Ukraine, Poland, Romania and Slovakia. For 85 publications, we extracted information about the study area, land cover at different time periods, and the main drivers of change. In approximately half of the cases, data was provided directly by authors of the paper. For the remaining publications we extracted the data using a structured form. From the total of 85 publications, we selected and analyzed those 66 papers (listed in the Appendix 1) that (1) were based on spatially-explicit data (historic maps, aerial photographs, and satellite imagery) and not only statistics; (2) examined land cover at least two points in time, and (3) included spatial data regarding the study location or coordinates of the study region. We excluded papers that did not meet at least one of the three criteria (Appendix 2). We hereafter refer to a case study as being a single geographical location at which either forest or agricultural (or both) land cover was reported during a given time period. Some papers contained several case studies, reporting land-cover change in multiple locations. We did not include in our meta-analysis recent broad-scale remote sensing land change studies based on Landsat data (Alcantara et al., 2012; Baumann et al., 2011; Griffiths et al., 2014; Knorn et al., 2012b, 2009; Kuemmerle et al., 2011, 2009a, 2008, 2007; Prishchepov et al., 2012), due to their significantly different spatial extent, frequent overlap among studies, and generally short duration, but we considered them in the discussion of change drivers. In sum, the 66 papers contained a total of 102 case study locations, for which change rates were calculated for one or more time-periods (Figure 1.1 and Table 1.1). The spatial extent of the individual studies spans from 240 ha (Wolski, 2001) to over 2 million hectares (Grekov, 2002), with the median at 12,500 ha (Figure 1.1b). On a temporal scale, the shortest time period covered by case studies at a single location was 10 years (Grekov, 2002) , and the longest 238 years (Mojses and Boltižiar, 2011). The mean time covered was 105 years.

Analysis

We developed a common land-cover class catalogue, which was applied to all studies. In most instances, this necessitated the aggregation of classes (e.g., 'permanent' and 'seasonal crops' were combined into 'agriculture'). The final product was land-cover data for 'forest' ,'agriculture' and 'other' land covers. We calculated the annual rate of change for each land-cover class following the model of FAO forest change assessments (Pandey, 1995) which uses a formula based on the compound interest law in order to compare among sites ((Puyravaud, 2003):

$$Ann_{change} = \left(\frac{A_2}{A_1}\right)^{1/(t_2-t_1)} - 1$$

(*Equation 1)*

A_1 and A_2 represent the area of land cover of interest (forest or agriculture land) at the times t_1 and t_2. When a case study reported multiple rates within one of the five analyzed time-periods, we calculated weighted averages. Studies that reported a single rate of change across multiple time periods were mapped using a different symbol, as these depict change only between the beginning and end of the first and last period, missing variation within the selected time window. We defined change rates between +/- 0.1% change/year as 'stable' land use. Centroids were digitized to represent the location of each study and rates of change were calculated for each study and time period under investigation (Figure 1.1).

To identify the main drivers, we conducted a qualitative review, categorizing the major types of driving forces as suggested by Geist and Lambin (2004) and Bürgi et al. (2005): institutional, economic, social-demographic, cultural, and climatic. Because our analysis only captured changes in land cover and not in land-use intensity, technological drivers, such as the introduction of fertilizers, or mechanization, which would mostly lead to increased yields or crop rotation, where considered jointly with the economic factors. For each case study, we identified the two most important drivers of change as described by paper authors and regional experts. We counted the number studies that mentioned each driver and qualitatively reviewed each driver across case-studies and the four land change processes of interest (deforestation, reforestation, agricultural expansion, and agricultural abandonment).

Case study representativeness and robustness check

The case studies ranged widely in extent (240 ha to 2.1 million ha) and duration (from 2 to 180 years). We tested for correlation between the absolute values of the annual rate of change and (a) the size of study area, (b) the temporal extent of the studies and (c) the percentage cover at the beginning of the study, but found only weak associations (adjusted R-squares of 0.036, 0.018, and 0.033 respectively). Spatially, land change research was concentrated in the Carpathian Mountains, while lowland areas were underrepresented, except in Ukraine. The highest density of studies was in Poland and Slovakia (Figure 1.1). Since 2000, case-studies on agricultural and forest change were relatively sparse due to the short time period under consideration (12 years).

In order to check if case studies represented the general conditions of the respective country's share of the study area, we examined three physical variables, mean elevation, mean slope, and dominant soil type, for each case study and compared mean values of the case-studies with the mean of country's share of the study area. We found that the dominant soil across all countries was Cambisol, as was the case for most of the case-studies, except in Hungary where Luvisols and Fluvisols were overrepresented (Figure 1.2). In terms of slope and elevation, case studies in the Czech Republic, Slovakia and Ukraine studies represented their country's physical conditions well. In Poland and Romania, many studies were carried out at higher-than-average elevations and slopes, but the means for the country's share of the study area fall close to the 1st quartile of the case studies distribution in all cases (Figure 1.2).

Results

Forest cover increase was the most common land-cover change over the past 250 years in the majority of studies. Among the time periods, we found the highest proportion of case studies reporting decreases in forest cover during the K.u.K. Monarchy (over 22% of studies). However, even this period, stable forest cover was the most common pattern (mean annual change +0.08%). Forest cover increased during all other periods, especially during the Transition and EU period (mean annual change +1.07% and +0.89%). In the Interwar period, 92% of studies reported stable or increasing forest cover (mean annual change 0.35%, Figure 1.3). A high proportion of studies reported forest cover increase (65%) for the Socialist period, in particular in the northern part of the Carpathians (annual mean 0.33%), followed by continuing increasing forest cover during Transition and EU accession periods (73 % and 72% respectively). After 2000, forest cover increased (annual mean 0.89%), but in Romania we found high rates of forest cover loss (Figure 1.3 and Figure 1.4).

Agricultural change was generally complementary to forest change, where forests increased, agriculture decreased, and vice-versa. However, during the K.u.K Monarchy period, agriculture increased (70% of studies, mean annual increase of 0.12%), while forest cover was mostly stable (45% of studies), indicating agricultural expansion into other land covers (Figure 1.3, Figure 1.5). The mean annual change of agricultural land change during the Interwar period was -1.28%, despite relatively stable agricultural cover (55% of studies, ± 0.1% annual change) reported in most studies. After 1945, most studies (> 75%) reported a decrease of agricultural land-cover. During the Transition and EU accession periods, there were substantial decreases in agricultural cover (mean annual change of -1.61% and -1.20% respectively). Across time periods, the proportion of studies documenting loss of agricultural land increased constantly until 2000, but dropped slightly after the EU accession (Figure 1.3).

There were interesting regional patterns of change though: forest decreased during the K.u.K. Monarchy in the Romanian, Ukrainian, and Slovakian Carpathians, while it increased in the Polish Carpathians, and was stable in the Czech Republic (± 0.1% annual change). During the Interwar period the majority of the forest change case-studies (48%) reported stable or increasing (44%) forest cover (>0.1% annual change) but most of them were in Slovakia, and Poland, while cases of forest loss occurred in Hungary, Romania and Slovakia. Thus, across the region, forest transition occurred during the Interwar period, though we caution that patterns at elevations over

1000m in Ukraine and Romania were different (Shandra et al., 2013). The most rapid forest increase during the Socialist period occurred in the border region between Poland, Ukraine, and Slovakia (Figure 1.4), while deforestation occurred in lowland areas (e.g., Hungary) as well as in the mining district of central Slovakia. After 1990, forest cover increased across Poland, Slovakia, Czech Republic and Hungary, but there were still cases of forest loss in the Eastern Romanian Carpathians and southwestern Slovakia.

Agricultural change varied regionally: during the K.u.K. Monarchy, agriculture expanded mostly in the lowlands of Hungary, Czech Republic, and Ukraine, concurrent with forest loss, while agriculture decreased in the mountains of Slovakia and Poland. In the Interwar period agricultural land use peaked in parts of Hungary and southwest Slovakia, while agriculture declined in parts of the Polish Carpathians and northern Slovakia. During the Socialist time period, low but positive annual rates of agricultural expansion occurred in Romania and southeast of Hungary. In Slovakia and the Czech Republic, agriculture decreased slowly, whereas in Poland, agricultural land decreased by up to 5% per year (Woś, 2005). Since 1990s, agricultural decrease was least pronounced in the lowlands of Hungary, Ukraine, and the Czech Republic. In mountain areas, lower abandonment rates were reported in Ukraine, contrasting with higher rates for Romania and Slovakia (Figure 1.5). Since 2000 agriculture declined in 69% of the studies, but we caution that there are only few studies for this period.

Our analysis of the main drivers of land change examined the number of times at least one of the selected drivers of change (institutional, economic, socio-demographic, cultural, and climatic) was deemed important by the case-study authors and collaborators for each of the change processes. We found that institutional and economic factors were the most important drivers of agricultural expansion and deforestation, jointly accounting for more than 75% and 65%

respectively of the case studies. This class of drivers also included the technological developments that led to agricultural intensification and support forest transition, but our focus on land-cover areas did not allow to examine technological drivers in detail. In contrast, socio-demographic factors like migration or sector employment were more important for agricultural abandonment (42% of cases) and forest succession (36% of cases, Figure 1.6). Physical factors were also mentioned as drivers of change, for example climate supported forest succession on abandoned mountain pastures, where the timberline shifted to higher altitudes (Mihai et al., 2006; Shandra et al., 2013). Overall, abandonment of agriculture was largely driven by socio-demographic (42%) and institutional (31%) factors, with the economy playing a less important role (24%) (Figure 1.6).

Discussion

We identified temporal and spatial patterns of land-cover change and their driving forces over the last 250 years across the Carpathian Basin. Our results showed that forest change was closely related to agricultural dynamics and that rates and patterns of change were heterogeneous among politically distinct time periods, and varied regionally. Deforestation was less widespread than we had expected, and the observed changes differed from our expectations in particular during the K.u.K. Monarchy and Interwar periods. Between WWI and WWII, forest cover decrease stopped across the region. Our findings are concurrent with other studies (Kozak, 2003; Kuemmerle et al., 2011), indicating that the region as a whole experienced a forest transition during the Interwar period, despite regional differences (Shandra et al., 2013). After WWII, the observed forest cover increase was in line with our expectations (Table 1.2). While agricultural abandonment was widespread throughout the 20th century, increase in agricultural cover occurred only during the K.u.K. Monarchy. Contrary to our expectations, agricultural abandonment started early, being a prominent process across the region already during the Interwar and Socialist periods. However, abandonment rates increased after the collapse of the Socialism. In general, forest and agricultural dynamics were complementary, but there were exceptions to this rule due to rapid urban or grassland-related land-cover changes. Agricultural expansion and deforestation were mostly driven by economic and political events, while land abandonment and reforestation were mostly driven by socio-demographic factors.

Our analysis highlighted regional variation in land change patterns, and in the major drivers of change across the study area. We primarily focused on patterns of two broad scale processes: deforestation followed by agricultural expansion and forest cover increase, related to agricultural abandonment. The rise of the Habsburg Empire and Austro-Hungarian Monarchy, which brought German settlers to the Carpathian region, and the industrial revolution of the 19th century, caused significant population growth, increasing demands for agricultural products (Vepryk, 2002). Deforestation for agricultural development was both an economic and a cultural process (Boltižiar and Chrastina, 2006; Mojses and Boltižiar, 2011; Skokanová et al., 2012), and as such, patterns of deforestation varied by land ownership. While Ukrainian smallholders cleared forest patches for agricultural use in lowland areas, large landowners did not deforest, but replaced mixed forest stands with spruce plantations for pulp production at high elevations (Vepryk, 2001). While forest clearing for agriculture was common (Chrastina and Boltižiar, 2010; Konkoly-Gyuró et al., 2011; Vepryk, 2002), deforestation was also related to expanding grassland and urban cover. For example, on Ukrainian mountain meadows, livestock farming increased partly due to Hungarian and Czech investment up to WWII, lowering the timberline (Sitko and Troll, 2008). In the Northern Romanian Carpathians, net forest cover decreased at timberline since 1880s, but generally net forest cover increased at timberline due to decline of transhumance (Shandra et al., 2013).

Similarly, economic growth led to the drainage of wetlands for agriculture in Hungary (Biró et al., 2012; Konkoly-Gyuró et al., 2011; Nagy, 2008), the Czech Republic, and Slovakia (Demek et al., 2008; Drgona, 2004; Gerard et al., 2010, 2006b; Mojses and Bezák, 2010) and to the conversion of grasslands to row crops in Hungary (Chrastina and Boltižiar, 2008), Romania (Schreiber, 2003), and the Czech Republic (Chrastina and Boltižiar, 2008; Havlíček et al., 2011). During the Socialist time, annual forest cover loss was high due to the clearing of forested area of no economic value (small isolated patches and shrubby vegetation) in Slovakia and the Czech Republic (Demek et al., 2008; Špulerová, 2008; Stránská, 2008). Political goals of increasing agricultural production caused agricultural expansion in the Czech Republic (Demek et al., 2008; Skokanová et al., 2009; Štych, 2007). There was also considerable regional variation related to agricultural expansion: in some mountain areas (e.g., parts of the Polish and Slovak Carpathians) agricultural land remained privately owned and agriculture did not expand (Kozak, 2010; Mojses and Petrovič, 2013), while some agricultural expansion occurred in Romania (where 80% of the population was already employed in agriculture at the time of collectivization), and in the Great Plain of Hungary (about 50% of the population) (Kligman and Verdery, 2011). Deforestation between 1945 and 1990 was, however, not always related to agricultural expansion. For example, tourism and industrial development led to forest cover loss in the Southern Romanian Carpathians (Huzui et al., 2012) and the Tatra Mountains (Gerard et al., 2010, 2006a, 2006b). Similarly, since 1990, selective logging for household needs, illegal harvesting, and large scale clear-cuts due to loopholes in the forest laws of some countries (Irland and Kremenetska, 2009; Kuemmerle et al., 2009a) caused forest losses (Grozavu et al., 2012; Mihai et al., 2007, 2006) with particularly heavy illegal logging reported in Romania (Knorn et al., 2012b; Shandra et al., 2013), and Ukraine (Kuemmerle et al., 2009a).

On the other hand, agricultural abandonment and reforestation occurred mostly after WWII, with few local exceptions during earlier times (Patru-Stupariu, 2011). Since 1880, forest cover increased along the timberline throughout the study area (Shandra et al., 2013). During the 19th and early 20th century, marginal agricultural sites in the Polish mountains exhibited the most abandonment due to harsh environmental conditions (Ostafin, 2009), while agriculture expanded in more favorable areas with little terrain, in line with the forest transition theory (Lambin and Meyfroidt, 2010; Lambin et al., 2001). The agricultural decrease was related to a shift of agricultural activities to more productive lands, as well as to industrialization (Gerard et al., 2010, 2006a, 2006b). During the Socialist time period, the forced industrialization of the 1970s led to migration from rural areas to cities, causing farmland abandonment, for example, in Romania (Schreiber, 2003). In the same period, forests increased along inaccessible areas of the Iron Curtain in the Czech Republic (Skokanová and Eremiášová, 2012), and Slovakia (Kalivoda et al., 2010).

After the collapse of socialism, the lack of agricultural subsidies, decreased profitability (Müller et al., 2013a; Prishchepov et al., 2012), and the bankruptcy of most large agricultural enterprises (Petrovič and Hreško, 2010; Turnock, 2002; Zaušková et al., 2011) caused widespread abandonment followed by reforestation (Boltižiar and Chrastina, 2008; Havlíček et al., 2009; Zaušková et al., 2011). Increasing emigration to western Europe (Munteanu et al., 2008; Petrovič, 2006) resulted in decreasing employment in the agricultural sector, reducing pressure on land and allowing forest succession to take place (Kozak, 2003; Kozak et al., 2007; Smaliychuk, 2010). In the Ukraine, after 1990, abandonment occurred mostly on large agricultural fields, while subsistence agriculture reemerged on marginal lands in the mountains (Baumann et al., 2011). Last but not least, nature conservation policies contributed to stabilize or increase forest cover after 1945, and especially since 1990, in parts of Slovakia, Hungary and Poland (Gerard et al., 2006b; Konkoly-Gyuró et al., 2011; Olah and Boltižiar, 2009), even though the effectiveness of protected areas in Romania is uncertain (Knorn et al., 2012b). In mountain areas, forest increase was also triggered by decreasing grazing pressure (Mihai et al., 2007; Tirla et al., 2012; Zaušková et al., 2011) and changing climate (Mihai et al., 2006; Shandra et al., 2013; Tirla et al., 2012). On the other hand, after the EU accession, nature conservation and agricultural policies alongside with awareness of the loss of valuable mountain grasslands, resulted in a shift from arable land to high-nature value meadows and from forest to pastures (Bezák and Halada, 2010; Cebecaurová and Cebecauer, 2008; Zaušková et al., 2011).

Most of our case studies reported interactions among the drivers of land change, with broader political decisions being often the underlying factors constraining economic and social conditions (Cebecaurová and Cebecauer, 2008; Janicki, 2004; Sitko and Troll, 2008).The same driver also often caused different land change patterns in different parts of the region: for example during the Socialist time period, national policies led to agricultural expansion on fertile soils in Hungary (Chrastina and Boltižiar, 2008), while forced industrialization as a national policy caused migration and abandonment of agriculture in areas of Romania (Schreiber, 2003). Relative to other drivers of change, the effects of culture on land use may only become apparent at long temporal scales. This means that culture may not have been an important driver at the temporal scale of some of our case studies, which reported change on the order of decades rather than centuries, and culture thus being less prevalent in our summaries than its overall importance would suggest. Furthermore individual effects of drivers were difficult to isolate because of the interplay between social, economic and political elements that lead to local land-use decisions.

It was beyond the scope of our analysis to assess changes in land-use intensity, since most case studies did not map these explicitly. However, across the region, notable changes include agricultural intensification and shifts in forest management. Intensification was driven mostly by economic and technological development throughout the 19th century (Demek et al., 2008; Havlíček et al., 2011; Skokanová et al., 2009), when both crop rotation and industrial fertilizers were introduced. Similarly, Soviet agricultural policies led to intensification (Cebecaurová and Cebecauer, 2008; Mojses and Bezák, 2010; Skokanová et al., 2009) while nationalization of land caused increase in property sizes and the shift from small-scale farms to large state-owned agricultural operations (Boltižiar and Chrastina, 2006; Krivosudsky, 2011; Štych, 2007; Štych et al., 2012). These changes did not necessarily affect the land cover, but let to landscape homogenization (Krivosudsky, 2011; Mojses and Boltižiar, 2011; Špulerová, 2008). Conversely, changes in forest use affected forest patterns and fragmentation: non-native species were planted for timber production (Chrastina and Boltižiar, 2010; Nagy, 2008) and heavy logging and clearcuts occurred during Soviet times in Romania and Slovakia (Boltižiar and Chrastina, 2008; Grozavu et al., 2012; Niculita et al., 2008) due to increased demand for wood. Despite the documented overall forest cover increase after 2000 (0.89% mean annual change), extensive forest disturbances - which do not necessarily alter the land-cover type - occurred in Romania, Poland, Ukraine and the Czech Republic (Griffiths et al., 2014; Kuemmerle et al., 2009a).

Overall, our analysis provided a synthesis of land change patterns and processes during time periods with very different and rapidly changing political and economic conditions. The strength of our analyses lied in the multi-language data sources as well as in the fact that we complemented this information with traditional library research, accessing a wide base of local knowledge. Furthermore, by synthesizing land changes in 102 case-studies, our analysis improves the understanding of overall trends, and acknowledges regional and temporal differences, rather than extrapolating findings of single micro-scale studies. We showed that rates of change differed markedly over the past 250 years: after the collapse of the Austro-Hungarian Empire agricultural land declined, while the collapse of the socialism accelerated agricultural abandonment and forest cover increase. We also showed that recent land change trends do follow long term land changes in terms of direction of changes but the magnitude of these processes differs substantially across periods, with high rates of change being captured since the collapse of socialism. We acknowledge that some case-studies were focused on capturing change based on unique conditions, such as depopulated areas of Poland (e.g., Maciejowski, 2001; Warcholik, 2005; Wolski, 2001) or flooded villages in Slovakia (Petrovič and Bezák, 2010) so that our analysis might describe the very peaks of observed processes. However, despite the abrupt changes in political and economic systems, which might disrupt gradual land transitions, the forest transition theory holds true in this region with the shift from decreasing to increasing forest cover occurring between the two World Wars for the most case studies.

Our results show that despite repeated shocks, which can alter the intensity of long-term, gradual changes, forest transition theory holds true in the Carpathian region. The change point from forest decrease to forest increase occurred between the two World Wars in most of the areas. Around the world, the forest transition occurred at different points in time, highly dependent on the socio-economic, institutional conditions and global marked dynamics. For example, western European countries like France and Britain experienced forest transition already in the second half of the 18th century (Mather, 1998, 1992) as a function of their land use specialization and developing economies (Barbier et al., 2010; Lambin and Meyfroidt, 2010). Countries, such as India, China, Vietnam, Chile, El Salvador, on the other hand, experienced forest transition recently (second half of the 20th century), driven by governance, global market dynamics and displacement of land use abroad (Mather, 2007; Meyfroidt et al., 2010).

In the Carpathians, the agricultural change was mostly mirrored by forest cover and also involved other land-cover classes, for which data availability was limited. Agricultural expansion up to the early part of the 20th century, coincides broadly with the trends observed during the 19th century in other developed regions such as the US, Canada or USSR, where agriculture expanded mostly over grasslands and forests (Goldewijk, 2001). In developing tropical countries, agricultural expansion and intensification is a more recent process (Keys and McConnell, 2005). Countries like Bhutan, Brazil, Costa Rica or China experience large increases in agricultural covers only in the second half of the 20th century (Meyfroidt et al., 2010). In contrast, during the same time, many post-soviet countries face land abandonment since the collapse of socialism (Alcantara et al., 2012; Prishchepov et al., 2013), a similar trend to the one we observed in the Carpathians. Regional differences were notable, especially due to physical factors and several interacting driving forces, but institutional, policy and economic drivers were most influential in shaping both deforestation and agricultural expansion. Socio- demographic factors like rural population decline were the key drivers for land abandonment. Overall, we highlighted the value of longitudinal studies of land change to reveal the strong effects that repeated socio-economic and institutional changes have on land-use and land-cover.

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Tables and figures

Table 1.1 Time periods, their duration, the expected land changes and the number of studies that report land change for the specific period. The first number (*) indicates that the annual rate of change has been calculated for only one period. The second number (**) indicates that the case-study spans at least two time periods, and the annual rate of change is calculated based only on land cover at the beginning and end of the considered time span.

Time period	Duration	Expected land change process		Number of case studies	
		Forest	Agricultural	Forest (n)	Agriculture (n)
K.u.K Monarchy	1750-1914	-	+	31* / 51**	24* / 43**
Interwar	1914-1945	-	+	29* / 72**	28* / 46**
Socialist	1945-1990	+	+	46* / 96**	37* / 63**
Transition	1990-2000	+	-	46* / 84**	42* / 68**
EU accession	2000-2012	+	+	37* / 60**	26* / 47**

Table 1.2 Comparison of expected and observed land changes for each time period and the mean annual rates of change, calculated for all the case studies for which change rates were not spanning more than one period (marked * in Table 1.1). For these calculations, only studies that report annual change for single periods were considered.

Time period	Expected land changes		Mean annual rate of change		Observed land changes	
	Forest	Agriculture	Forest	Agriculture	Forest	Agriculture
K.u.K Monarchy	-	+	0.08%	0.12%	0	+
Interwar	-	+	0.35%	-1.28%	+	-
Socialist	+	+	0.33%	-0.54%	+	-
Transition	+	-	1.07%	-1.61%	+	-
EU accession	+	+	0.89%	-1.20%	+	-

Figure 1.1 a) Study area, including spatial extent of case studies (grey) and centroids for 102 case study locations (triangles). Country codes: AT: Austria, HU: Hungary, PL: Poland, CZ: Czech Republic, SK: Slovakia, UA: Ukraine, RO: Romania, MD: Moldova, HR: Serbia, SI: Slovenia. b) Spatio-temporal distribution of 102 study locations (one location may include multiple case-studies).

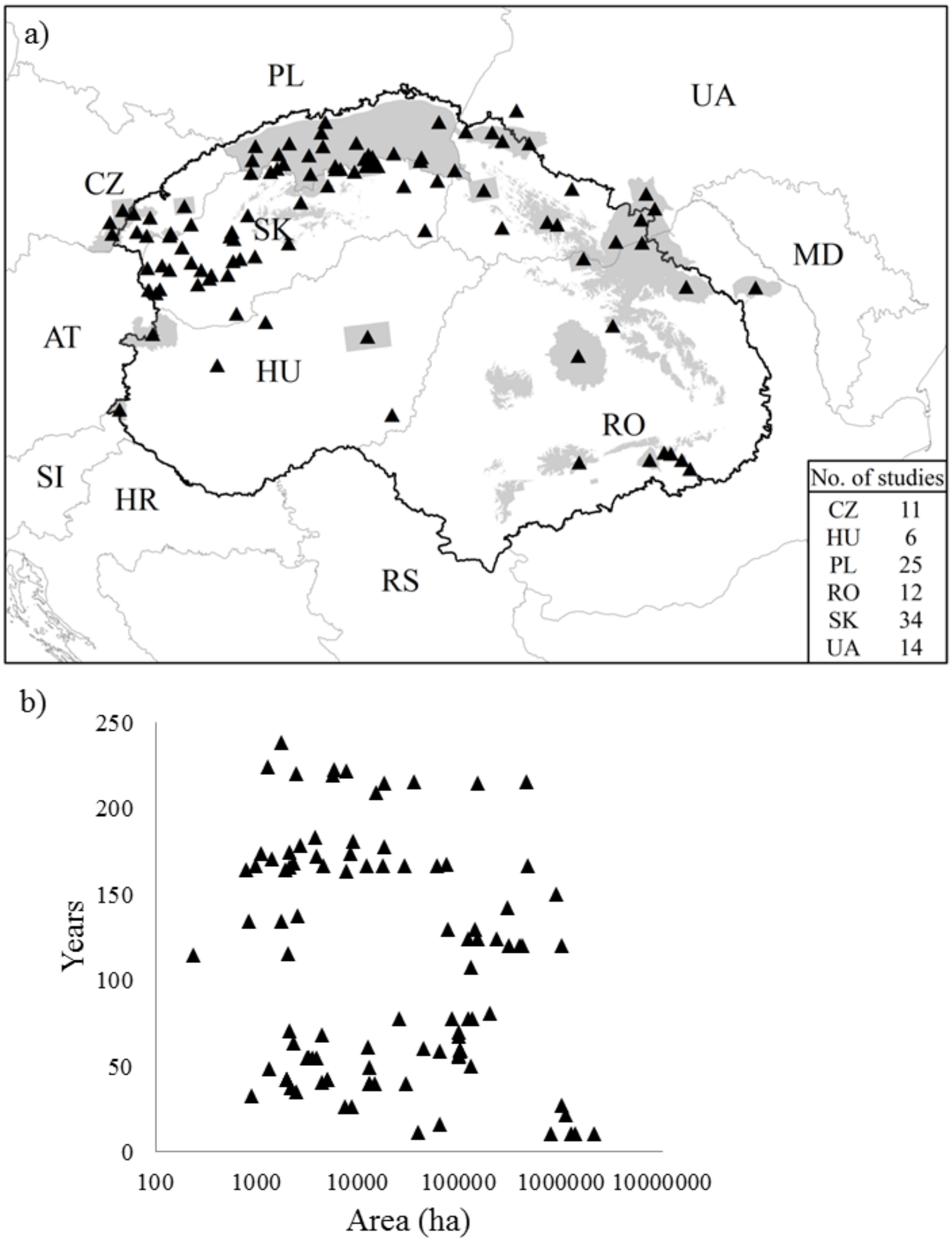


Figure 1.2 Representativeness check of case studies biophysical characteristics for the country's share of the study areas: comparison of a) elevation and b) slope. The grey line indicates the mean value for the country's share of the study area. c) Soil type distribution for the case studies in each country and for the region as a whole. Country codes: CZ: Czech Republic, HU: Hungary, PL: Poland, RO: Romania, SK: Slovakia, UA: Ukraine.

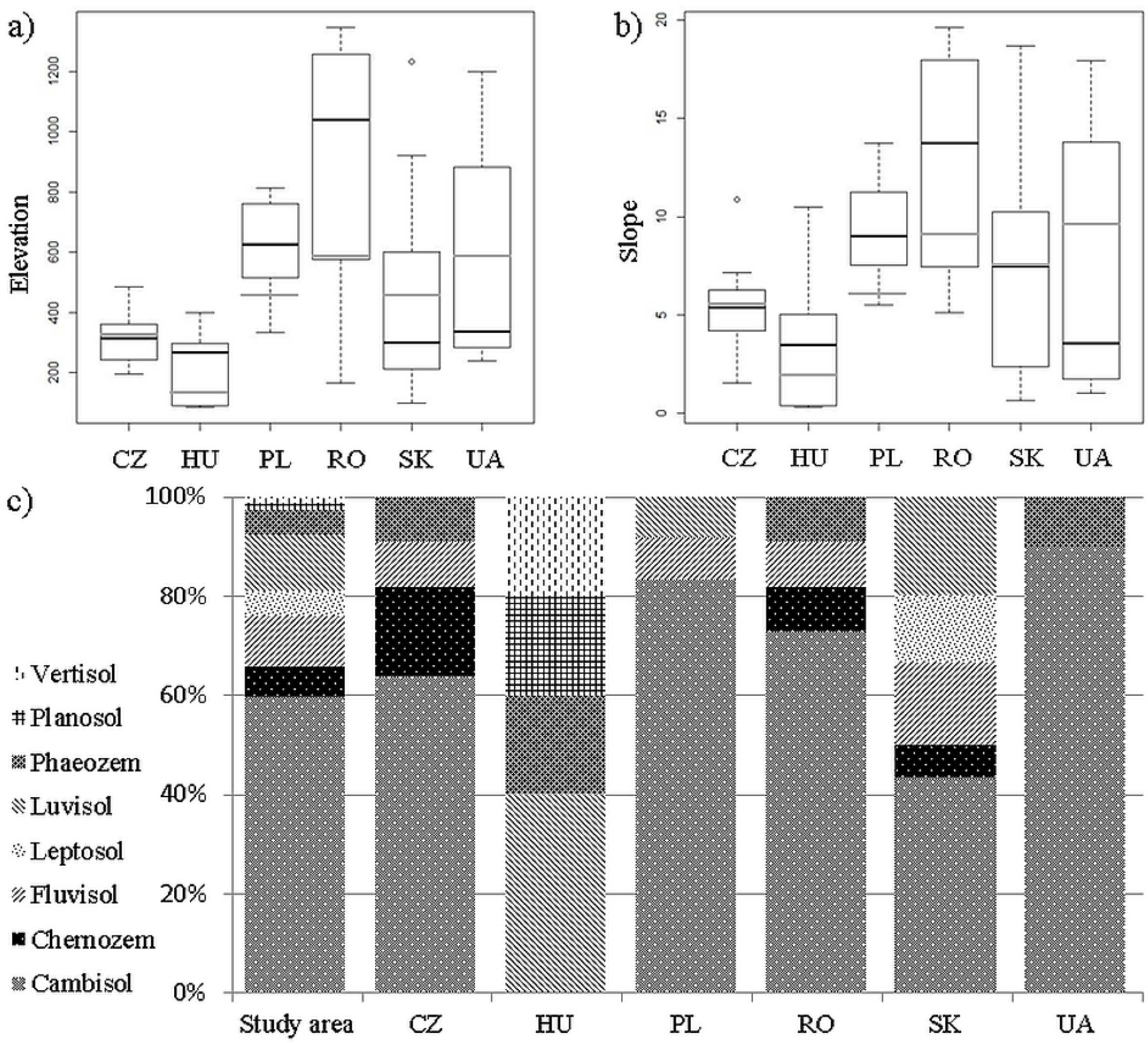


Figure 1.3 Proportion of studies reporting decreasing (<-0.1% annually), stable (-0.1% to 0.1% annually) and increasing (>0.1% annually) cover for each time period for a) forest and c) agriculture and distribution of annual rates of change per time period for b) forest and d) agricultural cover. Country codes: CZ: Czech Republic, HU: Hungary, PL: Poland, RO: Romania, SK: Slovakia, UA: Ukraine.

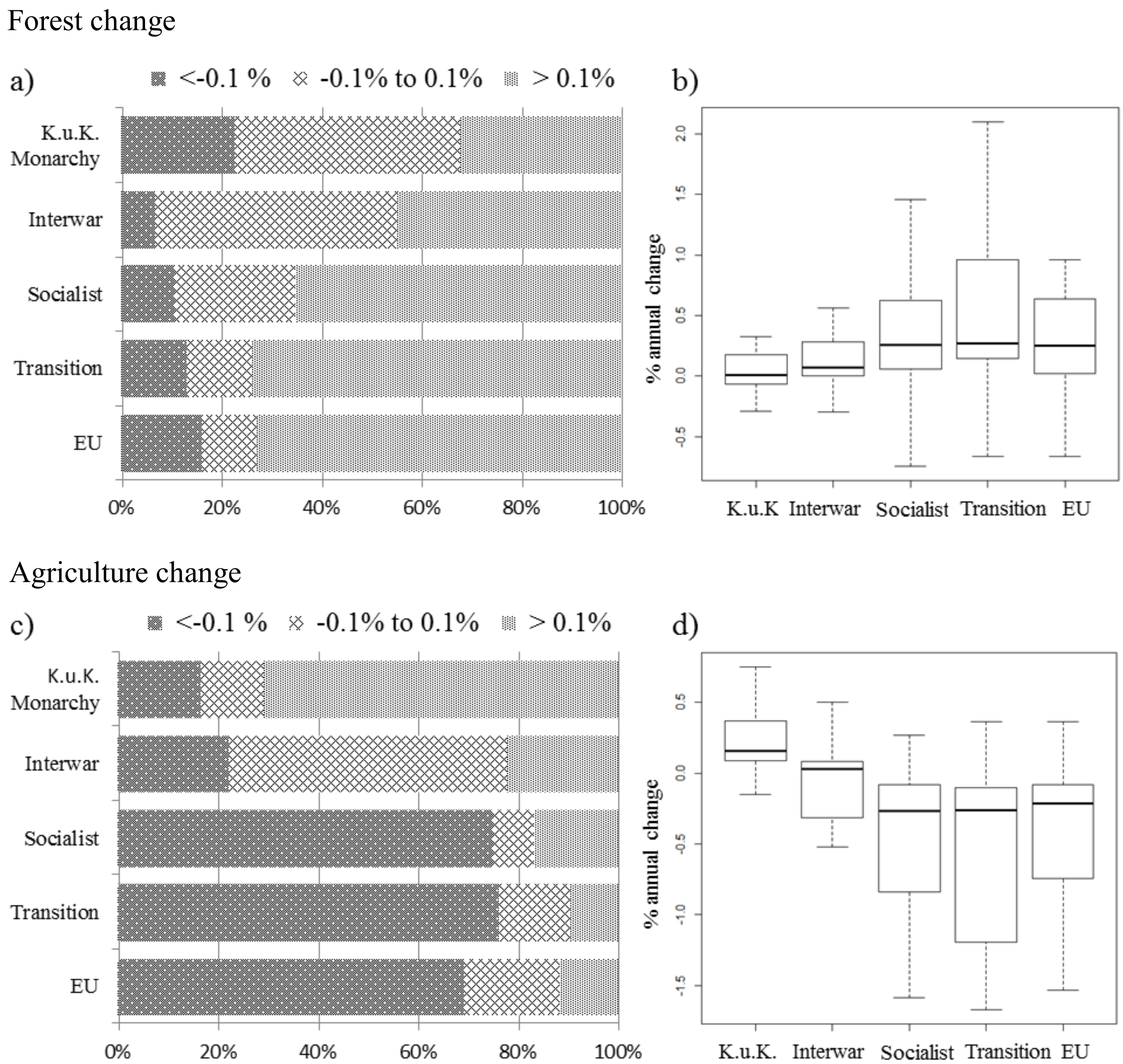


Figure 1.4 Spatial and temporal distribution of forest change case studies. Annual rates of change are mapped for each case study and time period. Studies are represented by centroids. The size of the symbols indicate the amount of change, the colors indicate the direction of change (increase/stability/decrease). Shaded colors indicate that annual rates are calculated for more than one time period. Country codes: CZ: Czech Republic, HU: Hungary, PL: Poland, RO: Romania, SK: Slovakia, UA: Ukraine.

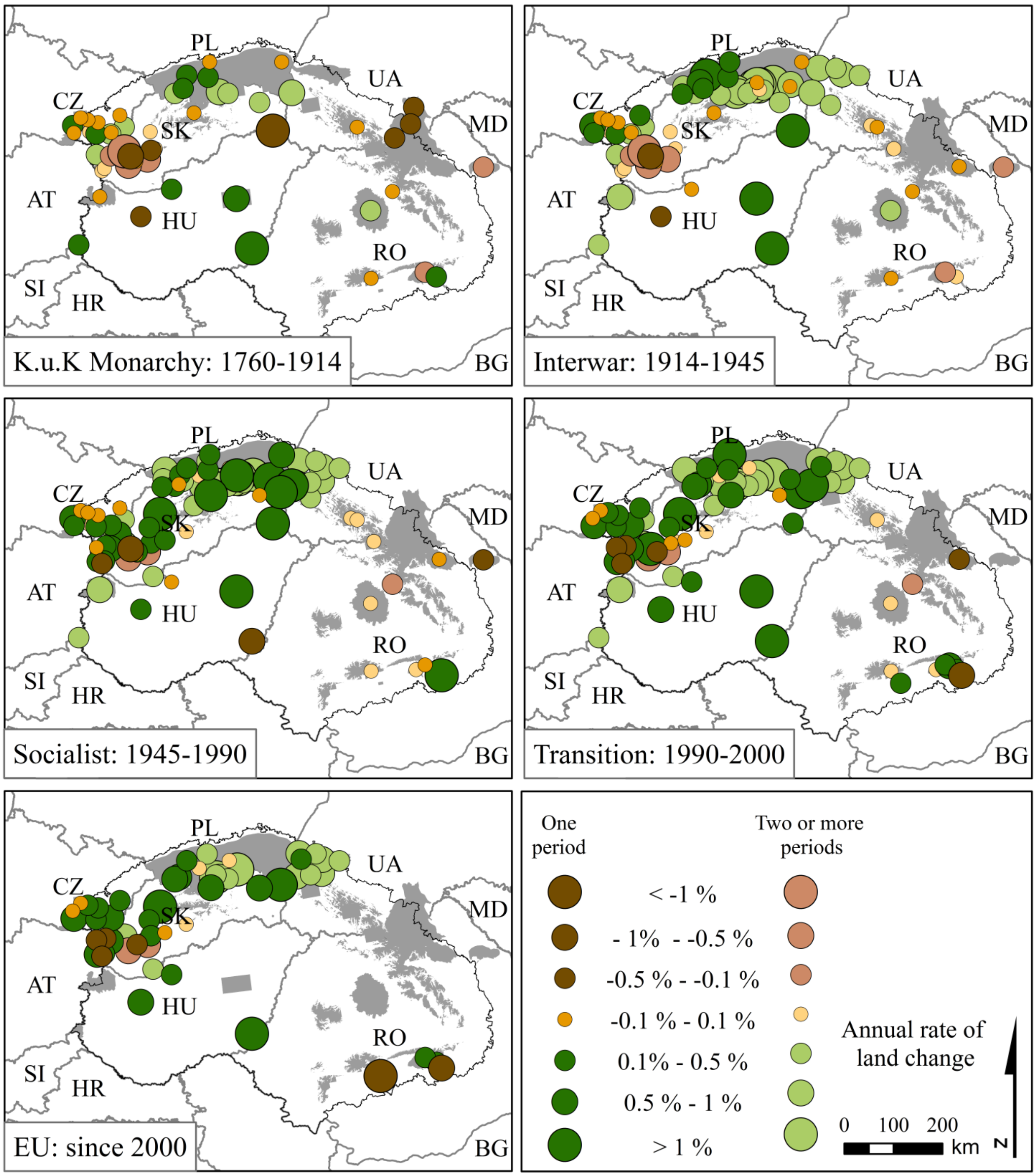


Figure 1.5 Spatial and temporal distribution of agricultural change case studies. Annual rates of change are mapped for each case study and time period. Studies are represented by centroids. The size of the symbols indicate the amount of change, the colors indicate the direction of change (increase/stability/decrease). Shaded colors indicate that annual rates are calculated for more than one time period. Country codes: CZ: Czech Republic, HU: Hungary, PL: Poland, RO: Romania, SK: Slovakia, UA: Ukraine.

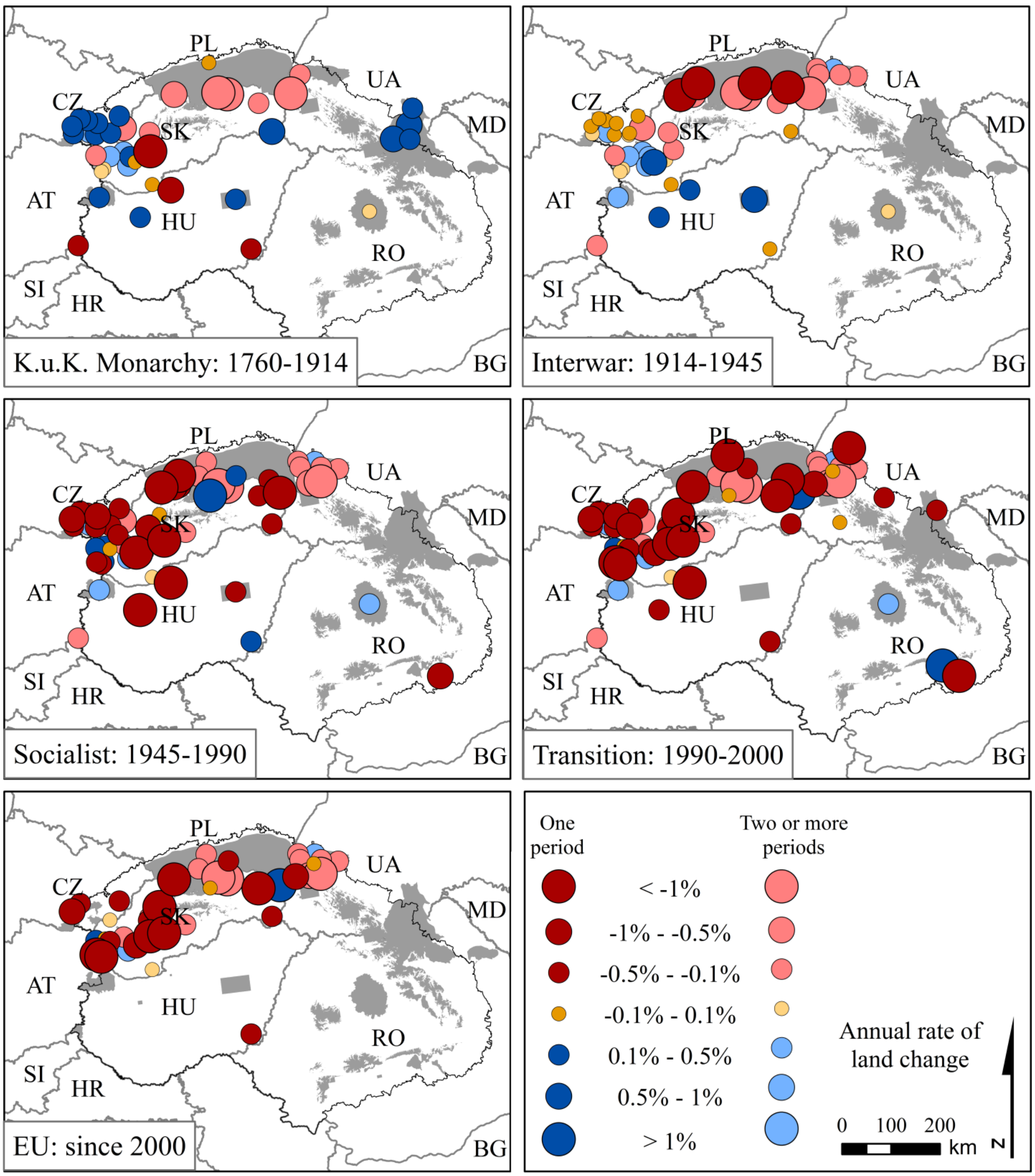
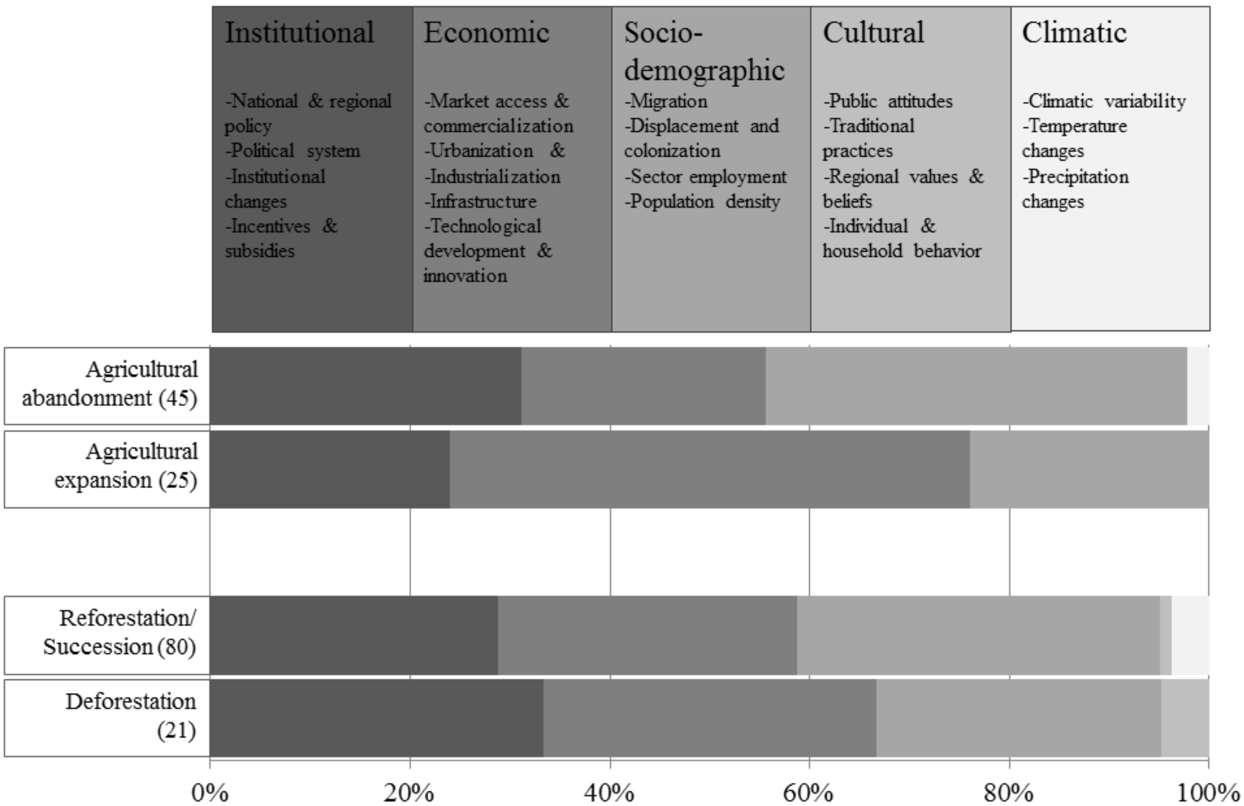


Figure 1.6 Main classes of land change drivers and the relative importance of drives for each land change process in the study area. The proportions are calculated based on the number of times a driver was deemed as important in influencing change.



Appendix

Appendix 1.1 List of publications included in the meta-analysis

Boltižiar and Chrastina (2006)
Boltižiar and Chrastina (2008)
Bugár et al. (2010)
Cebecaurová and Cebecauer (2008)
Chrastina and Boltižiar (2008)
Chrastina and Boltižiar (2010)
Dec et al. (2009)
Demek et al. (2008)
Drgona (2004)
Gerard et al. (2006a)
Gerard et al. (2006b)
Grekov (2002)
Grozavu et al. (2012)
Havlíček and Borovec (2008)
Havlíček et al. (2009)
Havlíček et al. (2011)
Hurbánek and Pazúr (2007)
Huzui et al. (2012)
Jančovič et al. (2010)
Janicki (2004)
Kaim (2009)
Kalivoda et al. (2010)
Konkoly-Gyuró et al. (2011)
Kozak (2003)
Kozak et al. (2004)
Kozak et al. (2007)
Kozak (unpublished)
Krivosudsky (2011)
Labuda and Pavličková (2006)
Maciejowski (2001)
Mihai et al. (2006)
Mihai et al. (2007)
Mojses and Bezák (2010)
Mojses and Boltižiar (2011)
Mojses and Petrovič (2013)
Monastyrskiy (2010)
Moyzeová and Izakovičová (2010)
Muchová and Petrovič (2010)
Nagy (2008)
Niculita et al. (2008)
Ostafin (2009)
Ostapowicz & Ostafin (in prep)
Ostapowicz and Kozak (2011)
Patru-Stupariu (2011)
Patru-Stupariu et al. (2011)
Petrovič (2006)
Petrovič and Bezák (2010)
Petrovič and Hreško (2010)
Petrovič and Muchová (2008)
Pietrzak (2002)
Reiser (2006)
Schreiber (2003)
Shandra et al. (2013)
Skokanová et al. (2009)
Špulerová (2008)
Štefunková and Petrovič (2011)
Stránská (2008)
Štych (2007)
Štych et al. (2012)
Vepryk (2000)
Vepryk (2001)
Vepryk (2002)
Warcholik (2005)
Wolski (2001)
Woś (2005)
Zaušková et al. (2011)

Appendix 1.2 List of publications not included in the meta-analysis

Paper not included	**Criteria not met**
Badea, (2011)	1
Bičík et al., (2001)	1
Bochko, (2010)	1
Boucníková and Kučera, (2005)	1,2
Feranec and Oťaheľ, (2008)	1,3
Feranec et al., (2000)	1,3
Feurdean, (2010)	1,3
Kilianová et al., (2008)	1
Konkoly-Gyuró et al., (2007)	3
Korjyk, (2001)	1
Kozak, (1994)	3
Lavruk, (2011)	1
Malahova, (2009)	1
Miklovoda and Gazuda, (2010)	1
Mulková et al., (2012)	1
Perovych et al., (2011)	1
Sitko and Troll, (2008)	1
Slivka and Savjuk, (2011)	1,3
Tirla et al., (2012)	3

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Chapter 2. Legacies of 19th century land use shape contemporary forest cover

Introduction

Land use and land cover change are major components of global change, causing daunting sustainability challenges (Foley et al., 2005; Lambin and Geist, 2006; Sarukhán and Whyte, 2005). The effects of past land use (hereafter 'land use legacies') on the structure and functioning of current land system can be long-lasting. Legacies manifest themselves in all parts of ecosystems (Foster et al., 2003; Wallin et al., 1994) and can persist for decades (Wallin et al., 1994) or even centuries (Boucher et al., 2013; Thompson et al., 2013). The ecological effects of past land uses on current ecosystem structure are fairly well understood (Boucher et al., 2013; Foster et al., 2003; Rhemtulla and Mladenoff, 2007; Thompson et al., 2013) and path dependency has been conceptually acknowledged in land change science as an uncertainty factor (Brown et al., 2005; Lambin and Geist, 2006; National Research Council, 1998; Verburg et al., 2004), but empirical evidence on how much land use legacies affect contemporary land use change and land management is still scarce.

Past land uses can affect all parts of ecosystems (Foster et al., 2003; Wallin et al., 1994). For example, soil composition and nutrient content that were altered in the Eastern US during European settlement, are affecting plant abundances today (Thompson et al., 2013). The vegetation composition of historically ploughed areas has fewer shrubs and a distinct understory vegetation compared to continuously forested areas (Eberhardt et al., 2011; Motzkin and Foster, 2002). Similarly, prior farming in sagebrush ecosystems causes lower shrubs and forb cover today (Foster et al., 2003; Morris et al., 2011) while the high proportion of shrubby vegetation in dry areas, such as Chaco, New Mexico is due to overharvesting by the Anasazi (800 BC) as well as overgrazing and high stocking densities in the 1800s (Brown and Archer, 1989; Foster et al., 2003; Fredrickson et al., 1998; Gibbens et al., 2005; Swetnam et al., 1999). Past land use decisions affecting possibilities of future change are probably best exemplified by urban area expansion, where path dependence constrains the possibility to revert an urban area to agricultural land (Lambin and Geist, 2006). Although land use legacies are widely acknowledged, the magnitude of their effect on contemporary land use dynamics at broad spatial and temporal scales is rarely quantified. The increasing number of studies and datasets capturing long term land use and land cover change (Başnou et al., 2013; Gerard et al., 2010) offers exciting new opportunities for the quantification of the legacies that past land uses exert on contemporary land change processes.

Forests are particularly likely to exhibit land use legacies, because they are persistent elements in landscapes due to the long lifespan of trees. Land use legacies can affect both forest structure and management decisions. For example, forests that were farmed during Roman times in Western Europe have a different seed bank than those that were always forested, including higher abundance of species that colonize abandoned land, and fewer seeds of poor dispersers (Dupouey et al., 2002a; Plue et al., 2009). Historic land use leads to the occurrence of fruit tree species in oak forest systems (Plieninger et al., 2010a) and affects both forest structure and composition including basal area, tree density, and woody plant richness (Plieninger et al., 2010a; Rhemtulla et al., 2009). Even in cases in which forest composition is similar to that of historic forests, for example after agricultural abandonment in the Northeastern US, the relative importance of tree species is different and depends on the historic use (Thompson et al., 2013). Similarly, Mayan overexploitation of forests affects forest structure until today, due to changes in micro-topography, soil moisture, nutrient content and the location of ancient settlements (Foster et al., 2003). However, while past land uses clearly affect current forest patterns, their impact is difficult to predict, especially if land management is constrained by such legacies.

Contemporary forest management may be severely constrained by historic uses and prior management practices, and land use legacies can play a defining role of the pathways of future forest change. Harvesting regimes can exert substantial legacy-effects because they establish an age-structure that can persists for several rotation cycles, even when management changes subsequently (Wallin et al., 1994). Similarly, rates of forest disturbance from either harvest or fires influence forest types in following decades, leading to less coniferous cover in the Russian Far East (Cushman and Wallin, 2000). Historic housing density, reforestation and fire suppression since the early 20th century affect forest management at landscape level at the end of the 20th century in the Midwestern US (Radeloff et al., 2001). In sum, both forest composition and structure are closely related to historic land uses, reaching back from decades to centuries.

However, while the long-term persistence of legacies in ecosystem structure and composition is relatively well understood in ecology, and path dependency has been an established concept in land change science (Lambin and Geist, 2006; National Research Council, 1998) the role of past land uses in modulating contemporary forest disturbance patterns has not been well quantified. Anecdotal evidence suggests that recent vegetation changes, such as shrub encroachment on overexploited agricultural land (Cramer et al., 2008; Foster et al., 2003) or reforestation on historically cleared pastures (Bezák and Mitchley, 2014; Sitko and Troll, 2008) are a consequence of past land uses. Moreover, past management affects ecosystem health and the susceptibility to change (Main-Knorn et al., 2009). Land use legacies may affect the pace and the timing of forest disturbance, making the consideration of land use history important when predicting future forest changes. However, the extent to which contemporary forest disturbance is determined by land use legacies remains unclear, especially in comparison to other major drivers of land change such as environmental or socio-economic factors. In other words, it remains unknown how much forest disturbance is modulated by historic land use, and how much by other factors (Amacher et al., 2003; Beach et al., 2005; Geist and Lambin, 2001).

Our goal was to analyze the effects of land use legacies on contemporary forest disturbance in the Carpathian region, by assessing (1) the magnitude of contemporary forest disturbance, (2) the relation to spatial determinants of forest disturbance, and (3) changes in main forest types. Here, we define forest disturbance as full loss of forest cover due to forest management (e.g., clear-cutting), natural disturbances such as pests and storms (often followed by salvage logging), and deforestation (conversion to other land uses). Our first hypothesis was that there is more contemporary forest disturbance in areas that were not forested in the mid-19th century (hereafter 'new forests') compared to areas forested at that time (hereafter 'old forests') because new forest, mostly plantations, are more likely to be intensively managed than old forests and because the age and species composition of old forests makes them more resilient to disturbance. Second, we expected to find that contemporary disturbance is higher in new forests irrespective of environmental, socio-political and accessibility variation. Our third hypothesis was that 'new forests' have a higher proportion of coniferous forest than 'old forests', due to forest management practices of the late 19th and early 20th century, including widespread plantations.

Methods

Study area

We studied the Carpathian region in Eastern Europe (~265,000 km^2), because the region experienced multiple socio-economic, political, and land management shifts over the past two centuries, providing an ideal 'natural experiment' for the study of land-use legacies (Munteanu et al., 2014). The study area includes parts of two major eco-regions, the Carpathian Mountains and the Pannonian plains, and parts of Romania, Slovakia, Ukraine, Poland, Czech Republic and Hungary (Figure 2.1). Our study period from 1860 to 2010 captured a century and a half of land-use history, starting with the peak of the Habsburg Empire in the mid-19th century.

The land cover in the Carpathian mountains consists of a mosaic of forests, small agricultural fields, grassland areas, and scattered settlements (Kozak et al., 2013b; Kuemmerle et al., 2008). The Carpathian mountains harbor some of the largest contiguous forests of Europe, a high proportion of which are ecologically valuable (Knorn et al., 2012a). The Pannonian Plains consist mostly of large agricultural fields (Kuemmerle et al., 2009b; Schiller et al., 2010), intermixed with forest plantations and urban areas. The study area has a temperate climate with elevations up to 2500 m above sea level and varying microclimates (Kozak et al., 2013b). At low elevations deciduous forests (Quercus sp, Fagus sylvatica, Carpinus betulus, Populus sp, and Robinia pseudoaccaia) are common, while at high elevations coniferous forests are dominant (Pinus sp, Picea abies, Abies alba). Pine plantations for pulp production occur in the lowlands of Hungary and Romania (Bartha and Oroszi, 1995). The average tree line in the Carpathian mountains is 1600 m (Kozak et al., 2013a). Historically, the land cover of the Pannonian plains was grasslands and wetlands, but due to the high fertility of soils and population growth, many natural ecosystems were converted to agriculture (Bellon, 2004; Frisnyák S., 1990; Jordan et al., 2005; Szilassi et al., 2006).

The current land-cover patterns reflect centuries of land management. Overall, forest cover increased in the Carpathian region since the turn of the 20th century. Most of the study region experienced a forest transition, i.e., a shift from net deforestation to net forest expansion, between the two World Wars (Kozak et al., 2007; Kuemmerle et al., 2011; Munteanu et al., 2014) and forest area increased especially after the breakdown of socialism in 1989, albeit at varying rates (Baumann et al., 2011; Griffiths et al., 2014). In the Carpathian mountains alone, forest area increased from 39.4% to 40.3% between 1985 and 2010 (Griffiths et al., 2014).

Large scale forest disturbances have occurred in the Carpathian region since the 19th century, partly because the forest management policies of the Habsburg Empire focused on timber production. After WWII, large areas of forest in Romania and Ukraine were harvested to pay war debts to the Soviet Union (Kligman and Verdery, 2011). Forest management for timber and pulp led to increased harvesting of hardwoods (Chirita, 1981) and to the establishment of spruce monocultures both before and during the socialist time period (Irland and Kremenetska, 2009; Keeton et al., 2013). After the collapse of socialism in 1991, disturbance rates were also high: from 1985 to 1995 disturbance peaks occurred in Poland, Czech Republic, Ukraine and northern Romania, and from 1995 to 2000 in the Romanian Carpathians (Griffiths et al., 2014). Overall, since 1985, as much as 20% of the Carpathian forests experienced stand-replacing disturbances (Griffiths et al., 2014). Following the collapse of the Soviet Union, most countries adopted restitution laws that reverted publicly-owned land to pre WWII owners (Bemmann and Grosse, 2001; Hartvigsen, 2014; Irimie and Essmann, 2009; Swinnen, 1999) who often harvested their forest for financial gains. However, differences in the timing of restitution laws, the strength of governance, and in economic and socio-demographic factors among countries caused differences in harvesting patterns (Griffiths et al., 2014, 2012; Kuemmerle et al., 2009d). In other words, while the institutional and socio-economic shifts associated with the transition to market-oriented economics certainly affected the rate of recent forest harvest in the Carpathian mountains

(Griffiths et al., 2014; Knorn et al., 2012b), the drivers of forest harvest and management have only been studied at broad scales (Levers et al., 2014) and the role of past land use for contemporary forest disturbance remains unclear.

Historic and contemporary land use and land cover data

We reconstructed historic forest area and historic forest types for the region in 1860s and 1960s from several collections of historical maps (Table 2.1), most of which were available in digital, georeferenced format (Arcanum Adatbázis Kft, 2015) . We verified point location accuracy by a back-dating approach that associates the location of the digitized point with nearby landmarks in all available maps. From the historic maps we extracted forest cover information at two points, first during the Habsburg Empire (1805-1918) and second, during Socialism (1945-1990). We labeled 92,000 points arranged in a regular 2 x 2 km grid as either forest or non-forest for each time point (roughly 21% of the points being forested in each time slice). Where possible, we also mapped forest types as coniferous, mixed, or deciduous. Depending on the time period, forest type information was available for 62%-96% of the data points. Our point grid matched that of the 2007 INSPIRE directive (Infrastructure for Spatial Information in the European Community) and LUCAS (Land Use and Cover Area frame Survey, Gallego and Delince´, 2010).

To estimate contemporary forest disturbance, we mapped forest disturbance at 5-year time intervals from 1985 to 2010, and forest types for 1985s and 2010s, based on 30-m resolution Landsat TM/ETM+ image composites with an overall accuracy of 85.8% for the forest disturbance map (Griffiths et al., 2014, 2013a). We assigned the disturbance information at the specific point location to each grid point in our historic dataset. Our dependent variable, forest disturbance, captured loss of closed-canopy forest cover either due to harvesting, which was predominantly clear-cutting, or natural disturbances, which were often followed by salvage logging. Selective logging was generally not captured, and we did not consider forest recovery or reforestation, which were beyond the scope of this paper. We analyzed forest disturbances between 1985 and 2010 (hereafter recent disturbance) because the interval captures two events that affected land management in the Carpathian region: the countries' transition to market economies (after 1989), and the accession to the European Union (in 2004 or 2007) of all countries in the study area, except Ukraine.

We defined a point as disturbed if it experienced forest loss in any 5-year time interval between 1985-2010 (Griffiths et al., 2014). We further restricted the definition of forest disturbance to only those areas that were forest in the 1960s maps in order to reconcile the remote sensing data (representing forest land cover), with the historic maps (representing forest land use). Via this step, we excluded cases of reforestation and spontaneous afforestation and of abandoned agricultural lands that were re-cultivated after 2000 (Griffiths et al., 2013b). Our data selection also minimized classifications errors in the 1985 classification due to limited Landsat image availability. We defined a point as not disturbed if it was continuously forested in the 1960s, 1985, 1990, 1995, 2000, 2005 and 2010. We eliminated data points above 1600 m, the average timberline in the Carpathians. In sum, for modelling purposes, we restricted our analysis to only those points that were forested in 1960s, a total of 19,947 points. For the forest type analysis we used a minimum of 12,497 points for the year 1860 and a maximum of 19,360 for the year 2010. Of all disturbed points, 43% experienced disturbance between 1985-1995, and approximately 4.6% of those were disturbed after 1985 and not reforested by 2010.

Land use legacy models

We selected 16 covariates that we expected to correlate to 1985-2010 forest disturbance. One covariate represented the historic forest cover in the 1860s and the rest captured environment (6 variables), socio- demographics (2 variables), and accessibility (7 variables, Table 2.2). We used the presence or absence of forest cover in 1860s as the indicator of land use legacy. We extracted all raster values for the 2-km point grid and used the binary response variables for forest disturbance (0/1) as the depended variable.

We fitted multiple logistic regression models (Hosmer and Lemesbow, 1980) to explain contemporary forest disturbance and to estimate the role of historic forest extent for recent disturbances. We fitted an overall model using the full dataset (19,947 data points), and country-specific models (Müller et al., 2009) to capture socio-economical and institutional diversity (Appendix 2.1). We performed variable selection using an exhaustive search (Hosmer et al., 2013) based on the Akaike Information Criterion (AIC) and retained the best performing model. Because we were interested in estimating the effect of historic land uses on recent change, we refitted the best model including the legacy variable for those countries where the best performing model did not include land use legacies (Ukraine, Hungary and Czech Republic). We found no changes in the signs of the model coefficients and also no major changes in coefficient values. The changes in AIC values were always less than 3 for the model including legacies. We tested for interactions between historic forest cover and two environmental variables (slope and elevation) to assess whether contemporary forest disturbance occurred in topographically marginal areas with historic forest cover (Müller and Zeller, 2002), but found that interaction terms were not significant and coefficients were close to zero (results not shown). 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.

To address our first objective regarding the importance of legacy effects for forest disturbance, we calculated the odds ratio of our logistic models, which compares the relative rates of forest disturbance in old and new forests depending on historic land cover. Values higher than 1 indicated higher odds of disturbance in new forests. We did not report significance levels or confidence intervals in our analysis because our data grid represents effectively a full census of historic and recent land cover and because the estimate of the effect that we observed is independent of sample size (Lohr, 2010).Finally, we checked model performance using receiver operating curves (ROC, (Freeman and Moisen, 2008)) and evaluated model utility by calculating the area under the ROC curve (AUC).

To address our second objective regarding the relationship between land-use legacies and other spatial determinants of forest disturbance, we compared the proportion of forest disturbance in old and new forests along a gradient of environmental and accessibility values (variables described in Table 2.2). We split our data into two groups (old and new forests), computed the proportion of disturbance in each group along gradients of other continuous variables in our data, and plotted partial dependence of the disturbance proportion.

To address our third objective of the effect of legacies on the forest types, we estimated the proportion of forest types at four time points. These estimates were based on historic land use maps for the 1860s and 1960s (Table 2.1) and forest-type classifications for 1985s and 2010s (Griffiths et al., 2014). For each time slice (Table 2.1) where forest type information was available, we calculated the percentage of each forest type in the overall forest. Forest type data was complete for the time layers 1960, 1985 and 2010, but was absent for approximately 15% of the whole area in 1860, and 49% of contemporary Poland. We assumed that forest types in areas with no forest type information followed the same pattern as in areas where forest type information was available (Appendix 2.5). Here, we considered the legacy effects of past management by assessing changes in forest types and shifts in the proportion of coniferous, mixed and deciduous forest over time. We also analyzed the historic forest types of recently disturbed forests, the 2010 forest types of new forests for each country as well as the 1860 and 2010 forest types of old forest. When we calculated the percentage of each forest type in 2010 for areas not forested in 1860, we compared our results with the 1960s forest types in new forests to check for consistency between the two time periods.

Results

Land use legacies were strongly related to recent forest disturbance in the Carpathian region. Forest disturbance occurred more often in new forests, established after 1860, than in areas that were already forested in 1860. Legacy effects remained important when controlling for other determinants of forest disturbance. Together, land-use history, topography, climate, and accessibility explained patterns of forest disturbance in the Carpathian region well in our overall model, but there were differences among countries (see below). However, probabilities of disturbance were always higher in new forests, irrespective of environment, accessibility and socio-politics. Legacies of past land use also affected the proportions of forest types. Areas with a historically high coniferous cover (e.g., Czech Republic and Ukraine) decreased the percentage of coniferous forests by 2010. In Romania and Hungary, on the other hand, recent disturbance occurred mostly in historically deciduous and mixed forests, and the percentage of coniferous forests increased.

Forest disturbance legacies

Across all Carpathian countries, forest disturbance was more likely in areas that were not forested in 1860s (new forests), compared to forested areas in 1860s (old forest) (Figure 2.2). From the total set of 19,947 points, 73% were forested in 1860s and still forested in 1960s, 1985s and 2010s. Observed forest disturbance between 1985-2010 in old forests was 13% (of forested area), but 18% in new forest (Figure 2.2, Appendix 2.1). The ratios of forest disturbances in new relative to old forests, were consistently higher in all countries, with the maximum percentage of observed disturbance in old forests in the Czech Republic and Ukraine (22% and 16%, respectively) and the maximum percentage of observed disturbance in new forest in Czech Republic (26%), Slovakia (21%) and Ukraine (21%) (Figure 2.2).

The logistic regression results suggested that even when controlling for environmental, accessibility and socio-political factors, the odds of forest disturbance were 49% higher for new forests than for old forests (Figure 2.3). However, legacies varied by country: they were strongest in Poland (odds 88% higher),weakest in Ukraine (odds 34% higher), and not important in the Czech Republic and Hungary (Figure 2.3, Appendix 2.2).The AUC for the seven models varied from 0.62 (Czech Republic) to 0.78 (Poland). The overall model had an AUC value of 0.66. Our findings suggest that even after controlling for the environmental, accessibility and socio-political differences in the study region, the historic land uses played an important role in determining the location of recent forest disturbance.

Spatial determinants of disturbance

Our models confirmed the importance of environment (topography, temperature, length of growing season) and accessibility (distance to cities and settlements) for forest disturbance in all

Carpathian countries. In the overall model, slope, annual mean temperature, and the length of the growing season were important predictors, alongside our country dummy variable, which captured at national level, processes not captured by other variables, such as land reforms, strength of institutions, or accessibility differences (Levers et al., 2014; Müller and Sikor, 2006). In all countries, areas with steep slopes were less likely to be disturbed, and areas afar from major cities, and close to human settlement were more likely to be disturbed (Appendix 2.3). Our models did not show strong quantitative evidence for a relationship of forest disturbance with population density in the 1990s or distance to railroads (Appendix 2.3).

Our comparison of the proportion of disturbance in old and new forests across the full range of slopes, temperatures, precipitations, and accessibilities, indicated that the proportion of disturbance was consistently higher in new forests both when we summarized our data (Figure 2.4) and when modelling disturbance while controlling for other spatial determinants of change (Appendix 2.4). Disturbance decreased with increasing slope, temperature, crop suitability, and length of the growing season in both old and new forests, but the consistently higher proportion of disturbance in new forests remained. The shorter the growing season, the more new forests were disturbed. Within 15 km of roads, new forests were more likely to be disturbed, and although at distances higher than 20 km, older forests were more likely to be disturbed, we had only few observations in this data range. Forests closer to settlements were also more likely to be disturbed.

Changes in main forest types

We analyzed forest type abundance in the Carpathian region for four time points (1860s. 1960s, 1985s, and 2010s). We found that coniferous forest cover declined in all countries except

Romania and Hungary. Slovakia and Czech Republic reached their peak coniferous forest cover in the early socialist period (1960s) while Hungary, Romania and Ukraine reached a peak in the late 1980s.The forests of most countries were mainly coniferous and mixed in 2010 (65% to 98% in Ukraine and Romania respectively). Only Slovakia and Hungary had over 50% deciduous forests in 2010. Overall, coniferous cover in 2010 was 24%, roughly 5% lower than in 1860.

When we analyzed the 1860s forest types of areas that were disturbed after 1985, we found that over 50% of the disturbance occurred in 1860s coniferous stands, except for Romania and Hungary where the proportion of coniferous forest was low in the 1860s (Figure 2.5a). Overall, the 2010s forest types in new forests were 28% coniferous, 27% mixed, and 40% deciduous, but there were marked differences among countries: in Romania, Hungary and Slovakia, over 50% of the forests were deciduous and mixed, while Ukraine and Czech Republic had an approximately equal proportion of deciduous, coniferous, and mixed forests (Figure 2.5d). The proportion of coniferous and deciduous new forests was very similar in 1960 and 2010. Most recent disturbances (1985-2010) occurred in 1860s coniferous stands, less Hungary, where there were few coniferous to start out with (Figure 2.5b). The proportion of forest types in old forests shifted towards less coniferous in all countries except Romania and Hungary (Figure 2.5c and e). Generally, there was a higher proportion of coniferous in new forests than in old forests across countries (Figure 2.5d and e). Forest disturbances between 1985 and 1995 also affected forest types in 2010. Of all disturbed points that were initially coniferous, only 37% remained coniferous after disturbance. Conversely, 90% of the disturbed deciduous and mixed forests retained their composition.

Discussion

Our results showed that land-use legacies were an important spatial determinant of forest disturbance in the Carpathian region. These results are important because land-use legacies are rarely included in models analyzing drivers of forest change (Levers et al., 2014; Pazúr et al., 2014; Verburg et al., 2009). Our results are unique among land-use legacy studies (Bellemare et al., 2002; Dupouey et al., 2002a; Foster et al., 2003), because we provided evidence for legacies affecting forest management decisions and subsequent rates of forest disturbance. Land-use legacies from 150 years ago greatly affected recent patterns of forest disturbance even when controlling for environment, accessibility and socio-political factors. Indeed, areas not forested in the 1860s (new forests) had 49% higher odds of recent disturbance, than areas forested in 1860s (old forests). The probability of disturbance was consistently higher in new forests, across the full range of covariates, underpinning the importance of considering land-use legacies when assessing and modeling forest change. Forest management caused a decrease of coniferous in old forests between 1860 and 2010 and a higher percentage of coniferous in new forests than in old forests.

Forest disturbance legacies

The Carpathian region is a hotspot of cultural, political and socio-economic diversity with a rich land management history (Munteanu et al., 2014), thus providing an ideal 'natural experiment' to assess the effects of land-use legacies on rates of disturbance and the abundance of forest types. In the 19th century, a large proportion of the study region was part of the Habsburg Monarchy, later the Austro-Hungarian Empire, which managed forests intensively for wood production. In the mountainous regions of contemporary northern Romania, Ukraine, northern Slovakia and southern Poland (historical regions of Bessarabia, Bukovina, Galicia, and Maramures), forest harvest intensified during the Habsburg rule (Bohateret, 2012). In addition, fast growing, productive tree species such as Norway spruce (Picea abies) were widely planted for pulp production and erosion control. In the lowlands, following a period of agricultural expansion and timber scarcity, forests were planted outside their prior ranges during Hungarian and Austrian rule, and later again during Socialism (Konkoly-Gyuró et al., 2011, 2012). Especially Hungary, Slovakia and Romania planted large areas of poplar (Populus sp.), black locust (Robinia pseudoacacia) and pine (Pinus sp., Bartha and Oroszi, 1995; Chirita, 1981; Konkoly-Gyuró et al., 2011). With hardwood rotation ages of about 70 years for pulp and 120 years for saw-timber (Chirita, 1981; Disescu, 1954), it is likely that early 20th century plantations have recently reached a harvestable age, which may be one reason for the high rate of forest disturbance in new forests. Furthermore, natural disturbance events, such as wind throws or insect outbreaks, preferentially affect forests vulnerable through previous management practices, such as plantations of even-aged monocultures (Klopcic et al., 2009; Schelhaas et al., 2003; Svoboda et al., 2012). When natural disturbances occur, salvage logging is common, which may be another explanation for the strong legacy effect that we observed. Spruce plantations in the Carpathians are susceptible to pests such as bark beetle (Keeton et al., 2010), pollution (Carrier and Krippl, 2009; Main-Knorn et al., 2009; Modrzyński, 2003), floods (Glenz et al., 2006), wind and snowstorms (Falťan et al., 2009), and fluctuations in climate (Bouriaud and Popa, 2008a), all potentially causing higher disturbance rates in new forests. We caution though, that plantations are also common in old forests, especially in mountain regions of Romania where historic mixed stands have been recently replaced by spruce. Other past management practices that may still affect rates of disturbance are forest grazing and litter raking, common in the Habsburg Empire since the 19th century (Erb et al., 2013). Likewise, historic forest ownership structures may affect current disturbance rates when land owners decide to preserve or to manage forests for timber production (Ostafin, 2009). Irrespective of the mechanisms, which likely vary in space, our results showed that recent forest management is greatly restricted by historic land uses and forest management decisions.

Spatial determinants of disturbance

We analyzed the proportion of forest disturbance (logging, and natural disturbances typically followed by salvage logging) in old and new forests in relation to environmental and accessibility variables and found that disturbance was consistently higher in new forests, across the entire range of spatial determinants of change. The relationship of disturbance to the different determinants of change is interesting in its own right as well though.

We included variables that captured known spatial determinants of land-use change and forest management (Geist and Lambin, 2001; Müller et al., 2013a; Pazúr et al., 2014). We did not include data on policies, markets and economic factors that may underlie forest disturbance patterns (Amacher et al., 2003; Beach et al., 2005; Geist and Lambin, 2001; Lambin et al., 2001) because these were only available at country level, and our sample size did not allow us to examine country effects. However, we captured these differences partly via the country dummy variable and explored them in country-specific models.

Our results indicated that areas with less rough terrain were more likely to be disturbed (probably due to difficult access). Our results are thus consistent with other analyses of drivers of forest cover change, which found higher disturbance probability in areas with less rough terrains and mild slopes (Levers et al., 2014; Nagendra et al., 2003; Wendland et al., 2011), and that such areas often represent deciduous and mixed forests at lower elevations. We found slightly more disturbance in areas farther away from cities and roads, but most of our data was concentrated at distances less than 10km away from roads.

Areas with low crop suitability experienced higher rates of disturbance. High rates of forest disturbance on low quality soils are common in areas that have been spruce plantations for long times (Chirita, 1981) because of soil acidification. Furthermore, new forests in Hungary, Romania and Slovakia were often planted in areas prone to erosion and on poor soils that were depleted of nutrients. Areas with low soil quality generally have more forest health problems (Schulze et al., 1989). We note that deforestation is often higher on better soils (Pfaff, 1999; Veldkamp et al., 1992), but this is due to their suitability for agriculture (Etter et al., 2006; Grau et al., 2005; Veldkamp et al., 1992) rather than natural causes due to forest management. In the recent land use history of the Carpathian region, agricultural clearing is not common, and only some of the recently abandoned agricultural land has been brought back into production (Griffiths et al., 2013b).

We found interesting differences among countries in terms of the importance of land use legacies in relation to other spatial determinants. Areas afar from cities were less likely to be disturbed in Poland and Czech Republic than in Romania and Ukraine, most likely because the former countries have reliable forest protection system and a high percentage of state-owned land (Kuemmerle et al., 2009c), and have experienced fewer institutional changes and shifts in environmental policies in recent decades ("Polityka ekologiczna panstwa w latach 2009-2012," 2008). On the other hand, Romania and Ukraine had higher occurrence of disturbance in remote areas, most likely because institutions there are weaker, forest restitution caused widespread harvesting in private forests (Giurgiu, 2010a), and protection is not always effective (Irland and Kremenetska, 2009; Knorn et al., 2012b). Despite repeated suggestions that a high portion of the logging might be illegal due to poor regulatory framework (Knorn et al., 2012b; Kuemmerle et al., 2009a), it remains hard to quantify to what extent this influenced our results. In Hungary, disturbance was higher near settlements and rivers and in accessible areas that could be easily harvested. We speculate that this could be due to policies for erosion control, soil quality enhancement, and pulp plantations along river ways (Bartha and Oroszi, 1995; Konkoly-Gyuró et al., 2012).

Individual disturbance events can affect the observed relationship between old and new forests, if these disturbances are very large. In Slovakia, a large windthrow occurred in the Tatra Mountains in 2004 (Falťan et al., 2009; Griffiths et al., 2014). A large part of the windblown area was not forested in the 1860s and was subsequently planted with spruce thus becoming susceptible to natural disturbances (Falťan et al., 2009). A large part of the windblown area was already affected by a historic disturbances around 1915s and 1940s (Zielonka et al., 2010) and planted with spruce. The high likelihood of disturbance in new forests that our analysis uncovered in Slovakia may thus be at least partly influenced by this singular natural disturbance event.

Change in forest type

Land use legacies also affected forest types. Overall, new forest had a higher percentage of conifers than old forests, and the percentage of coniferous trees in old forests was higher in 2010 than in 1860 in all countries except Romania and Hungary, where the coniferous cover was low in the 1860s. Our results supported prior findings about the importance of historic management on recent forest composition, species abundance, and ecosystem health (Bellemare et al., 2002; Dupouey et al., 2002a; Foster et al., 2003; Wallin et al., 1994). In most Carpathian countries, historic extensive harvest for wood production and the susceptibility of spruce plantations to natural disturbances resulted in a decline in coniferous forests. Where natural regeneration occurred following clear-cuts in the late 19th and early 20th century, the forest shifted towards a larger proportion of mixed and deciduous tree types, and this was in particular the case in Ukraine, Slovakia and Czech Republic. Romania and Hungary had a high proportion of deciduous and mixed forests in the 1860s and an increasing proportion of coniferous over time. Here, contemporary forest disturbance occurred mostly in historically mixed and deciduous forests and we explain this diverging legacy by economically-driven plantations during Habsburg and Socialist times (Chirita, 1981; Dincă, 1955; Konkoly-Gyuró et al., 2011).

We argue that the relative abundance of forest types, similar to disturbance patterns, is the result of legacies related to forest management practices in each country. Norway spruce was the predominant production tree species across the Carpathian region since the mid-19th century (Irland and Kremenetska, 2009) due to its fast growth rate and because it provided both pulp and timber. Romania and Hungary increased their percentage of coniferous forests over historic deciduous forests due to Soviet pressure during the 1950s (Banu, 2004; Kligman and Verdery, 2011) to repay war debts in timber. Furthermore, our data indicated a strong increase of coniferous forests in Romania and Ukraine between 1960 and 1985. Here, after WWII, forests transferred to state ownership and intensive forest management for wood and pulp production led to widespread spruce plantations (Chirita, 1981; Irland and Kremenetska, 2009). However, while planting clearcuts with spruce was common in many regions, others relied on natural succession (Dincă, 1955; Goscincki, 2014).

We caution that the interpretation of forest type changes relies on the assumption that the composition of all forests followed the same distribution as the forests for which we had forest type information in the 1860s maps. We did not report country results for Poland here, because we were missing 1860s forest type data for half of its area in the study region. We caution that the legacy effects that we revealed could vary slightly depending on data preprocessing, the definition of legacy effects and the methodology used to map forest disturbance. Here, we relied on forest-non forest data and on forest type classifications as indicators of past land management and legacies. We tested the consistency of the observed differences between old and new forests using nine different definitions of disturbance, and found a consistent pattern of more disturbances in new forest in all cases (results not shown). Furthermore, the historical data used in our analysis depicts land use, whereas the recent remote sensing analysis captures land cover, and in order to make the two datasets comparable, we restricted our analysis to forest disturbances within 1960s forests. Including reforestation and disturbance on abandoned fields in the analysis dataset could also potentially alter the observed legacy effect, but analyzing this was beyond the scope of this paper. We also caution that our data does not capture historic forest harvests – but including historic clear-cuts in our models, would likely increase the observed disturbance difference between old and new forests. Given the nature of our dataset our results should be interpreted at broad, national and regional scales. Furthermore, in the Carpathian region, our analysis may reflect particularly strong legacy effects, due to political shifts and land management changes (Munteanu et al., 2014).

Conclusions

Our study showed that contemporary forest disturbance patterns were heavily influenced by 150-year old land-use legacies, even when controlling for environmental, accessibility, socio-political spatial determinants. Specifically, forest disturbance was more likely in areas where forests occurred for a shorter time period. This is good news for the conservation of Carpathian forests that have been in place for a longer time and highlights that past land uses are important when deciding which areas to protect or harvest. In a scientific context, theconsideration of past land uses as spatial determinants of change could enhance the performance of forest change assessments and of predictions of future land change trajectories. Our results suggest strong land use legacy effects can be present over centuries. This is of concern because we are currently in a phase of rapid land use change globally (Baumann et al., 2014; Grau et al., 2008; Meyfroidt and Lambin, 2009), and land use legacies may restrict management possibilities, in the Carpathians and worldwide, while creating legacies for future generations. Forests are lost at rapid rates in many areas of the globe (Hansen et al., 2013). Knowledge of legacy effects of these trends could help land managers when making decisions which areas to use for timber production, agriculture, or conservation in the future.

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Tables and figures

Table 2.1 Maps and satellite images used for forest cover mapping

Time layer	**Data range of maps**	**Map scale/ resolution**	**Map source/ description**
1860s	1819-1873	1:28.800	Second Austrian Military Survey
1960s	1949-1983	1:50.000 and 1:25.000	Soviet and National Topographic Maps from the Cold War period
1985s	1984-1987	30m	Landsat TM composite
1990s	1988-1992	30m	Landsat TM composite
1995s	1993-1997	30m	Landsat TM composite
2000s	1998-2002	30m	Landsat TM/ ETM+ composite
2005s	2003-2007	30m	Landsat TM/ ETM+ composite
2010s	2008-2012	30m	Landsat TM/ ETM+ composite

Table 2.2 List of predictors used in the forest disturbance models (n=19947), including data sources, measurements in units (Unit), their spatial resolution (SpRes), mean values (Mean), standard deviation (SD), range (Min, Max)

	Variable	Description	Source	Unit	SpRes	Mean	SD	Min	Max
Response	dist_8510	Forest disturbance 1985-2010	Griffiths et al, 2013	Yes/No	30m	factor	N/A	N/A	N/A
Historic land use	FNF1860	forest cover 1860	see Table 2.1		vector	factor	N/A	N/A	N/A
Environmental	elev	elevation	Farr et al, 2007	m	90m	693.83	327	77	1598*
	slope	slope	Farr et al, 2007	°	90m	12.79	7	0	54
	temp	Annual Mean Temperature in C*10 from WORLDCLIM	Hijmans et al, 2005	C * 10	~1km	67.86	18	6	114
	precip	Annual Precipitation in mm from WORLDCLIM	Hijmans et al, 2005	mm	~1km	767.21	118	524	1481
	crop_si	Crop suitability index	FAO (GAEZ), 2014	%	~8km	3466.58	2221	0	10000
	grow_ss	Length of growing season	FAO (GAEZ), 2014	days	~8km	205.21	19.93	143	253
Accessibility	acc_50k	accessibility to nearest 50k inhabitants town, time in minutes	Nelson, 2008	min	~1km	175.24	131.42	1	869
	dist_city	Euclidean distance to nearest major city in km	ESRI, 2008	km	vector	44.36	19.55	1	96
	dist_settl	Euclidean distance to nearest settlement in km	EEA, 2013	km	vector	2.97	2.51	0	17
	dist_road	Euclidean distance to nearest road	CIESIN & ITOS, 2013	km	vector	7.97	6.64	0	50

	Variable	Description	Source	Unit	SpRes	Mean	SD	Min	Max
Socio-political	dist_ border	Euclidean distance to nearest current border in km	calculated	km	vector	52.72	49.64	0	213
	dist_ rail	Euclidean distance to nearest railroad in km	ESRI, 2008	km	vector	13.94	11.76	0	70.46
	dist_ river	Euclidean distance to nearest main river in km	Vogt et al 2007	km	vector	5.28	3.43	0	19.97
	cntry	country delineation	ESRI, 2008	N/A	vector	factor	N/A	N/A	N/A
	pop90	population count for year 1990	CIESIN, 2005	pers	~5km	1081.45	1927.00	0	38026

**The maximum elevation was truncated at 1600m, the average timberline for the Carpathian Mountains (see Methods)*

Figure 2.1 Study area in Eastern Europe and forest cover maps for the 1860s, 1960s and 2010s. CZ: Czech Republic, HU: Hungary PL: Poland, RO: Romania, SK: Slovakia, UA: Ukraine

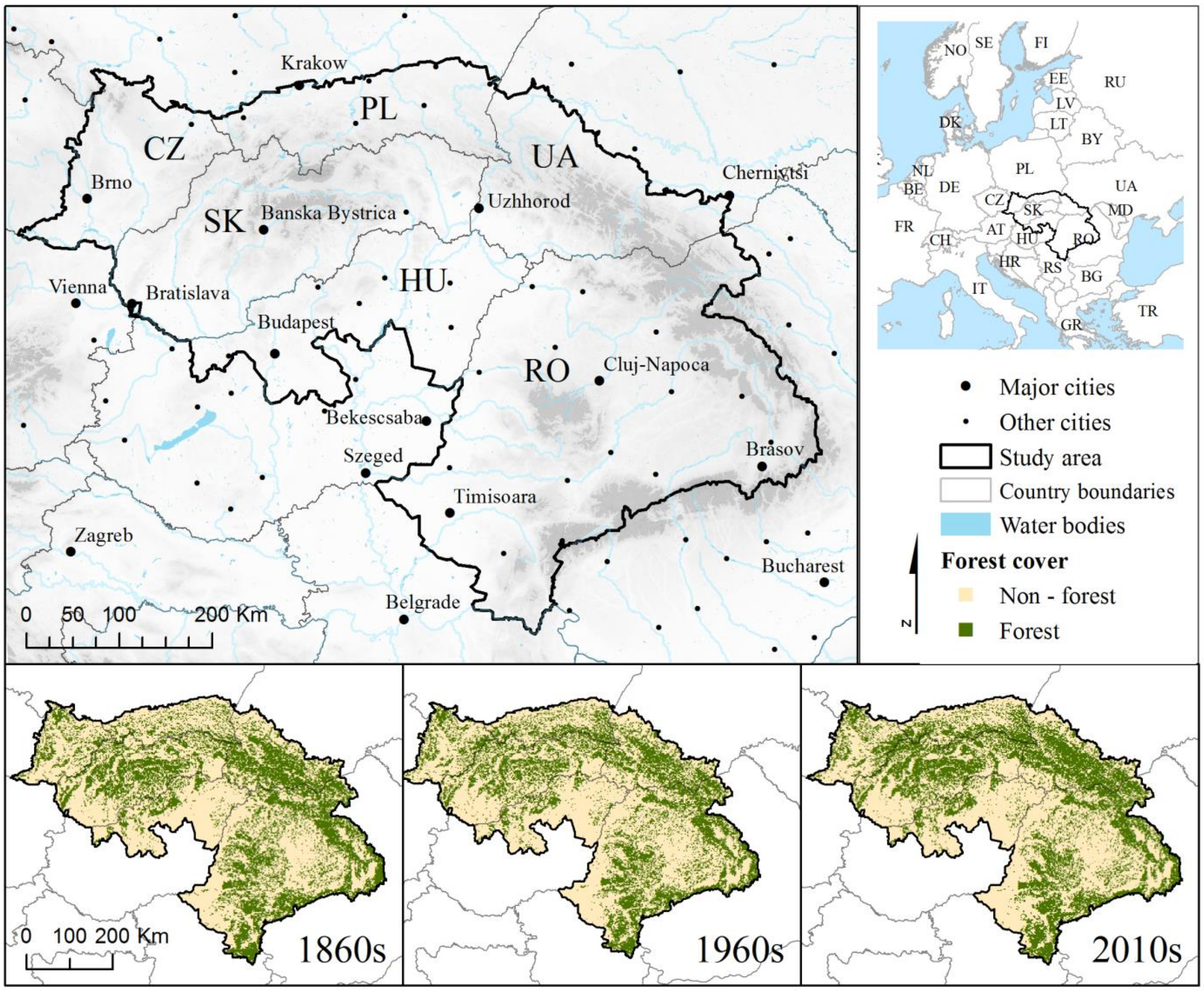


Figure 2.2 Percentage forest disturbance in the Carpathian Region (overall) and by country (RO: Romania, SK: Slovakia, UA: Ukraine, PL: Poland, CZ: Czech Republic, HU: Hungary) in old forests and new forests. Old forests refer to areas that were forested throughout 1860s-1985, new forests to areas not forested in 1860s, but forested in 1960s. The graph indicates consistently more forest disturbance in new forests. Number of observations per country in brackets.

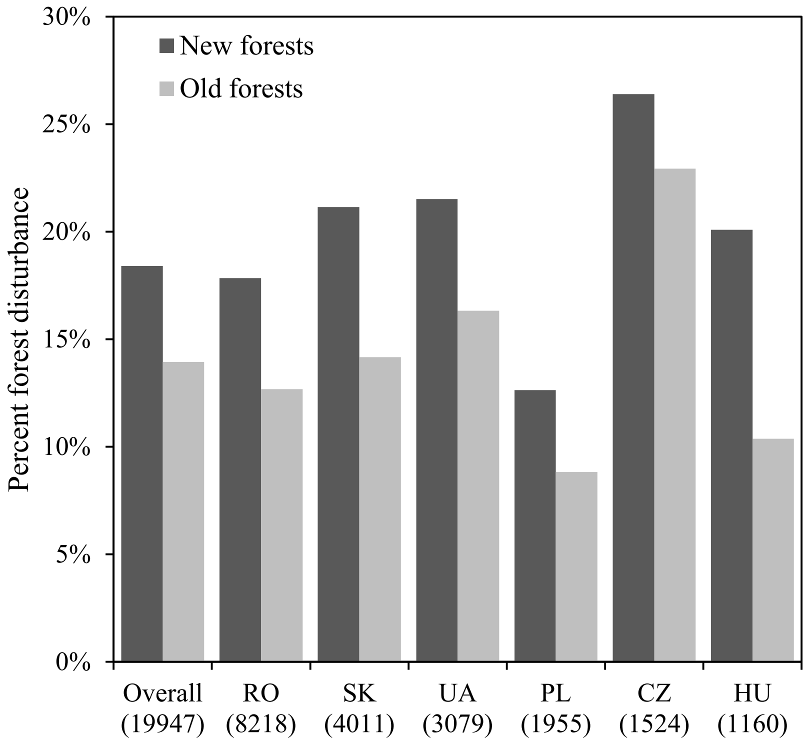


Figure 2.3 Odds of forest disturbance (in %) in new forests (not forested in 1860s) compared to old forests (forested in 1860s), overall and in country models (RO: Romania, SK: Slovakia, UA: Ukraine, PL: Poland, CZ: Czech Republic, HU: Hungary)

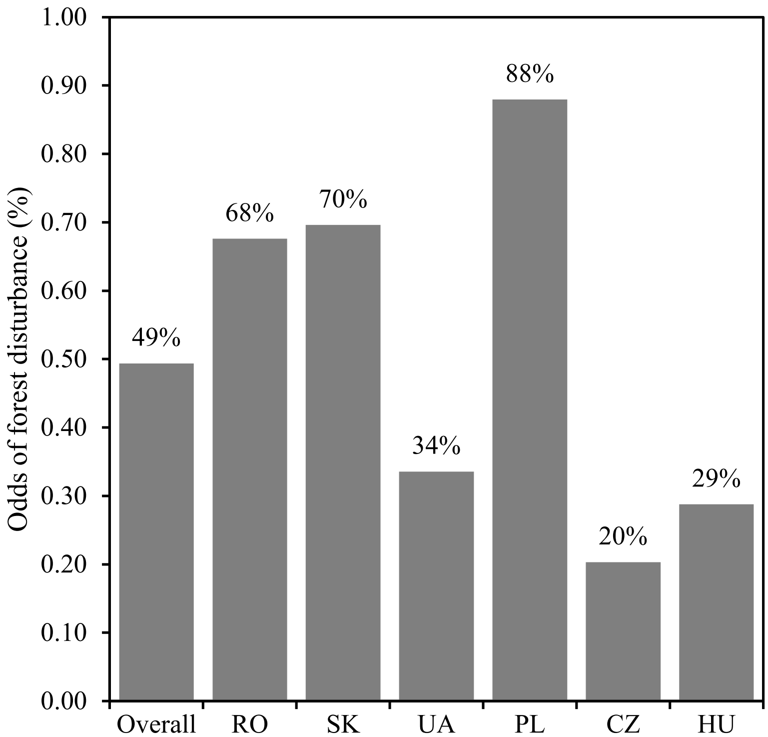


Figure 2.4 Proportion of forest disturbance (left y axis) in old forests (black line) and new forests (grey line) in relation to elevation, slope, annual mean temperature, annual precipitation, crop suitability, length of growing season, accessibility, distance to cities, settlements, roads and rivers. The graph represents a data summary of all observed disturbance. The dotted line represents number of forest observations in 1985 (right y axis). Continuous variables were divided in 30 equal interval data bins and the proportion of disturbance as well as the mean number of forest observations was plotted for each bin. For model based results please see Appendix 2.4

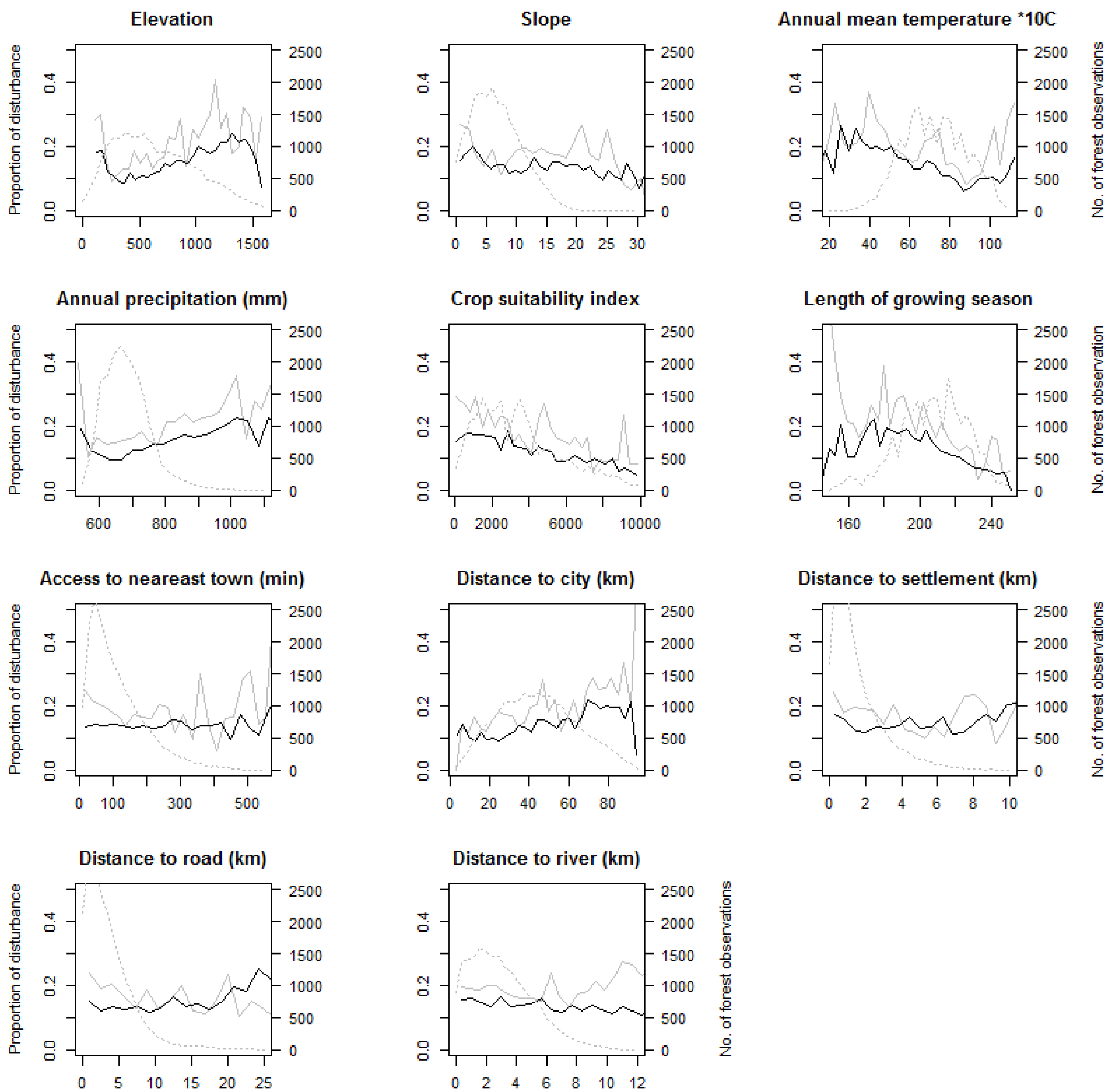
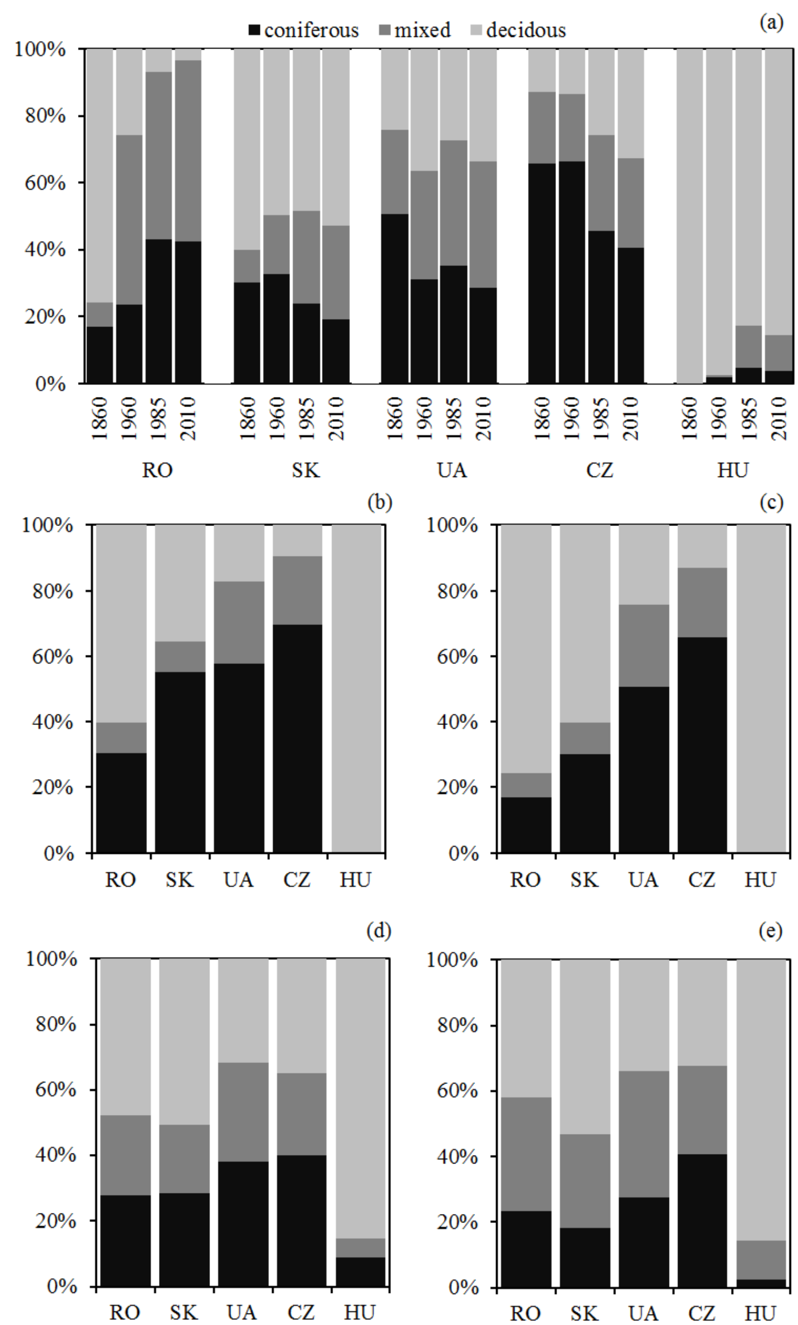


Figure 2.5 (a) Forest types by year and country since 1860s, (b) 1860s forest types of disturbed forests between 1985-2010, (c)1860s forest types of old forests (d) 2010s forest types in new forests, and (e) 2010s forest types of old forests . RO: Romania, SK: Slovakia, UA: Ukraine, CZ: Czech Republic, HU: Hungary. Poland has been excluded from this graph due to scarcity of forest type data. Note: Figures are not for entire country territory but for the study region depicted in Figure 2.1. Forest type distribution in (a) is not identical to Griffiths et al (2013) because the data presented here is restricted to 1960 forest cover.



Appendix

Appendix 2.1 Number of observations for the entire dataset and for each country for each old forests (F) and new forests (NF). Not disturbed = forested in 1960 and never disturbed between 1985-2010, Disturbed = forested in 1960 and disturbed at least once in a five year time step between 1985-2010.

	1860 NF	1860 F
Overall model		19947
not disturbed	2336	14703
disturbed	527	2381
ROMANIA		8218
not disturbed	847	6276
disturbed	184	911
SLOVAKIA		4011
not disturbed	302	3114
disturbed	81	514
UKRAINE		3079
not disturbed	281	2277
disturbed	77	444
POLAND		1955
not disturbed	560	1198
disturbed	81	116
CZECH REPUBLIC		1524
not disturbed	159	1008
disturbed	57	300
HUNGARY		1160
not disturbed	187	830
disturbed	47	96

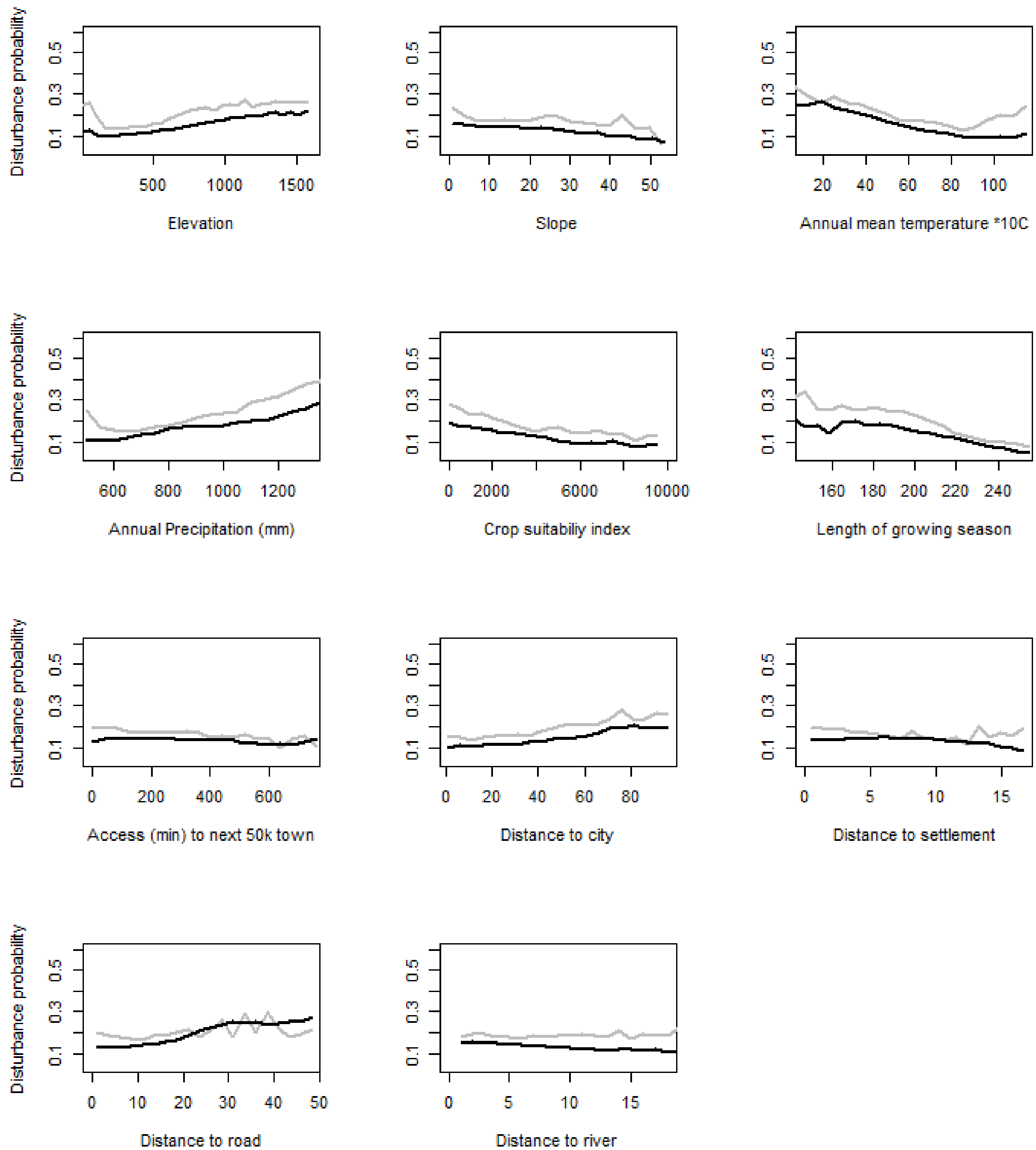
Appendix 2.2 Model outputs for best selected models: regression coefficients, odds ratio (OR) of disturbance on historic non forest vs forest, and model performance as area under ROC curve (AUC). An odds ratio>1 indicates higher rate of disturbance on 1860 non-forest areas.

Model	**Coefficients**	**OR**	**AUC**
Overall	-0.401	1.494	0.66
RO	-0.516	1.676	0.682
SK	-0.529	1.698	0.685
UA	-0.289	1.336	0.643
PL	-0.631	1.879	0.784
CZ	-0.186	1.204	0.622
HU	-0.253	1.288	0.698

Appendix 2.3 Number of best performing models (ΔAIC < 3), of those number of models that include land use legacy as an explanatory variable, ΔAIC of best model including legacies. The second part of the table shows the odds ratios for each selected variable in the exhaustive search

	Overall	**RO**	**SK**	**UA**	**PL**	**CZ**	**HU**
Exhaustive model search							
Number of models ΔAIC <3	10	31	65	93	45	154	117
Number of legacy models ΔAIC <3	10	31	65	46	45	2	2
ΔAIC of legacy model	0	0	0	0.12	0	2.83	2.7
Odds ratios and coefficient signs							
(Intercept)	5.17	10.6	17.26	22.00	0.002	0.02	853
FNF1860	1.52	1.69	1.69	1.35	1.89	1.20	1.28
elev			1.00	0.99			0.99
slope	0.96	0.97	0.95	0.96	0.93	0.96	0.96
temp	0.98	0.97	0.98		1.07		0.95
precip	1.00				1.00		
crop_si	0.99	0.99	0.99				
grow_ss	0.99	0.99	0.98	0.97	0.97	1.01	0.98
acc_50k	0.99		0.98		0.99		
dist_city	1.00	1.00	1.00	1.01	0.98	0.99	
dist_settl	0.93	0.95	0.92	0.91	0.96		1.22
dist_road	1.01		1.02	1.01			
dist_border		0.99					1.00
dist_rail			0.97	1.01			
dist_river	0.97		0.97		0.92		
pop90					0.99		
cntry							
HU	1.11						
SK	0.85						
UA	0.81						
CZ	1.44						
PL	0.55						

Appendix 2.4 Disturbance in old forests (black line) and new forests (grey line) in relation to elevation, slope, annual mean temperature, annual precipitation, crop suitability, length of growing season, accessibility, distance to cities, settlements, roads and rivers. The graph represents regression results once we controlled for all other spatial determinants of change. For a data-based summary please see Figure 2.4



Appendix 2.5. Numbers of observations for forest type data by year and country. Forest type (FT) column indicates the number of points for which forest type information was available. No forest type (NoFT) column indicates the number of data points that were identified as forest but for which forest type information could not be retrieved. (RO: Romania, SK: Slovakia, UA: Ukraine, PL: Poland, CZ: Czech Republic, HU: Hungary)

	1860		**1960**		**1985**		**2010**	
	FT	**NoFT**	**FT**	**NoFT**	**FT**	**NoFT**	**FT**	**NoFT**
RO	5227	1031	7390	1	7806	412	7995	223
SK	2881	383	4009	0	3948	62	3854	157
UA	1500	358	3024	8	3001	78	2987	92
PL	662	641	1003	0	1919	36	1934	21
CZ	1301	216	1524	0	1481	43	1478	46
HU	926	234	990	0	1091	69	1112	48

Chapter 3. Historical forest management in Romania is imposing strong legacies on contemporary forests and their management

Introduction

Land use dynamics have transformed the Earth's ecosystems to an unprecedented extent (Foley et al., 2005). Long-term forest changes, in particular, have major consequences for ecosystem functioning, carbon storage, climate regulation and biodiversity (DeFries et al., 2004; Newbold et al., 2015). Globally, forest cover loss increased from roughly 7% in 1700 to over 21% in 1990 (Ellis et al., 2013; Goldewijk, 2001) although several countries in Europe and Asia experienced a forest transition (Mather, 1998) in late 19th and early 20th century (Meyfroidt and Lambin, 2011) and are currently increasing in forest cover, and carbon sequestration (Erb et al., 2013; Rautiainen et al., 2010). Even though deforestation is declining in some countries (Gold et al., 2006), forest loss due to harvesting and natural disturbances remains high in many areas of the globe (Hansen et al., 2013; Potapov et al., 2014). Forest change is clearly related to socio-economic, political, institutional and environmental drivers (Lambin et al., 2001) but uncertainty about the role of past land uses, also referred to as path dependency, remains a concern for land change assessments. Long term human influence on forests can create legacies that may affect ecosystem functioning, structure and management of ecosystems for centuries, (Foster et al., 2003; Munteanu et al., 2015a) but the link between past and contemporary land management practices is still poorly understood.

Historical land management decisions affect contemporary landscape patterns across the globe (Foster et al., 2003) and land use legacies can manifest themselves in many aspects of forest ecosystems such as occurrence of disturbance, composition or age patterns. In Eastern Europe, forest disturbance occurs more frequently in areas that were not forested a century ago, indicating that disturbance patterns are affected by past land management (Munteanu et al., 2015a). Similarly, past forest fires and harvests diminish the coniferous forests in the Russian Far East (Cushman and Wallin, 2000) and historically farmed forests in Western Europe show a higher abundance of species that colonize abandoned land, and fewer poor dispersers (Dupouey et al., 2002b; Plue et al., 2009). Furthermore, the intensity of historical farming affects forest species composition (Atkinson and Marín-Spiotta, 2015; Plieninger et al., 2010b)., indicating that effects of past management may persist for a long time into the future. Finally, age structure can also be a reflection of past land management, because age-patterns established by harvesting can persist for multiple rotation cycles, even under different management practices (Wallin et al., 1994). In summary, this highlights the persistence of land use legacies even after changes in land use type (Munteanu et al., 2015a; Thompson et al., 2013) indicating that past land management may constrain forest management for centuries thereafter.

Although forested areas have increased in Europe in the 20th century (Fuchs et al., 2015; Gold et al., 2006; Munteanu et al., 2014), forest disturbance in the past decades is high in Eastern Europe (Griffiths et al., 2014; Hansen et al., 2013) and the forest composition and age structure are altered (Munteanu et al., 2015a; Vilén et al., 2012). Contemporary patterns of forest harvesting in Europe vary among countries and have been explained by a suite of factors including site conditions, forest resource availability (Levers et al., 2014), institutional and political context (Baumann et al., 2011; Kuemmerle et al., 2007), ownership structures (Kuemmerle et al., 2009c) and level of protection (Butsic et al., 2015a; Knorn et al., 2012b). However, most of these factors can act at different spatial and temporal scales and their effects can change over time, so that the links between past drivers and contemporary change remain unclear.

Eastern Europe represents a particularly interesting natural experiment for studying the relationship between past and contemporary forest change in relation to land tenure, political systems and conservation efforts because the region has a long history of human use (Giosan et al., 2012), very good data records starting as early as the 18th century (Timár et al., 2010) and experienced multiple shifts in institutions, land tenure, and socio-economic pressures both in time and space (Munteanu et al., 2014). Furthermore, current rates of forest harvesting are high (Griffiths et al., 2014) and controversial (Knorn et al., 2012a; Kuemmerle et al., 2009a), but their relationship to past forest management is still largely unexplored.

Our goal here was to examine the connections between historical forest management (as depicted by historical forest cover, species composition, age structure and harvesting) versus contemporary forest patterns in Romania. Specifically, we investigated how past and contemporary forest disturbances (harvesting or natural disturbances which are often followed by salvage logging) are related to ownership structures, forest composition and forest age distribution. We explored possible cause-effect relationships based on forestry census data and remote sensing estimate and focused on lingering effects of historical management in contemporary forests, such as altered forest composition, age structure and shifting disturbance patterns related to forest ownership.

Methods

Study area

We studied forest legacies in Romania (238 381 km^2) because the region represents an ideal natural experiment of changing forest management over time. Currently all forests in Romania are managed under the same legislation and consistent forest management plans (Ioras and

Abrudan, 2006), but the region has historically experienced very different forest management regimes because it was split between the Habsburg and Ottoman Empires during the 18^{th} and the 19^{th} century (Munteanu et al., 2015a).

Romania is ecologically highly diverse, including parts of five major vegetation ecoregions: Carpathian Montane Coniferous Forests, Pannonian Mixed Forests, Central European Mixed Forests, East European Forest Steppe and Pontic Steppe (European Environment Agency, 2003). The climate is temperate, with continental influences in the northeast and Mediterranean influences in the south. The mean elevation is 330 m and 27% of the country is covered by forest (National Institute of Statistics, 2012). Romania has a total population of 22 million (National Institute of Statistics, 2012), mostly concentrated in urban regions and a per capita GDP of $13200 (Central Intelligence Agency, 2013), among the lowest in the EU. Historically, land tenure in Romania was split between private owners, churches, institutions and state (Bouriaud, 2008). Historical forest management in Romania was mostly focused on natural regeneration. In the early 1900s, roughly 25% of the Romanian forests were coppice forests, and the remaining 75% were either selectively logged or high forests (i.e., even-aged). Of the high forests, about 10% would be usually clear cut, the rest being managed as shelterwood cuts. Even clearcuts had to retain 50 trees/ha for natural regeneration (Antonescu, 1909).

After the Second World War (WWII) all land was nationalized and managed by the state. Soviet policies heavily influenced forest management leading to widespread clear cuts and planting of fast-growing species. With the collapse of the Soviet Union in 1990, land was partially returned to former private owners following three restitution laws in 1991, 2000 and 2007 (Ioras and Abrudan, 2006). In 2007, Romania joined the European Union, which brought with it new regulations to increase nature conservation (Butsic et al., 2015a) and new land management regulations, such as a requirement for management plans for private forests (Ioras and Abrudan, 2006). However, forests experienced high levels of disturbance after 1990, and particularly after 2000 (Griffiths et al., 2014; Potapov et al., 2014), including the loss of valuable ecosystems and old-growth forests (Knorn et al., 2012a). Contemporary forest management in Romania is largely based on natural regeneration (Schulze et al., 2014). In 2014, only about 1% of the forests were clear-cut and about 12% were shelterwood. About a half of the forests are managed solely by sanitary harvests and about 30% were thinned (Institutul National de Statistica, 2015a).

In addition to the national-level analyses, we conducted three case studies situated in the Eastern Carpathian Mountains to compare historical and contemporary management at a finer spatial resolution. All studies were situated at elevations between 700 – 1100 m and had a total area of 14000 ha (Figure 3.1). The three case study areas are characterized by similar ecological conditions (temperate climate, average yearly temperature around 7 Celsius, average precipitation of 800 mm, dominant soil class of Cambisol, (Institutul de Cercetări şi Amenajări Silvice Bucureşti, 1951; Ministry of Agriculture and Forestry, 1945; Romanian Church Forest Administration, 1926) and hence similar historical forest composition (beech and mixed beech, fir, and spruce forest). Forest management practices and policies were homogeneous since the 1950s until the early 1990s in all three areas because they were under state management, but forests in Humor are currently mostly state managed and in Oituz and Madaras mostly privately managed (Institutul de Cercetări şi Amenajări Silvice Bucureşti, 1951; Ministry of Agriculture and Forestry, 1945; Romanian Church Forest Administration, 1926). Furthermore, our case study areas differed highly in their historical policy, management practices and ownership structures because they were situated on either side of the Ottoman-Austrian-Hungarian border (Table 3.1). This means that the case study areas captured a variety of historical forest management types and hence provide a great opportunity to examine the role of forest management legacies on current forest composition, structure and disturbance patterns.

Overview of long term forest dynamics

We analyzed long-term forest dynamics in Romania in relation to major socio-economic shifts and ownership changes based on an extensive literature review and national-level statistics. We relied on forest cover statistics about major forest types (coniferous, beech, oak, others) for the years 1924, 1954, 1964, 1980, 1985,1994, 2006 and 2010 (Directia Centrala de Statistica, 1985, 1980, 1964; Directiunea Statisticei Generale, 1954; Institutul National de Statistica, 2010, 2006, 1994; Ministerul Agriculturii şi Domeniilor, 1924). We used average disturbance data reported in the 1924 forestry statistic for the decade of 1912-1922, in combination with age structure data to reconstruct average disturbance for the decade of 1902-1912. We only extrapolated the age structure for young forest classes because this method will result in estimates with high uncertainties for mature forests. The disturbance value for 1870 is reported in the literature (Nicolau-Barlad, 1944). For the years 1960 to 2014 we calculated disturbed areas based on FAO harvest volume data (FAO (United Nations Food and Agriculture Programme), 2015), which we converted to area estimates (ha) using an average volume/ha value of 400 cubic meters. The conversion factor was chosen based on average dendrometric values for contemporary forests of harvestable age in Romania (i.e. forests 80 years of age or older) (Rusu and Cojinovschi, 2014) and is comparable to timber volumes for clear-cuts in other parts of the world (Masek et al., 2011). We cross validated these estimates with annual disturbance rates reported in remote sensing analysis (Griffiths et al., 2014; Potapov et al., 2014) and found differences of only 1-2% in disturbance of forest areas for the overlapping years. However, our estimation is rather conservative because we assumed that harvest volumes stayed constant over time for the period

1960-2014. Volume density may have increased in recent years (Rautiainen et al., 2010; Vliet et al., 2015) and if this was the case for Romania too, our estimates of disturbance may underestimate the amount of historical harvest.

We analyzed national ownership patterns based on 1924 statistical data at the county level (Ministerul Agriculturii şi Domeniilor, 1924) and national statistics for 2010 and 2014 (Curtea de Conturi a Romaniei, 2013). We relied on bibliographical sources on ownership data for 1940 and for the socialist period (1948-1990) (Bouriaud and Popa, 2008b; Giurescu, 1981; Nicolau-Barlad, 1944). We compared the proportions of three ownership types in each time periods: public (state owned), institutional, and private.

Since the mid-19th century Romania experienced five major land privatization events concomitant to socio-economic and political shifts such as wars and revolutions. In 1872 serfs were liberated and received land for farming, and in 1921 WWI soldiers received land as war compensation. After WWII all land was nationalized and managed by the state. Following the collapse of the Soviet Union in 1990, three restitution laws, ensured that forest passed back into private ownership in 1991, 2000 and 2007 (Ioras and Abrudan, 2006) (Fgure 3.2).

Historical and contemporary spatial data

Our spatial analysis was largely based on forest inventory data for two spatial scales (country level and forest management unit) and focused on two time periods: early 20th century when the study region was under influence of the Habsburg and the Ottoman Empire (hereafter historical) and following the collapse of the Soviet Union and EU accession (hereafter contemporary). In order to analyze forest extent, composition, age classes and disturbances we relied on county-level forest inventory statistics for the historical period (Ministerul Agriculturii şi Domeniilor,

1924) and aggregated spatial and statistical data at the county level for the contemporary time period. We digitized forest statistics on age classes and forest composition for 1924 and yearly forest disturbance for the decade 1912-1922. Data was available for the 60 historical counties of Romania according to the 1930 administrative boundaries (Max Planck Institute for Demographic Research and Chair for Geodesy and Geoinformatics, 2015) (Figure 3.1). For the contemporary time period, we integrated four major data sources: two national statistics (Institutul de Cercetări şi Amenajări Silvice Bucureşti, 2015a; Institutul National de Statistica, 2015b) and two spatial broad scale data sets, one on forest disturbance (Hansen et al., 2013) and one on forest composition (Brus et al., 2011). We aggregated these data at the county level using administrative boundaries of the 42 Romanian counties of 2014 (Figure 3.1). In order to limit effects of inconsistencies in our data sources and ensure comparability, we used the baseline of national statistics, to which we assigned disturbance rates and species composition from the spatial datasets (Table 3.2).

At the forest management unit level, we obtained forest extent, composition, age and disturbance from forest management plans dated from 1926 to 1945 (Table 3.2). Contemporary forest management plans for the years 2008 to 2014 were available in GIS format and we compared them with digitized historical records to assess shifts in composition, disturbance and age structure.

Forest disturbance

For our analysis, we define disturbance as loss of forest cover due to forest harvest and natural disturbances (which are in Romania most commonly followed by salvage logging). At the national level we relied on historical disturbance data from 1912 to 1922 from forestry statistics

(Ministerul Agriculturii şi Domeniilor, 1924). Historical data on forest harvest was reported by foresters in the field and subsequently centralized for each county, and we expect that this data could underestimate the amount of historical harvest. For the contemporary period (2000-2013) we mapped disturbance at county level using remote sensing data (Hansen et al., 2013) complemented with county level statistics for selective and shelterwood logging, because remote sensing data does usually not capture fine-scale disturbances (Kittredge et al., 2003). At the forest management unit level we compared the historical and contemporary occurrence of disturbance based on the forest management plans.

Forest composition

For all of Romania, we compared historical and contemporary extent of four major tree species (beech, oak, fir, and spruce) at the county level using the 1924 and 2014 statistics and reported change as percentage of the total forested area. 1924 data was summarized by 1930 administrative regions. For the contemporary dataset we compiled two data-sources of species distribution: statistical data on the area covered by major forest type (coniferous, deciduous and mixed) at the county level (Institutul National de Statistica, 2015b) and spatial information on the distribution of tree species groups in Europe at 1 × 1 km (Brus et al., 2011). We calculated percentage of tree species per county and assigned them to major forest types. We finally summarized tree species areas by county in order to obtain more detailed statistics. At the forest management unit level, composition is reported as percentage species in a given stand. For the three case studies, we compared historical and contemporary extent and percentage of species for each forest management unit.

Forest age

Across Romania, statistical data on age class distribution was available to us only at regional level for 2014 (Institutul de Cercetări şi Amenajări Silvice Bucureşti, 2015a), and at the country level for 1964 (Directia Centrala de Statistica, 1964) and 1924 (Ministerul Agriculturii şi Domeniilor, 1924). We aggregated all data at the national scale and analyzed changes over time. At forest management unit level, we compared shifts in age distribution between the historic and contemporary time periods at the stand level.

Comparison of historical and contemporary data with alternative data sources

Because the reliability of historical forestry statistics is often questionable (Kuemmerle et al., 2011; Schelhaas et al., 2003), we compared the historical datasets used in our analysis with other values reported in the literature and with statistical surveys carried out in the same region by other actors. For the contemporary time period we compared our data with remote sensing estimates and alternative national statistics for Romania (Table 3.3). Overall, we found only small differences between datasets, indicating that datasets used in our analysis captured the status of Romanian forests well. We found the smallest difference between the French forestry statistics from 1900 (Ministere de L'Agriculture du Commerce de L'Industrie ed des Domaines, 1900) and the Romanian forestry statistic dated 1924, with a 0.4% percentage difference (Ministere de L'Agriculture du Commerce de L'Industrie ed des Domaines, 1900; Ministerul Agriculturii şi Domeniilor, 1924) (Table 3.3). The largest difference between datasets occurred in the case of forest disturbance between 1900 and 1924 by 12.5% percent, but this is very likely due to the difference in the reporting year (Table 3.3a). We also checked the correlation of datasets available on contemporary forest cover, disturbance and composition and observed a maximum correlation of 0.98 for disturbance estimates and a minimum correlation of 0.81 for species distribution (Table 3.3b).

Results

Overview of long term forest dynamics

Historical forest management, in particular past, extensive forest harvest is strongly reflected in contemporary age structure, composition and disturbance patterns across Romania. Overall, forest area increased in Romania by roughly 308000 ha since 1924, and the country experienced forest transition (i.e., the shift from decreasing to increasing forest area) in the first half of the 20th century. The lowest forest cover occurred sometime between 1920s, when disturbance was particularly high (93000 ha) and 1955 when forest inventory area was as its minimum (5735000 ha). Forest harvest reached its highest point in the late 19th century (with over 100000 ha being harvested in one year, Fgure 3.2 and Figure 3.3). The contemporary Romanian forest inventory reports 6.3 mil ha of forest, which does not include shrub encroachment and forest succession on abandoned lands (estimated at 2.2 mil ha, Hansen et al., 2013). Overall, annual forest disturbance decreased from 1.40 % of the total forest cover in 1924 to 0.71% in 2013.

Forest composition also changed substantially in Romania, with the proportion of deciduous forests decreasing strongly since 1924, when beech accounted for 39% and oak for 22% of the total forest cover. The maximum coniferous cover was reached in Romania in the mid-1980s (31%) (Fgure 3.2).

Forest ownership changed drastically during several historic land reforms and post-socialist privatization. Our data indicated that in Romania in 1924, land ownership was divided between private land owners (3298000 ha), state (1556000 ha) and other institutions (1217000 ha),i.e., roughly 54, 26 and 20% respectively. Privately owned land decreased by 1940 to 48% of the total forest area. In 1948 all forest was passed into state ownership (Ioras and Abrudan, 2006). Total state ownership lasted until 1991 when following the collapse of the socialism land started being privatized. Post socialist statistics report a shift in ownership to 30% private, 53% state and 17% other institutions, with a higher percentage of publicly owned forests than before WWII (Fgure 3.2). In 2014, private forests represented roughly one third of the private forest in 1924. The cross-tabulation of forest disturbance and ownership patterns showed that in 1924, 54% of the forests were privately owned, but as much as 66% of the disturbances occurred in privately owned forests and only 20% in state forests. Spatial information on disturbance by ownership type for 2010 was not available to us.

Forest disturbance

Forest area increased in Romania since 1924 (when it covered 6072000 ha) by 5% and the annual amount of forest harvested (clear cuts and final cuts) between 2000-2013 dropped by 50% (~ 42000 ha/ year) compared to 1912-1922 (~85000 ha/year). Historically, forest harvest was concentrated in the more accessible, lowland areas of Romania, especially in the south and east of the country, where individual counties had annual harvesting rates between 4-6% of their forest cover (Constanta, Ilfov, Vlasca, Olt and Covurlui). Contemporary forest harvesting is concentrated mostly in Northern Carpathians and the northern half of Transylvania (Suceava, Bistrita-Nasaud, Harghita, Covasna, Cluj, Mures, Neamt, Bacau), as well as in the south-east of the country (Calarasi, Ialomita), where forest cover was low to begin with (10% of the county territory). In contrast to overall lower harvesting rates across Romania, in some of the Eastern Carpathian counties, contemporary forest disturbance was higher than historic forest disturbance (Figure 3.3).

At the local level, disturbance decreased in all cases, but most prominently in the case of Humor, where there was almost no disturbance in the period 2000-2010. For the Madaras and Oituz cases, the difference in the amount of harvest was small, but the disturbances were historically clustered in space and more evenly distributed in the contemporary time period. (Figure 3.4)

Forest composition

We found that the total area, proportion and spatial distribution of main tree species changed drastically across Romania since 1924. Forest composition shifted towards higher proportion of coniferous (Picea sp, Pinus sp, Larix decidua and Pseudotsuga menziesii) and some deciduous species (Tilia cordata, Populus sp, Betula sp, and Alnus sp), which are now more homogenously distributed in space. Norway spruce increased in area since 1924 (by 6.75%), currently covering an area of 1590000 ha in Romania. Spruce was historically concentrated at higher elevations and in the northern part of the Carpathians, but is now also found at lower elevations. Beech and fir decreased in area (by 14.66% and 1.05% respectively), losing a total of 861000 ha, mostly to spruce plantations. For both species, we found a more spatially homogeneous distribution amongst most counties of Romania: beech declined in the southern Carpathians and the west of Romania and increased slightly in the south of the country. Contemporary oak cover was roughly the same in Romania as in 1924 (ca.1400000 ha, amounting 22% of the forest cover) but the abundance and spatial distribution shifted greatly from a center of their distribution in southern Transylvania and the western part of the country towards the southern and eastern regions of the country. We recorded highest loss of oak from the historic regions of Alba de Jos, Tarnava Mica and Tarnava Mare where oak comprised between 30-50% of all forests in 1924 to only 10-20% in 2010 (Figure 3.5).

At the local scale, our three case studies confirmed the trends observed for Romania as a whole: a drop in the percentage of fir, beech (and oak in Oituz, where it was present to start with) as well a strong increase in spruce. Overall, forest stands were historically larger and fairly homogeneous in their species composition but became patchier in the contemporary time period. Spruce was more widespread in early 21st century with the exception of Madaras, where forest cover decreased altogether due to contemporary natural disturbances. In the Humor case study, fir area decreased from 1440 ha to 970 ha, being largely replaced by spruce (350 ha) and beech (115ha). Beech experienced a slight increase from 955 ha to 1030 ha (Figure 3.6). In the Oituz case study, the decline of fir, beech and oak was mirrored by an increase in spruce and hornbeam, with generally smaller homogenous stands (Figure 3.6).

Forest age

In contemporary Romania, more forests are even-aged and the area of old forests decreased compared to the historical time period. Age structure data was available only at regional level for 2014, and at the county level for 1924. We complemented this dataset with national level statistics for 1964 and aggregated all data to the national level. Old forests (over 80 years) had a higher percentage in 1924 (25 % of all forests) compared to 2014 (21% of all forests). In 1924 as much as 49% of all forests were in age classes below 40 years old, with a total of 1887000 ha being younger than 20 years old. Overall, we observed an equalization of age structure over time, with roughly 10-17% forest in each age class. Between 1924 and 2014, forests over 100 years declined from 14% to 9% and forests between 80-100 increased by 1% (Figure 3.7).

When cross-tabulating ownership and age structure, we found that historically the largest proportion of forests under 20 years old (61%) was privately owned, whereas old forest (>100 years) where roughly evenly distributed between state, institutional, and private land owners. In 2014, only a small proportion of old forests (17%) was privately owned, and the state owned most of the old forests in Romania, as much as 191000 ha more than in 1924.

At the local scale, our results indicated that forests were historically older compared to the contemporary period, with the exception Madaras, where a long history of spruce plantations led to successive wind disturbances and very young forest. In both Humor and Oituz, we found a high loss of forests in age classes older than 100 years, and an overall tendency of even distribution among age classes. In the case of Humor, contemporary stands were mostly 20-60 years old, whereas in Oituz most stands were 100 years or older. (Figure 3.7).

Discussion

Overview of long term forest dynamics

Our results showed that age structure, composition and disturbance patterns have changed greatly since the early 20th century in Romania and we argue that legacy effects of forest management from nearly a century ago are still greatly reflected in contemporary forests. Forest cover increased in Romania and disturbance is much lower than in early 20th century; but due to intensive management in the past, contemporary forests have a higher percentage of spruce and less beech and oak. We suggest that major shifts in the amount of disturbance and in species composition may be related to changes in governance and land tenure because disturbance peaked around the time of agrarian reforms in the 1920s and post-socialist privatization in the 1990s and 2000s.

Our study captured several major changes in land tenure systems, and we suggest that forest disturbance was closely related to changes in forest ownership. Specifically, our data captured three land-ownership trends: a) decrease in private land from 1926 to 1948, following the agrarian reform of 1921(Ioras and Abrudan, 2006; Ministerul Agriculturii şi Domeniilor, 1924; Nicolau-Barlad, 1944), b) entirely state-owned land from 1948 to 1989 (Bouriaud and Popa, 2008b; Giurescu, 1981; Nicolau-Barlad, 1944), and c) increase of private land as the result of three privatization laws (Law 18/1991, Law 1/2000 and Law 247/2005) from 1990 to 2014 (Ioras and Abrudan, 2006). These three periods roughly coincide with a decrease, stagnation, and increase in the amount of forest disturbance, suggesting that forest disturbance may be related to changes in land tenure, and specifically to the share of privately owned land. Our results are in line with global forestry literature which indicates that forests with stable ownership have significantly lower rates of harvest (Jin and Sader, 2006), and that harvest rates are higher in private forests (Kittredge et al., 2003). In Romania, missing or unclear regulations and the widespread lack of management plans for privately owned forests may provide a potential explanation for the high rates of contemporary harvesting in private forests that we observed. With 50-75% (roughly 700,000ha) of its private forests lacking forest management plans, Romania is one of only five European countries in which management requirements are not fully consolidated across land ownership forms (Schmithuesen and Hirsch, 2010). Our results suggest that despite of 50 years of Socialism, when all forests were managed by the state (Ioras and Abrudan, 2006) legacies of historical shifts in governance can affect forest ecosystems far into the future, and may be related to the loss of old growth forests and changes in species composition. Similarly, our results highlighted the importance of stable governance and land tenure in maintaining forest area, age structure, composition and harvest rates.

Forest disturbance

Based on our results, forest cover increased in Romania since the 1920s and forest transition, i.e., the shift from a decrease to an increase in forest cover (Mather, 1998; Rudel et al., 2005), occurred approximately in the Interwar period, consistent with case-studies in the region (Munteanu et al., 2014). Forest area in the current Romanian territory was as high as 10 million ha until 1860s (Nicolau-Barlad, 1944). By 1900 forest cover decreased in Romania by 3 mil ha – (Giurgiu, 2010a, 2010b) due to agrarian reforms at the end of the 19th century, which granted forested land to serfs for farming (Giurgiu, 2010b; Hitchins, 1994). Harvest rates were very high between 1912 and 1922, lowering the total tree cover to a minimum of 5023000 ha in the mid-1920s due to high timber needs for war purposes. Another agrarian reform in 1921, caused around 1 mil ha of clearings (Florescu, 1937; Giurescu, 1981; Giurgiu, 2010b; Sabau, 1957). Overall our study suggested that changes in regulations and high demand for agricultural products led to a rapid decrease in forest cover until WWII.

Following WWII, and especially after 1975, Soviet policies increased forest cover (Marea Adunare Nationala, 1976) by establishing forest plantations outside the historical range of forests (Munteanu et al., 2015a). All forest were managed centrally and harvests were planned for 10-year time intervals, making reported forest harvest relatively constant (Marea Adunare Nationala, 1976). We observed a peak in harvest around 1965, partly due to war reparations paid to Russia in oil and timber (Banu, 2004). Disturbance peaked again in 1982-1985 when Romania was paying off loans to the International Monetary Fund (Ban, 2012a). Following the collapse of the Soviet Union, disturbance rates were also high in Romania (Griffiths et al., 2014; Hansen et al., 2013; Knorn et al., 2012b; Potapov et al., 2011, 2014) especially following major privatization laws in 1991, 2000, and 2005 (Ioras and Abrudan, 2006). This finding provided further evidence on how institutional instability may increase harvesting patterns (Baumann et al., 2011; Dragoi et al., 2011; Prishchepov et al., 2012). However, we highlight that rates of forest harvesting after 1990 were lower than pre-1990, a fact that is missed by most post-socialist studies.

We found higher historical harvest in the Ottoman and Romanian regions than in the Austrian ones, and attributed this to the increase in exports following the Adrianopole Peace Treaty and the removal of the Ottoman timber monopoly in 1829 (Cojocaru-Ţuiac, 2010). Furthermore, the impact of agrarian reforms was higher in fertile areas than in mountain regions (Giurgiu, 2010a). In Transylvania, counties located closer to Vienna and with less mountains experienced more deforestation. However, the Northeastern Carpathian region was heavily prized for its timber, both by Austrians and Ottomans (Cojocaru-Ţuiac, 2010), and this is where we observed widespread forest harvesting. During the post-socialist period, we found a shift in disturbance patterns, where the mountain regions experienced higher disturbance rates, likely due to more abundant forest resources and increased accessibility.

Forest composition

Our results indicated an overall homogenization of the spatial distribution of tree species, with an increase in spruce (especially in Transylvania) and a shift in the spatial distribution of oaks (especially to Moldova and Wallachia). Our results also suggested that historical forest management - different across empire borders - may have increased the abundance of conifers on the Austrian and of oak on the Romanian side of the border. During the Austrian forest management of the 19th century, conifers such as spruce and pine were widely planted for pulp, timber and for erosion control in Transylvania (Popa, 2001). In contrast, historical Ottoman and later Romanian forest management was centered on the cut and leave method. This meant that entire watersheds would be clear-cut, but at least 50 trees / ha were left standing as seed sources to ensure natural regeneration (Ministry of Agriculture and Forestry, 1945), leading to dominance of beech and oak. In addition, several oak species *(Quercus rubra, Q. frainetto)* were planted historically for erosion control and land reclamation in southern and eastern Romania. However, the increasing percentage of oak and beech in lowland regions coincided with the reduction of the species' ranges in central Transylvania. Although Transylvania still hosts some of the most biodiverse oak wooded pastures (Hartel et al., 2013; Öllerer, 2014), their extent very likely declined severely both during Austrian and Socialist rule (Rus, 2014) due to high value of the timber and because they were cleared for grazing or agriculture (Giurescu, 1981; Rus, 2014).

Socialist forest management also affected the current ecosystem composition. Between 1948 and 1989 large clearcuts were prescribed to pay off war debts (Banu, 2004) and international loans, followed by extensive spruce plantations both within (Cojocaru-Ţuiac, 2010) and outside forest ranges (2 mil ha between 1948 and 1975, Marea Adunare Nationala, 1976). The area of spruce increased, while that of fir and deciduous species decreased.

Our local case studies provided additional evidence for legacy effects in forest composition. Madaras was mostly deciduous in Austrian military maps of the mid-19th century (Timár et al., 2010) and our data from the early 20th century indicated that spruce plantation occurred in the early 20th century. The area was clear-cut and restocked with spruce several times which may explain the wide-scale wind throws followed by salvage logging which we observed in contemporary management plans. In Humor, the shift from fir to spruce and beech could be a result of spruce plantation which encouraged natural regeneration of beech instead of fir (Damian, 1978; Isciuc, 2010). Finally, in Oituz we found a relatively high proportion of successional species like hornbeam or pines which are a good indication of the effect of the cut and leave management. Beech and oak decreased here, likely because their regenerative power was smaller than that of successional species.

Forest age

In terms of forest age, Romania has less very young forests (0-20 years) since 1924 but also less forests older than 100 years. A relative equal distribution of age classes is desirable from a management perspective, because it ensures a sustained wood production for timber and pulp (Halbritter and Deegen, 2015). However, old-growth forests have a high natural and conservation value as they provide habitat for a wide range of species, provide ecosystem services and store carbon (Keeton et al., 2010; Wirth et al., 2009) and their loss is unfortunate from a conservation perspective.

Forest management in post WWII Romania aimed to maximize timber production (Banu, 2004; Giurescu, 1981) to pay war debts and economic loans (Ban, 2012a; Banu, 2004), and this led to a decrease in old forests, including some of the last old-growth forests of Eastern Europe (Knorn et al., 2012a; Veen et al., 2010). Although consistent with remote-sensing studies indicating the loss of old-growth forests in Romania (Knorn et al., 2012a), our results also highlight that a large proportion of Romanian forests were already managed in the early 20th century despite their old-growth like structure. However, mature secondary vegetation can provide important ecosystem services, have high biodiversity and conservation value (Newbold et al., 2015).

Local scale case studies confirmed the overall loss of old forests, especially in Oituz and Humor, where stands over 120 years old disappeared since 1924, likely as a result of socialist management aiming to maintain equal age classes (Giurescu, 1981). In Madaras, the young forests of 1945 reflect harvests and spruce plantations of the early 20th century, while the contemporary proportion of young stands is likely due to the wind-throws in 1995-1997 (Popa, 2000)

We caution that uncertainty may be introduced in our datasets by elements such as different methods in assembling forest statistics, clear definition of forest disturbance across data sources and ability for clear forest species identification. Overall, we expect that our historic estimates are more accurate in Transylvania and Bucovina, where historic management plans were available (Nicolau-Barlad, 1938; Stinghe, 1939). We expect historic ownership data to be reliable because detailed inventories were required in the course of the agrarian reforms. The historic tree species compositions may include errors depending on surveyors' ability to differentiate between spruce and fir or various oak species.

Conclusions

Our results suggested that contemporary forests were heavily affected by historical forest management and that changes in institutions and ownership patterns may drastically and rapidly affect disturbance patterns and forest composition. We interpret these results to mean that effects of past management and institutional shifts can linger for centuries, and this is important because many regions of the world are currently experiencing drastic changes in their governance and ownership patterns. Such changes may have snowballing effects on forest systems, their functioning and the services they provide for a long time into the future, making a sound understanding of forest legacies important for both conservation and management. In a regional context, Romania harbors some of the last old-growth forests in Europe, which are in decline across the continent. Romania represents also a major source of timber internationally, although harvest rates have decreased. Our results highlight the need to protect the remaining old forests, which are declining, as well as the need to balance conservation and management goals in the future in order to ensure sustainable forests in Eastern Europe.

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Figures and tables

Table 3.1 The three case studies, including name, area, historic region, type of management and forest ownership

Case study	Area (ha)	Historic region	Historical management	Historical ownership	Contemporary ownership
Humor	3500	Bucovina	Austrian	Church	State
Oituz	9000	Moldova	Romanian	Private	Private
Madaras	1400	Transylvania	Hungarian	Private	Private

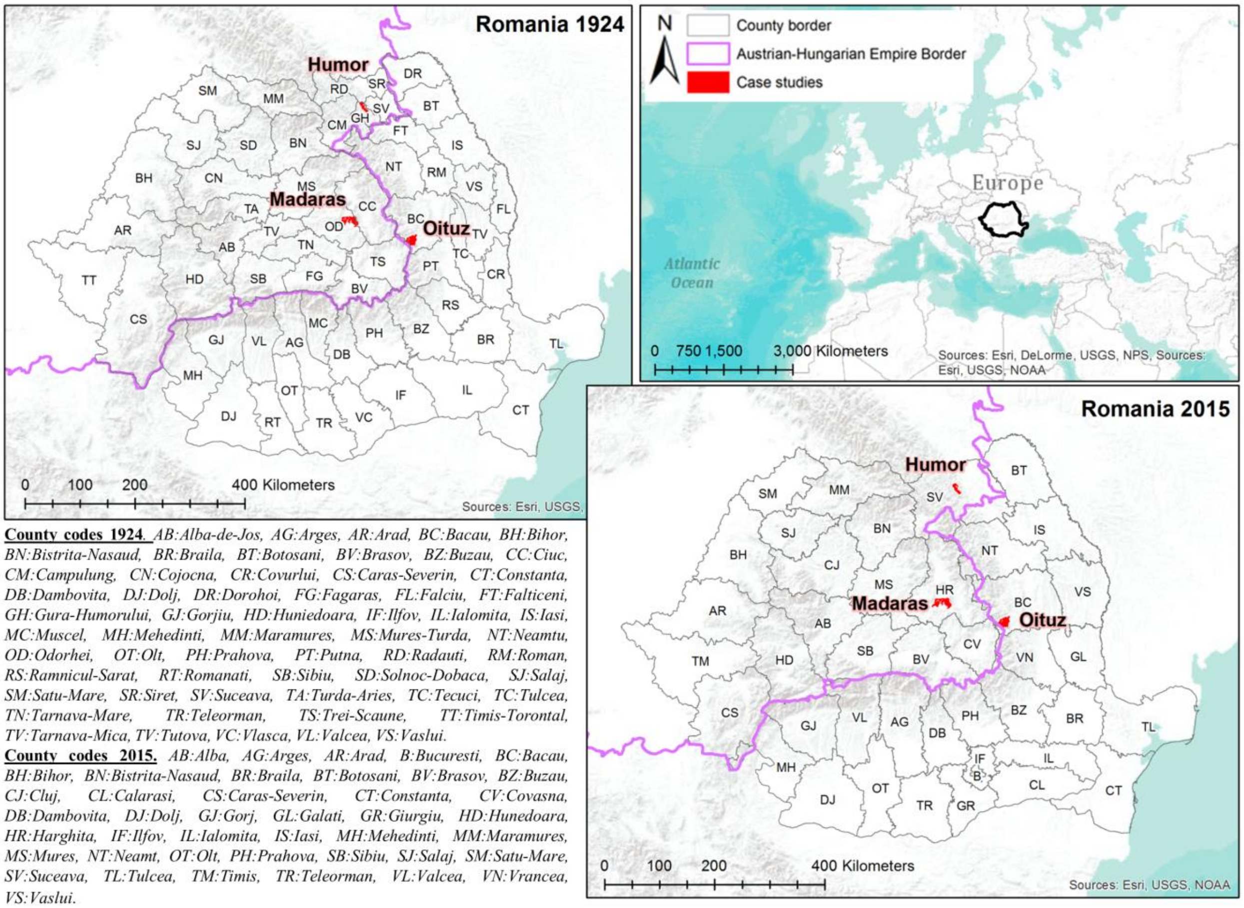
Table 3.2 Data sources for forest extent, composition, age classes and disturbances for two time periods and at two spatial scales

	Historical (1924-1945)	Contemporary (2000-2014)
Spatial scale: Romania, at county level		
Disturbance occurrence	(Ministerul Agriculturii şi Domeniilor, 1924)	(Hansen et al., 2013; Institutul National de Statistica, 2015b)
Forest ownership	(Ministerul Agriculturii şi Domeniilor, 1924)	(Institutul de Cercetări şi Amenajări Silvice Bucureşti, 2015a)
Age class distribution	(Ministerul Agriculturii şi Domeniilor, 1924)(Nicolau-Barlad, 1938)	(Institutul de Cercetări şi Amenajări Silvice Bucureşti, 2015a)
Species composition	(Ministerul Agriculturii şi Domeniilor, 1924)	(Brus et al., 2011; Institutul de Cercetări şi Amenajări Silvice Bucureşti, 2015a)
Spatial scale: Forest management unit: Humor, Oituz, Madaras		
Disturbance occurrence	(Institutul de Cercetări şi Amenajări Silvice Bucureşti, 1951; Ministry of Agriculture and Forestry, 1945; Romanian Church Forest Administration, 1926)	(Forest Design, 2010; Institutul de Cercetări şi Amenajări Silvice Bucureşti, 2008, 2006)
Age class distribution	(Institutul de Cercetări şi Amenajări Silvice Bucureşti, 1951; Ministry of Agriculture and Forestry, 1945; Romanian Church Forest Administration, 1926)	(Forest Design, 2010; Institutul de Cercetări şi Amenajări Silvice Bucureşti, 2008, 2006)
Species composition	(Institutul de Cercetări şi Amenajări Silvice Bucureşti, 1951; Ministry of Agriculture and Forestry, 1945; Romanian Church Forest Administration, 1926)	(Forest Design, 2010; Institutul de Cercetări şi Amenajări Silvice Bucureşti, 2008, 2006)

Table 3.3 Data sets used in our analysis and comparison to values from other sources such as forestry literature, statistical yearbooks and remote sensing estimates for (a) historical and (b) contemporary time periods

(a) **Historic**				
Compared content	Value used in Analysis	Cross-refencence in literature	Extent of comparison	Difference in %
Percentage of forest in Romania	25.875 % (Forestry statistic, 1900)	25.472 % (Forestry statistic, 1924)	Country level	-0.403%
Forest species composition 1900	Coniferous – 21% Oaks – 26 % Deciduous – 53% (Forestry statistic, 1900)	Coniferous – 25% Oaks – 23 % Deciduous – 52% (Forestry statistic, 1924)	Country level	Coniferous +4% Oaks – 3 % Decidous – 1%
Forest disturbance (ha)	590 327 (Forestry statistic, 1900)	524 698 (Forestry statistic, 1924)	Valahia and Moldavia, State and Communal Forest	-12.5%
Local Oituz Forest area (ha)	9008 (Forest inventory 1945)	9275 (Forestry statistic, 1924)	Forest management unit	-2.96%
(b) **Contemporary**				
	Data used in analysis	Cross-checking data source	Extent of comparison	R-squared
Percentage of county covered by forest	(Institutul National de Statistica, 2015c)	(Hansen et al., 2013)	N=42 counties	0.97
Area covered by major species	(Brus et al., 2011; Institutul National de Statistica, 2015b)	(Institutul de Cercetări şi Amenajări Silvice Bucureşti, 2015b)	N=15 (5 species, 3 regions)	0.81
Disturbance area	(INS, 2013)	(Griffiths et al., 2014; Hansen et al., 2013; Potapov et al., 2014)	Cross check for N=28 counties 91% of forest cover	0.98

Figure 3.1 Location of study area in Europe, imperial boundaries from 1900s, the location of 3 cases studies in the Carpathian Mountains and county borders for 1924 and 2015



<u>County codes 1924.</u> *AB:Alba-de-Jos, AG:Arges, AR:Arad, BC:Bacau, BH:Bihor, BN:Bistrita-Nasaud, BR:Braila, BT:Botosani, BV:Brasov, BZ:Buzau, CC:Ciuc, CM:Campulung, CN:Cojocna, CR:Covurlui, CS:Caras-Severin, CT:Constanta, DB:Dambovita, DJ:Dolj, DR:Dorohoi, FG:Fagaras, FL:Falciu, FT:Falticeni, GH:Gura-Humorului, GJ:Gorjiu, HD:Huniedoara, IF:Ilfov, IL:Ialomita, IS:Iasi, MC:Muscel, MH:Mehedinti, MM:Maramures, MS:Mures-Turda, NT:Neamtu, OD:Odorhei, OT:Olt, PH:Prahova, PT:Putna, RD:Radauti, RM:Roman, RS:Ramnicul-Sarat, RT:Romanati, SB:Sibiu, SD:Solnoc-Dobaca, SJ:Salaj, SM:Satu-Mare, SR:Siret, SV:Suceava, TA:Turda-Aries, TC:Tecuci, TC:Tulcea, TN:Tarnava-Mare, TR:Teleorman, TS:Trei-Scaune, TT:Timis-Torontal, TV:Tarnava-Mica, TV:Tutova, VC:Vlasca, VL:Valcea, VS:Vaslui.*

<u>County codes 2015.</u> *AB:Alba, AG:Arges, AR:Arad, B:Bucuresti, BC:Bacau, BH:Bihor, BN:Bistrita-Nasaud, BR:Braila, BT:Botosani, BV:Brasov, BZ:Buzau, CJ:Cluj, CL:Calarasi, CS:Caras-Severin, CT:Constanta, CV:Covasna, DB:Dambovita, DJ:Dolj, GJ:Gorj, GL:Galati, GR:Giurgiu, HD:Hunedoara, HR:Harghita, IF:Ilfov, IL:Ialomita, IS:Iasi, MH:Mehedinti, MM:Maramures, MS:Mures, NT:Neamt, OT:Olt, PH:Prahova, SB:Sibiu, SJ:Salaj, SM:Satu-Mare, SV:Suceava, TL:Tulcea, TM:Timis, TR:Teleorman, VL:Valcea, VN:Vrancea, VS:Vaslui.*

Fgure 3.2 Overview of the evolution of forest cover, species composition, disturbance and ownership patterns in Romania between 1870s and 2010, in the context of major land tenure changes

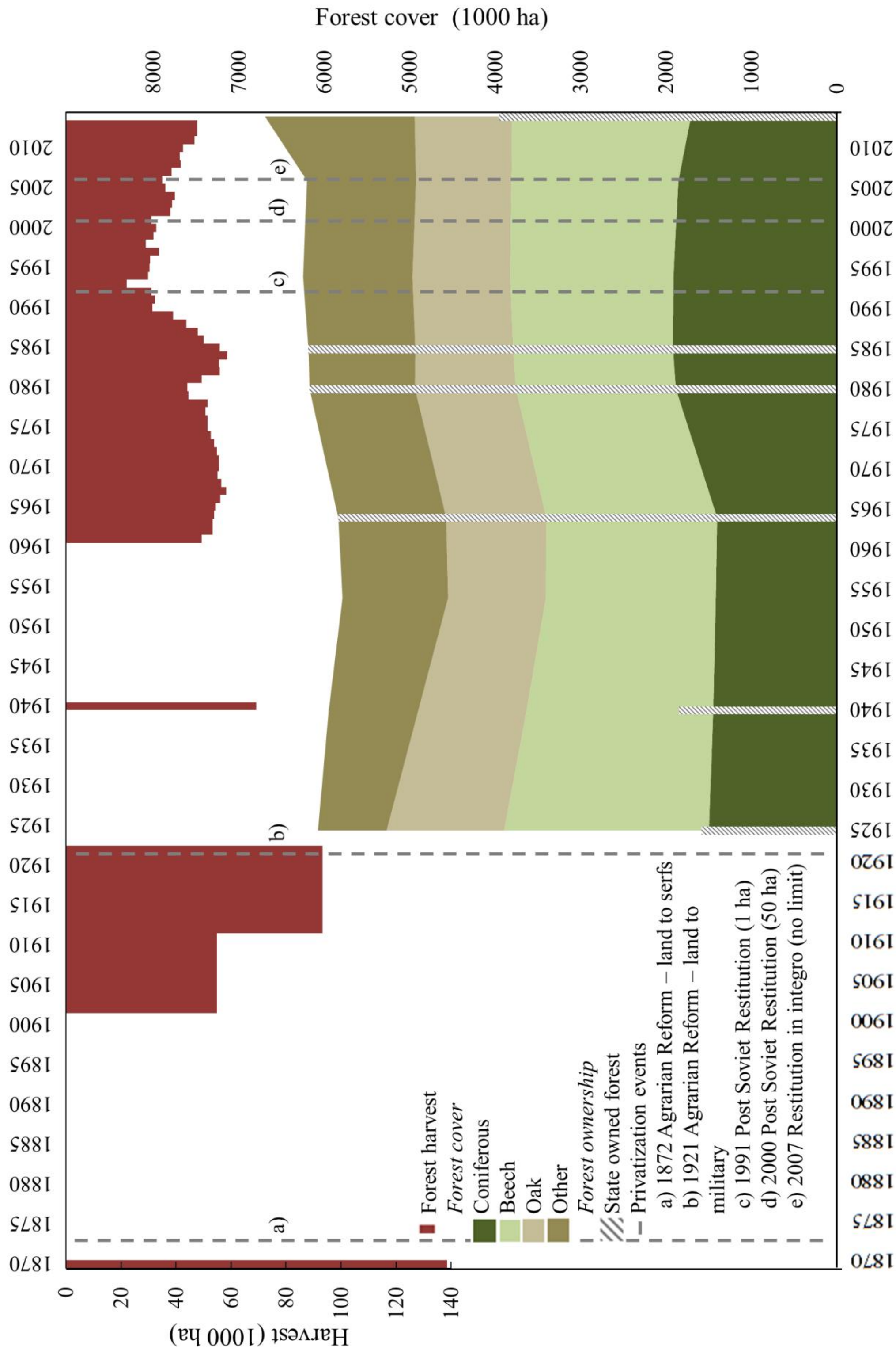


Figure 3.3. Percentage forest cover and forest disturbance in Romania historically (n= 58 counties) and contemporary (n=42 counties)

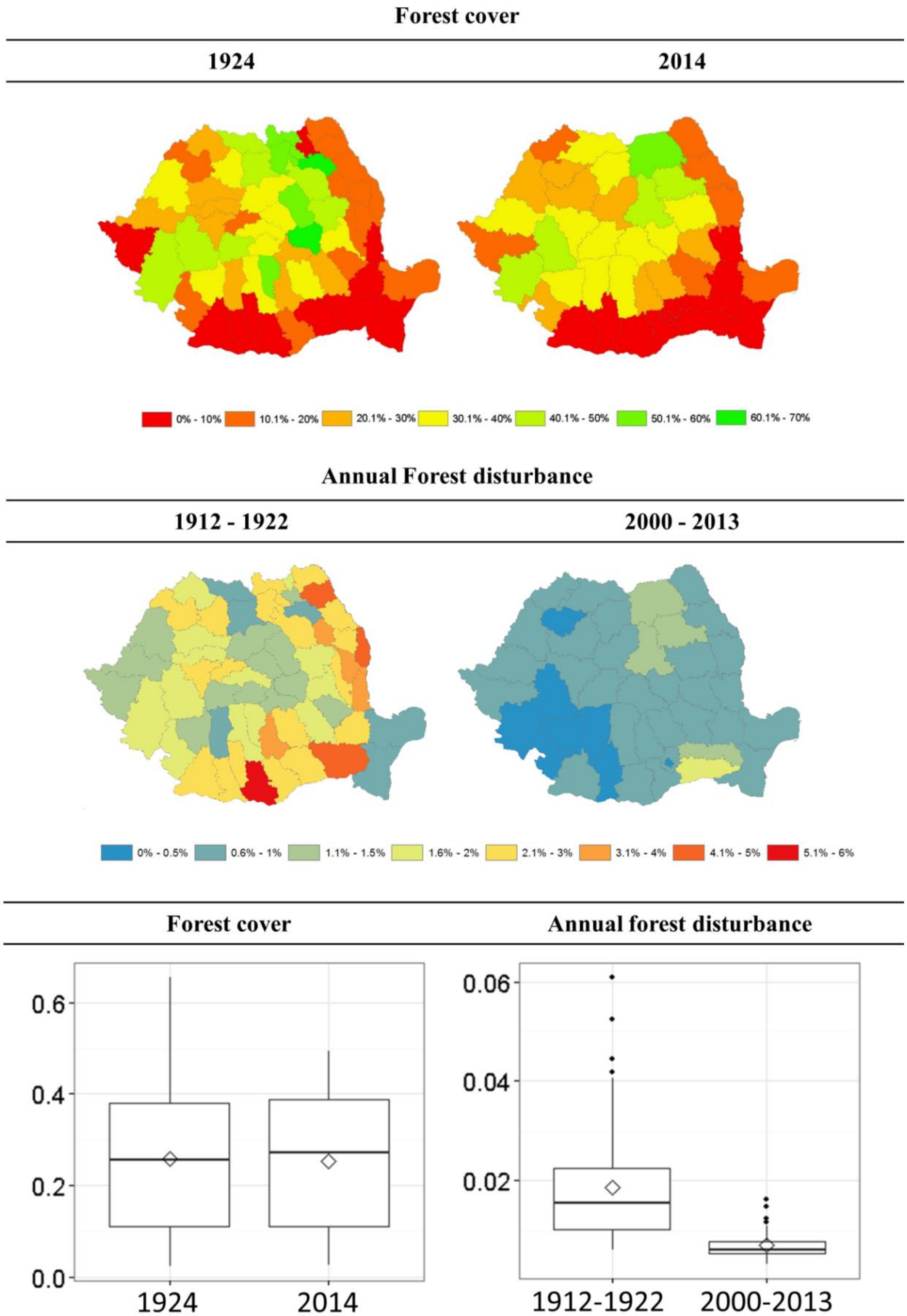


Figure 3.4 Historical and contemporary forest disturbance at forest stand level in three case studies: Humor (3500ha), Oituz (9000ha) and Madaras (1500ha)

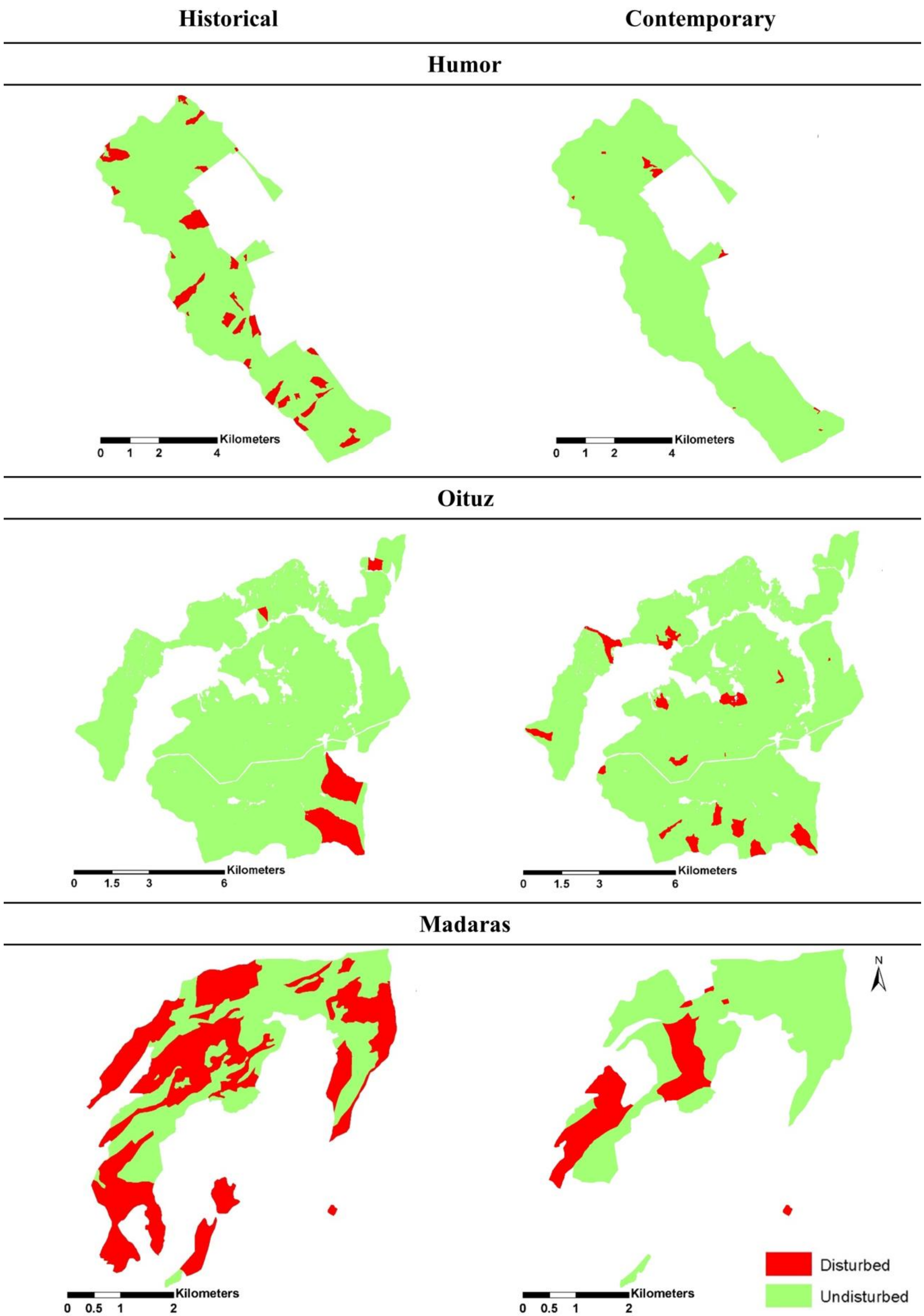


Figure 3.5 Percentage of major coniferous species (Picea abies, Abies alba) and major deciduous species (Fagus sylvatica, Quercus sp) within forest cover of Romanian regions in 1924 (n= 58 regions) and in 2014 (n=42 regions)

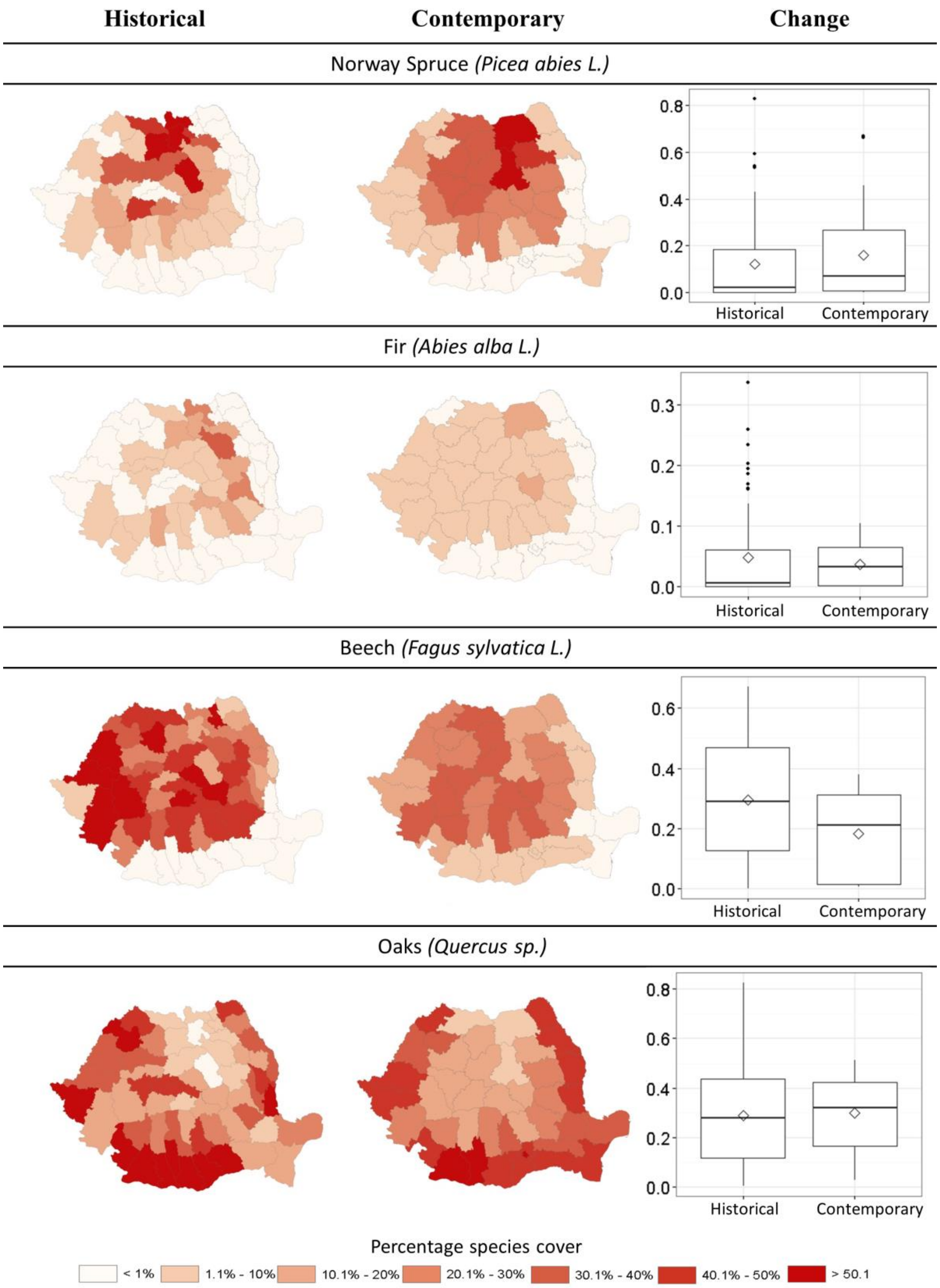


Figure 3.6 Species composition at local level in Humor (3500ha), Oituz (9000ha) and Madaras (1500ha) at the beginning of the 20th century and the beginning of the 21st century. Stands with species cover higher than 50% are represented in the graphic.

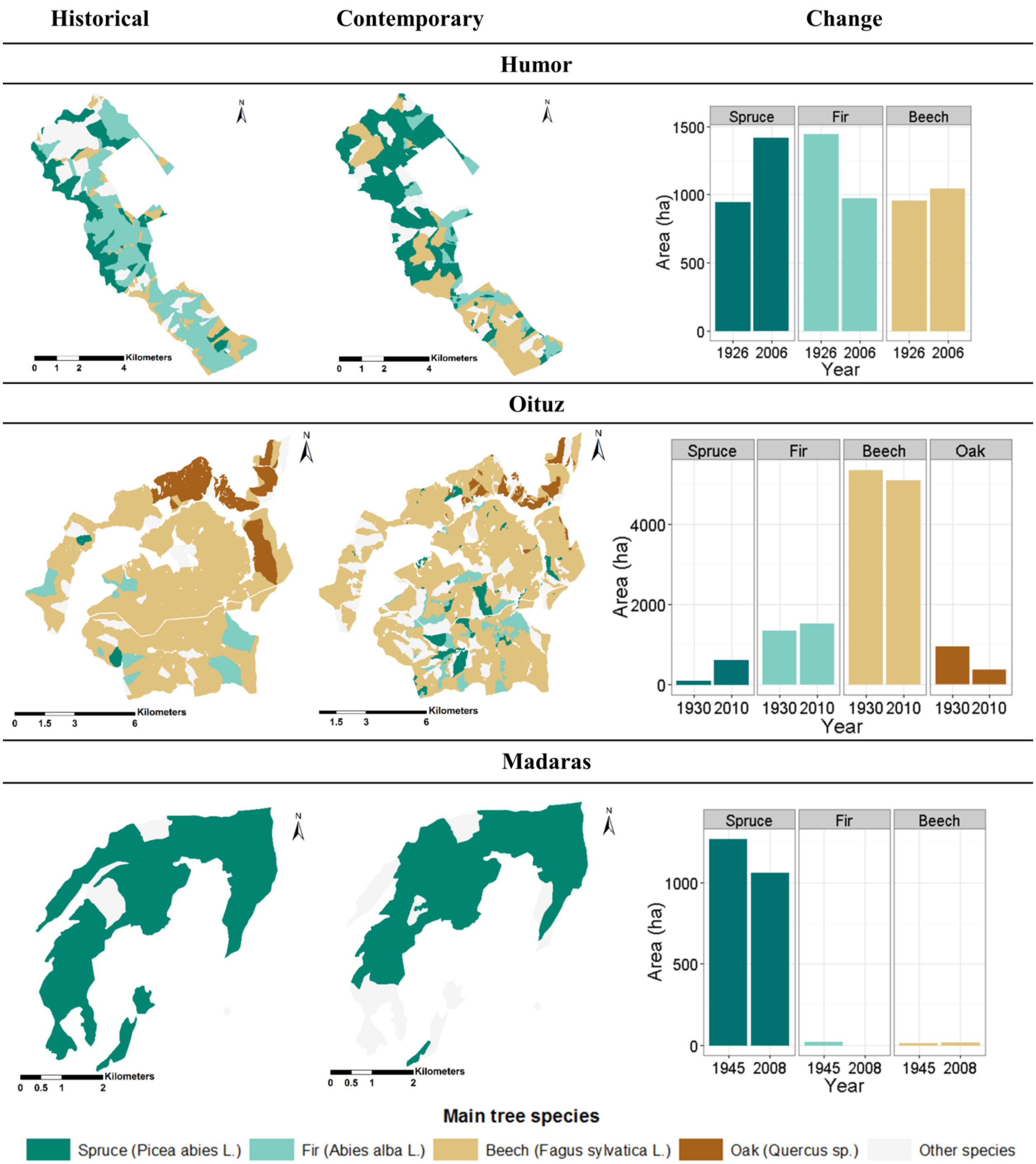
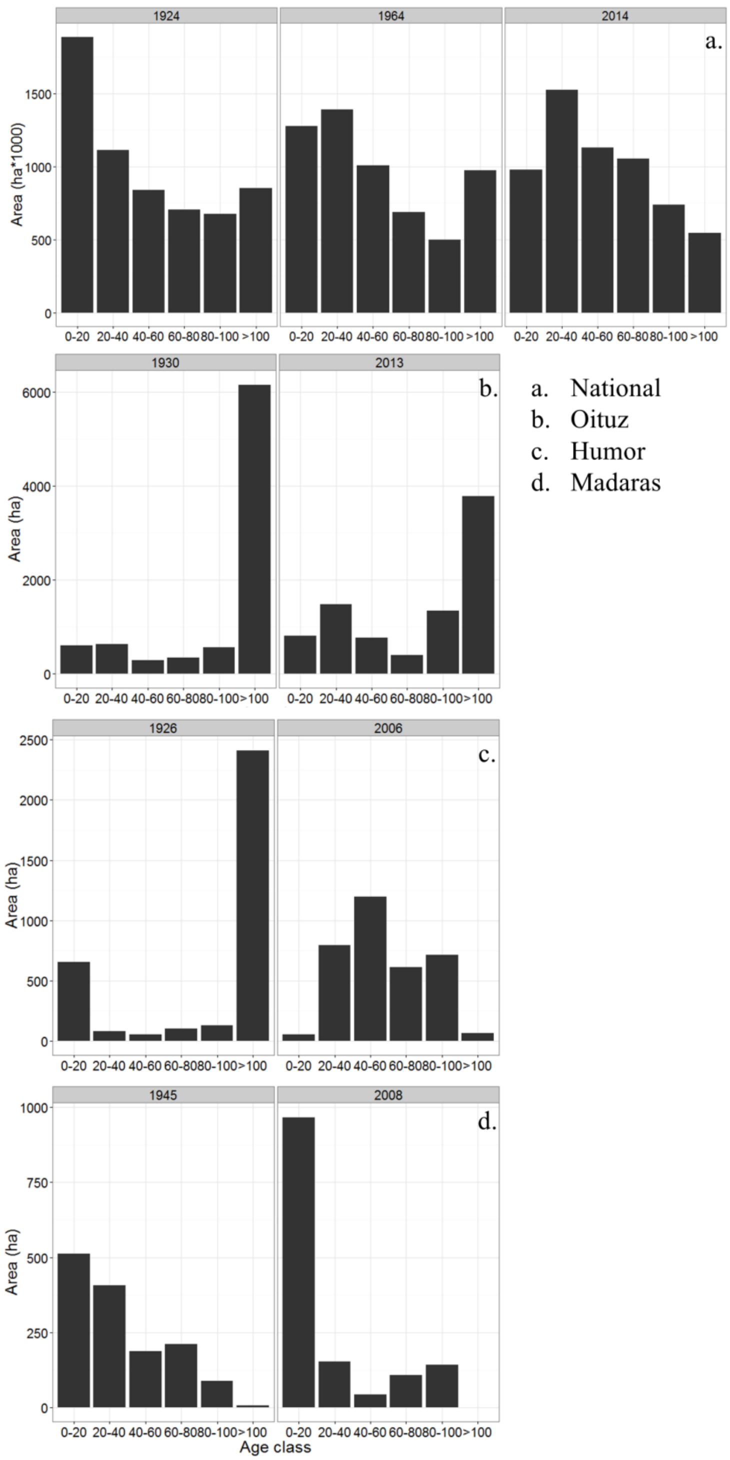


Figure 3.7 Forest age distribution in Romania in at (a) national level for the years 1924, 1964 and 2014 and at local case study level in (b) Oituz (9000ha) between 1930 and 2013, (c) Humor (3500ha) between 1926 and 2006 and (d) Madaras (1500ha) between 1945 and 2006.



Chapter 4. 19th century land-use legacies affect contemporary land abandonment in the Carpathians

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; J Plue et al., 2009), yet the effects of land-use legacies on environmental change remains 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; Ficetola 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 (Ficetola et al., 2010), constrain vegetation succession and productivity (Foster et al., 2003), and change seed bank, seed dispersal, and soil nutrients (J Plue et al., 2009; Plue et al., 2008). Agricultural legacies also affect beta-diversity in forest understory and hence ecosystem functioning (Mattingly et al., 2014), 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., 2015b). Path dependencies 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., 2015b). In swidden-fallow systems, path dependence shapes farmers' land-use choices (Coomes et al., 2011) and agricultural intensification is 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., 2013b; 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., 2013b). 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., 2016b). 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., 2010a). 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 socio-economic 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., 2013b; Munteanu et al., 2014), making this regions well suited to the effects of land-use legacies on contemporary abandonment.

Our overarching goal was to assess the role of long-term 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?

Methods

Study area

We studied an area of approximately 265,000 km^2 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 (Figure 4.1). We measured agricultural land use at six points in time: Habsburg era (1860), Interwar (1930), socialism (1960, 1985), and post-socialism (2000, 2010, Table 4.1). 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., 2015c). Agricultural land covered 23% of the region in 2010 (Griffiths et al., 2013b) (Figure 4.1).

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 ranges from small subsistence family farms to large private landholdings (Griffiths et al., 2013b).

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., 2013b; Munteanu et al., 2014).

Datasets

We reconstructed agricultural land use from 1860 to 2010 (Table 4.1 and Appendix 4.1). 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 4.1). We classified land use for a regular 2x2 km point sampling grid (Gallego and Delince´, 2010; Munteanu et al., 2015b).

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. To ensure consistency in point location across map sets, we developed a back-dating approach in which the location of the digitized point was verified in for subsequent dates relative to nearby landmarks (Kaim et al., 2016). This approach was employed for all points in Slovakia, Czech Republic, and Poland. For 3,409 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 (>80%

accuracy, Griffiths et al., 2013, Appendix 4.1). Based on the binary classifications (agriculture vs. non-agriculture), we mapped socialist abandonment (1960-1985) and post-socialist abandonment (1985-2010) (Table 4.1). 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 vs. non-agriculture classes for six time periods (Appendix 4.1). 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, 6,488 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, Appendix 4.3) 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, 2000).

Persistence of land use legacies

To quantify the persistence of land-use legacies over time (Objective 2), we compared the effect of Habsburg land-use on socialist (1960-1985) and post-socialist abandonment (1985-2010) (Appendix 4.2). We fitted multiple logistic regression models (Hosmer and Lemesbow, 1980). Our models included 20,501 points for the socialist abandonment models and 13,419 points for post-socialist abandonment (Appendix 4.4). 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 socio-political variation (2 variables) (Table 4.2). We estimated the effect of Habsburg legacy (Table 4.1) on 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) for a total of fitted fourteen models, seven for each abandonment period (Appendix 4.4).

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., 2015b). 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

We compared the effect of legacies from three historic time periods (Habsburg era, Interwar era, Socialist era) for post-socialist agricultural abandonment (Objective 3, Appendix 4.2). We modelled post-socialist abandonment using multiple logistic regression models (Hosmer and Lemesbow, 1980) that controlled for agro-ecological, accessibility, and socio-political variation (same 15 variables as in Objective 2,Table 4.2). 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 4.1) 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 4.1) 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 vs. Socialist legacy, Table 4.1) 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 3,424 for the socialist legacy model to 16,843 for Habsburg vs. socialist model (Appendix 4.5). 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 vs. Socialist model (AUC= 0.64) and highest for Poland in the Socialist legacy model (AUC=0.91) (Appendix 4.6).

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 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 (Figure 4.2). 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 (Figure 4.2).

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 post-socialism (33%, Figure 4.2).

Socialist agricultural expansion occurred predominantly in less suitable areas, while both Habsburg and the post-socialist agriculture were concentrated where agro-ecological conditions were favorable (AUC=0.82 and 0.89, respectively) (Figure 4.3 a and 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) (Figure 4.3 b), and agricultural 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) (Figure 4.3 c).

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 socio-political variation, the effect of land-use legacies were clearly evident, and persisted for as long as a century. Indeed, Habsburg legacies affected both socialist 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%, Figure 4.4 a). Aside from legacy effects, we found that socialist abandonment was concentrated near settlement, on steeper slopes, and in areas with low crop suitability (Appendix 4.7).

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 strong in Romania (86%) and Hungary (62%), but practically absent in Slovakia and Czech Republic, (10 and 9%, respectively, Figure 4.4b). 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 (Appendix 4.7). 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 (Appendix 4.5). Legacy effects were strong even when accounting for agro-ecological, accessibility and socio-political 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 (Appendix 4.8).

When comparing the legacy effects among the three time periods (Habsburg, Interwar, and socialist) we found greatest differences for the Habsburg vs. socialist legacy (Figure 4.4). 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 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, Figure 4.4 b,c,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), 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 modelling 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., 2015b) because these areas have low land rents. Overall, spatial reorganization of agriculture on suitable lands are 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 2nd World War (WWII), 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, 2012b). 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., 2015b, 2014) because the forest cover on former agricultural lands reestablishes only after a time lag.

Persistence of legacies

When modelling 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. 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 socio-economic 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 vs. 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 details 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 over 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 is 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 WWII, 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 definitions 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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Tables and figures

Table 4.1 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 the 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 the 1860s and to late Habsburg thereafter.*
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.*
Post-socialist era	In this manuscript, 1985-2010, during which most countries in the study region changed to marked economies and accessed the EU (except Ukraine).*
Socialist abandonment	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	Land abandonment that occurred between 1985 and 2010, mapped using Landsat images for 1985, 2000 and 2010.*
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 the 1860s on subsequent agricultural abandonment. This legacy captures the effect of early versus late Habsburg agriculture on abandonment.
Habsburg vs. Soviet legacy	The effect of the whether or not land was farmed prior to the 1930s on subsequent abandonment. This legacy captures the differences between land farmed during the Habsburg era and agricultural expansion during the socialist era.**
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 Soviet agricultural expansion on abandonment.

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

** The Interwar era represented a time of major political and socio-economic 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.

Table 4.2 List of predictor used in logistic regression models, including land use legacies, agro-ecological conditions, accessibility and socio-political 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		vector
	Interwar agriculture (1930)	mapped		vector
	Socialist agriculture (1960)	mapped		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	~1 km
	Distance to nearest major city	ESRI, 2008	km	vector
	Distance to nearest settlement	EEA, 2013	km	vector
	Distance to nearest road	CIESIN & 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
Socio-political	Country	ESRI, 2008	N/A	vector
	Population count 1990	CIESIN, FAO & CIAT, 2005	No.	~5 km

Figure 4.1 Study area. Country codes: CZ: Czech Republic, HU: Hungary PL: Poland, RO: Romania, SK: Slovakia, UA: Ukraine

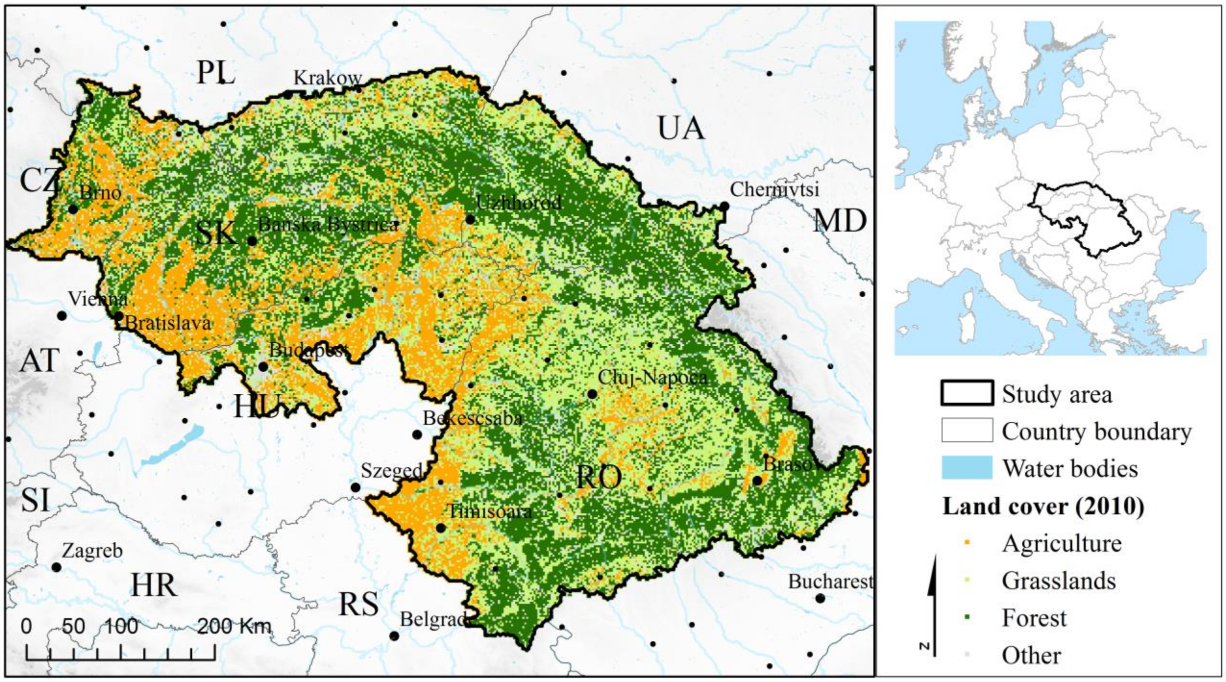


Figure 4.2 (a-f) Agricultural land between 1860 and 2010, (g-h) socialist and post-socialist land abandonment in the Carpathian region and (i) change of percent of total land in agriculture by country (see Table 4.1 for definitions).

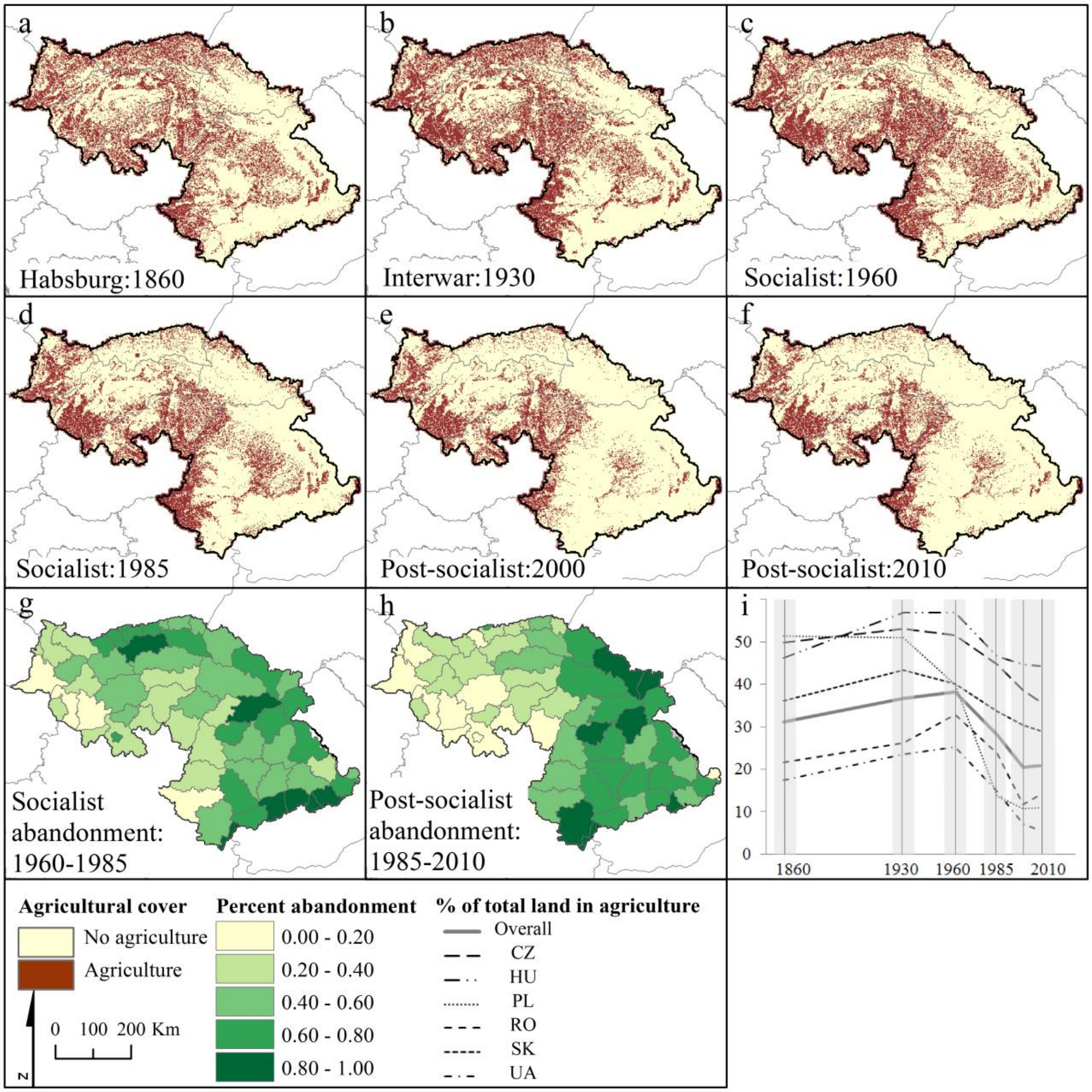


Figure 4.3 Model performance for distribution of agricultural land as a function of environmental variables during the Habsburg, socialist and post-socialist eras. Model performance is measured as AUC, where values close to 1 indicate high model performance.

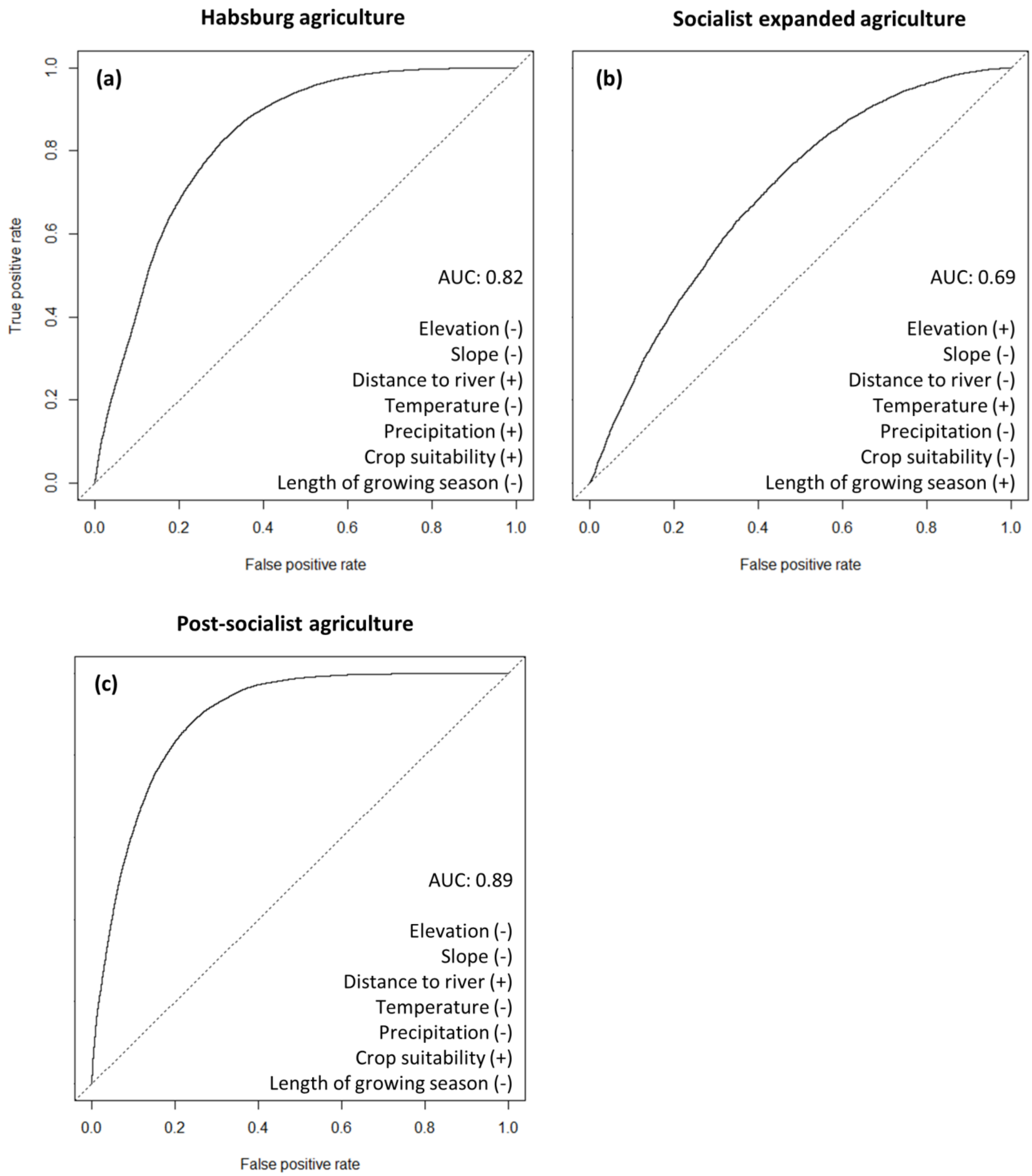
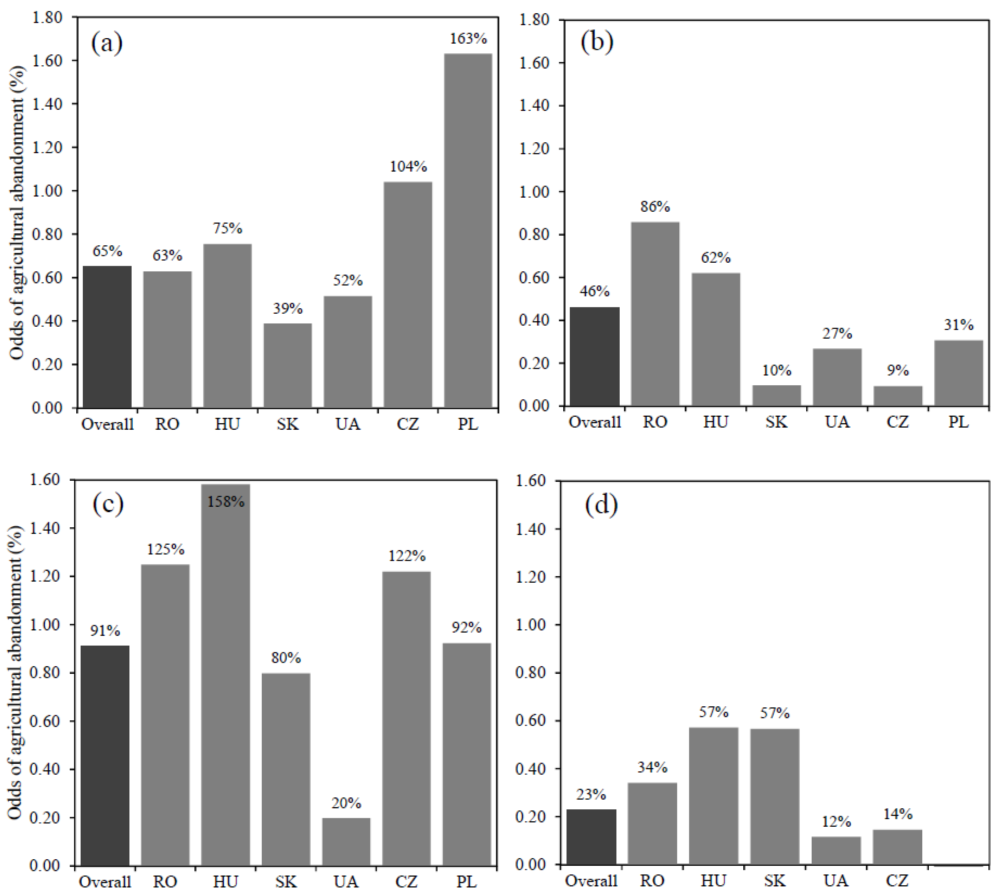


Figure 4.4 (a) and (b) Persistence of Habsburg land use legacies. Odds of (a) socialist and (b) post-socialist abandonment (in %) in areas that were not farmed by the Habsburgs in 1860, compared to areas farmed then. The odds of abandonment on land not farmed in 1860 were higher and the relationship was consistent across countries. For example, in Romania, the odds of socialist abandonment (a) were 63% higher in areas farmed in 1860, compared to areas not farmed then and the odds of post-socialist abandonment (b) were 86% higher. (b), (c) and (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.

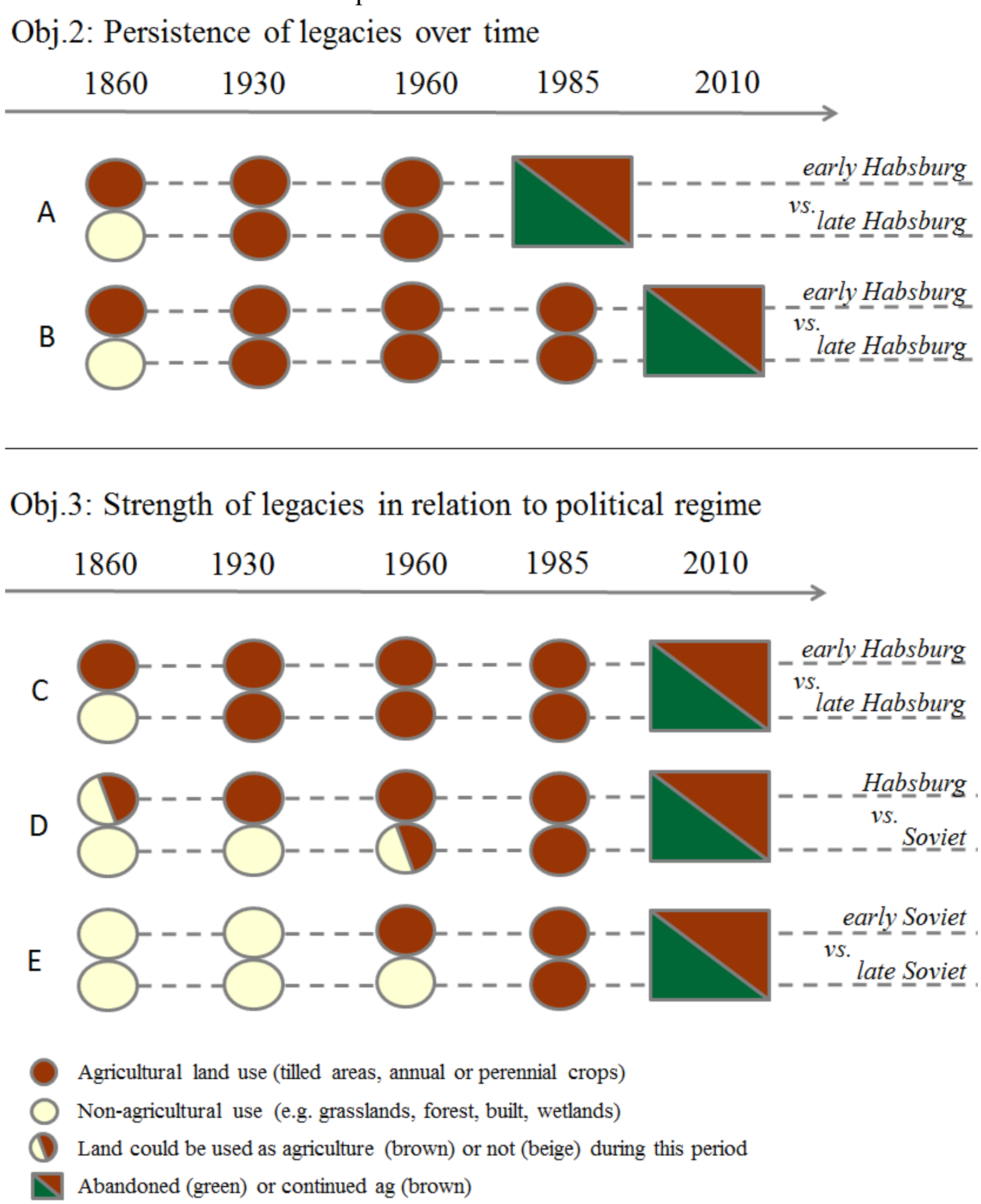


Appendix

Appendix 4.1 Map and remote sensing data sources used to map agricultural land cover in the Carpathians

Time layer	Data range of maps	Map scale/ resolution	Map source/ description
1860	1819-1873	01:28.8	Second Austrian Military Survey
	1864	01:57.6	Szathmari's Map/ Romania
1930	1919-1939	02:40.0	Maps of Wojskowy Instytut Geograficzny (WIG)
	1923-1938	01:20.0	Preliminary Beneš maps, Definitive Křovák maps
	1923-1945	01:25.0	Revised Third Military Survey, German
			topographic maps ("Messtischblatt", Karte der Slowakei, Karte der Tsechoslowakei)
	1940-1944	01:50.0	Topographic maps of Hungary
1960	1949-1983	1:50.000 and 1:25.000	Soviet and National Military Maps from the Cold War period
1985	1982-1987	30m	Landsat TM composite
2000	2003-2007	30m	Landsat TM/ ETM+ composite
2010	2008-2012	30m	Landsat TM/ ETM+ composite

Appendix 4.2. Study objectives: persistence and strength of land use legacies. For Obj. 1 we developed two models (A,B), both of which compared abandonment of 1930s agricultural land that was already farmed in 1860 with land that was not farmed then, and we modelled the effect of early versus late Habsburg agriculture on both A) socialist and B) post-socialist land abandonment.. For Obj. 2, we modelled the legacy effect of three periods, i.e., the C) Habsburg, D) Interwar and E) Socialist period, on post-socialist abandonment. Model C is identical to model B for objective 2. Model D compares land farmed at any point during the Habsburg era with land farmed at any time during the Socialist period. Model E refers to socialist agricultural expansion and compares abandonment on land farmed prior to 1960, i.e., during the early Socialist period, with land farmed after 1960 (i.e. late Socialist). Please see Table 1 for definitions of terms and time periods



Appendix 4.3. Dataset comparison for soil characteristics

Dataset 1: FAO Global agro-ecological zones

We used two variables to describe the suitability for agricultural production: the **crop suitability index** for low input level rain fed cereals and the **length of the growing season**. This dataset is available in a resolution of 30 arc seconds and is based on model output for the baseline 1961-1990. The modelled data for crop suitability is based on a water-balance model and climatic data such as radiation and temperature that affect crop productivity. Furthermore, the data includes reduction factors (such as pests or disease for each cereal crop) as well crop requirement data in terms of soil characteristics and conditions. Data ranges from 0-10000 where values higher than 5000 are considered good crop suitability by FAO. The length of growing period dataset refers to the number of growing period days and is calculated on the basis of average climatic parameters, including moisture supply from precipitation and soil moisture storage and reference evapotranspiration.

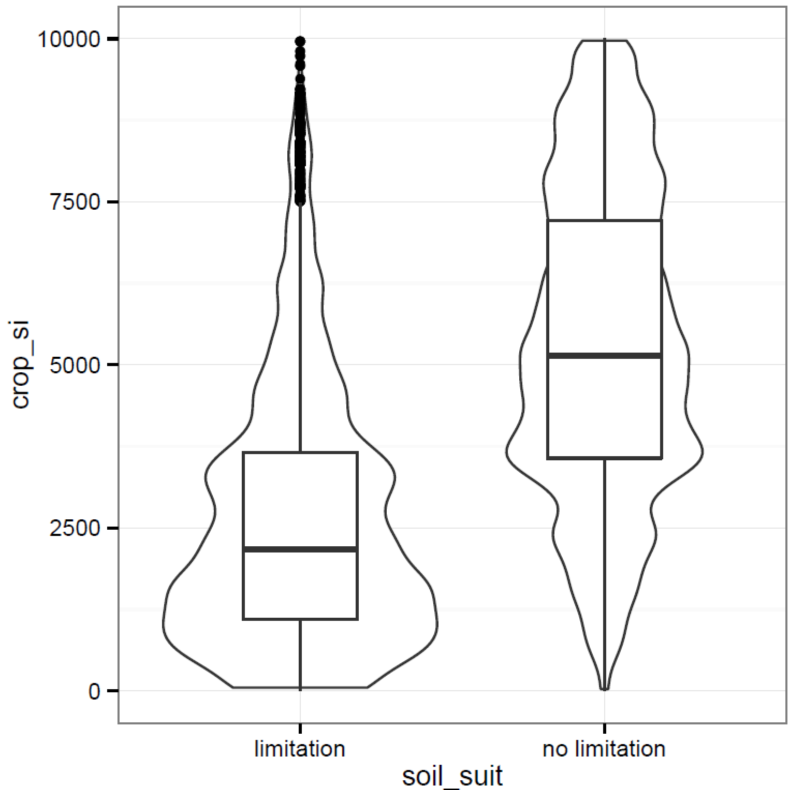
Data source: http://gaez.fao.org/Main.html#

Dataset 2: European Soil Database

The European Soil Database includes information on soil types and soil characteristics such as texture, water permeability at the level at soil topological units and is available at a spatial resolution of 1 km. The data is structured in categorical variables that each captures specific soil characteristics. The most relevant variables in this database to agricultural activity are the two most **important limitations to agricultural use** of the soil topological unit, which are available as categorical variables. We reclassified these variables in two classes: limitation/ no limitation to agricultural activity.

Data source: http://esdac.jrc.ec.europa.eu/content/european-soil-database-v20-vector-and-attribute-data

Based on the data content and resolution we decided to use Dataset 1 in all further analysis. The main advantages of this dataset include the more comprehensive assessment of suitability for agricultural production based on soil, climate and crops specific to the region and the fact that data is continuous. One potential disadvantage of this data is represented by the lower spatial resolution. We compared the two datasets, and found that overall, the Dataset 1 captures well the differences between the agricultural limitation groups of Dataset 2.



	Crop suitability	Limitation to agriculture	No limitation to agriculture
No obs.	69454	14872	54672
Mean	4730.73	2623.34	5302.72
Median	4547.00	2169.00	5134.00
STD	2531.06	1993.74	2352.37

T-test for two groups:

t = -139.4092

df = 27096.81
p-value < 2.2e-16

Appendix 4.4 Sample sizes for legacy persistence modelling

Socialist abandonment (1960-1985)		
	1860 Non-AG	**1860 AG**
Overall		**20501**
not abandoned	3013	10406
abandoned	2002	5080
ROMANIA		**6013**
not abandoned	924	3327
abandoned	577	1185
HUNGARY		**4114**
not abandoned	893	1956
abandoned	506	759
SLOVAKIA		**4586**
not abandoned	736	2407
abandoned	282	1161
UKRAINE		**1101**
not abandoned	169	378
abandoned	243	311
CZECH REPUBLIC		**2678**
not abandoned	248	1750
abandoned	160	520
POLAND		**2009**
not abandoned	43	588
abandoned	234	1144

Post-socialaist abandonment (1985-2010)		
	1860 Non-AG	**1860 AG**
Overall		**13419**
not abandoned	1988	7350
abandoned	1025	3056
ROMANIA		**4251**
not abandoned	355	1749
abandoned	569	1578
HUNGARY		**2849**
not abandoned	702	1666
abandoned	191	290
SLOVAKIA		**3143**
not abandoned	653	1988
abandoned	83	419
UKRAINE		**547**
not abandoned	40	91
abandoned	129	287
CZECH REPUBLIC		**1998**
not abandoned	213	1461
abandoned	35	289
POLAND		**631**
not abandoned	25	395
abandoned	18	193

Appendix 4.5 Sample sizes for strength of legacies in relation to political regimes

Habsburg legacy		
	1860 Non-AG	**1860 AG**
Overall		**13419**
not abandoned	1988	7350
abandoned	1025	3056
ROMANIA		**4251**
not abandoned	355	1749
abandoned	569	1578
HUNGARY		**2849**
not abandoned	702	1666
abandoned	191	290
SLOVAKIA		**3143**
not abandoned	653	1988
abandoned	83	419
UKRAINE		**547**
not abandoned	40	91
abandoned	129	287
CZECH REPUBLIC		**1998**
not abandoned	213	1461
abandoned	35	289
POLAND		**631**
not abandoned	25	395
abandoned	18	193

Habsburg vs. Socialist legacy		
	1930 Non-AG	**1930 AG**
Overall		**16843**
not abandoned	1496	9338
abandoned	1928	4081
ROMANIA		**5821**
not abandoned	372	2104
abandoned	1198	2147
HUNGARY		**3416**
not abandoned	396	2368
abandoned	171	481
SLOVAKIA		**3748**
not abandoned	451	2641
abandoned	154	502
UKRAINE		**901**
not abandoned	76	131
abandoned	278	416
CZECH REPUBLIC		**2283**
not abandoned	181	1674
abandoned	104	324
POLAND		**674**
not abandoned	20	420
abandoned	23	211

Socialist legacy

	1960 Non-AG	1960 AG
Overall		**3424**
not abandoned	934	562
abandoned	1084	844
ROMANIA		**1570**
not abandoned	153	219
abandoned	586	612
HUNGARY		**567**
not abandoned	228	168
abandoned	112	59
SLOVAKIA		**605**
not abandoned	340	111
abandoned	135	19

Socialist legacy (cont)

	1960 Non-AG	1960 AG
UKRAINE		**354**
not abandoned	40	36
abandoned	144	134
CZECH REPUBLIC		**285**
not abandoned	159	22
abandoned	89	15
POLAND		**43**
not abandoned	14	6
abandoned	18	5

Appendix 4.6 Model utility and performance (AUC) for three legacy models for the Carpathian region as a whole and by country

	Habsburg legacy	**Habsburg vs. Socialist legacy**	**Soviet legacy**
Overall	0.82	0.83	0.80
RO	0.76	0.75	0.68
HU	0.77	0.76	0.71
SK	0.81	0.81	0.80
UA	0.76	0.64	0.68
CZ	0.81	0.81	0.75
PL	0.71	0.72	0.91

Appendix 4.7 Variables selected in socialist abandonment models and sign of the coefficient indicating the direction of the effect

	Socialist abandonment (1960-1985)	Post-socialist abandonment (1985-2010)
Intercept	(-)	(-)
Historic agriculture	(-)	(-)
Slope	(+)	(+)
Precipitation	(+)	(+)
Crop suitability	(-)	(-)
Length of growing season	()	(+)
Distance to border	(-)	(-)
Distance to settlement	(-)	()
Country	(***)	(***)
AUC	0.787	0.82

Appendix 4.8 Variables selected in post-socialist abandonment models and sign of the coefficient indicating the direction of the effect.

	Habsburg legacy	Habsburg vs. Socialist legacy	Socialist legacy
Intercept	(-)	(-)	(-)
Historic agriculture	(-)	(-)	(-)
Slope	(+)	(+)	(+)
Precipitation	(+)	(+)	(+)
Crop suitability	(-)	(-)	(-)
Length of growing season	(+)	(+)	
Accessibility			(+)
Distance to border	(-)		
Distance to river			(+)
Population (1990)			
Country	(***)	(***)	(***)

Chapter 5. Bird conservation recommendations for the Carpathian Ecoregion in light of long-term land use trends and conservation responsibility

Introduction

European landscapes are changing rapidly due to agricultural intensification, reforestation and land abandonment (Estel et al., 2015; Levers et al., 2014; Munteanu et al., 2014). The resulting habitat loss (Newbold et al., 2015) and fragmentation (Jaeger et al., 2011; Jongman, 2002) make these changes a primary concern for biodiversity conservation (Balmford et al., 2002; Green et al., 2005). In Europe, bird populations are declining (Donald et al., 2001; Gregory et al., 2007). In agricultural systems the decline is caused by intensification and changes in the Common Agricultural Policy (Donald et al., 2002, 2001). Forest birds are in decline due to loss of nesting habitat and reduced forest health (Gregory et al., 2007). Grassland birds are also in decline due to agricultural activity, invasive species and habitat alteration (Busche, 1994; Skorka et al., 2010). However, there is also an opposite trend, where land use is becoming less intensive in some landscapes (Alcantara et al., 2013; Baumann et al., 2011), offering opportunities for habitat recovery (Ceaușu et al., 2015a; Navarro and Pereira, 2012). Local increases of some forest birds have occurred in Eastern Europe in response to habitat recovery (Reif et al., 2008). When land use becomes less intensive, the question for conservation is whether it is better to support natural succession (Navarro and Pereira, 2012) or maintain low-intensity land use practices, which can have conservation benefits in their own right (Fischer et al., 2012). This trade-off among different conservation goals is particularly relevant in regions with widespread agricultural land abandonment.

Globally, intensifying land use is threatening species habitat and survival, leading to questions about whether preserving intact tracts of habitat or supporting extensive agriculture may benefit biodiversity more (Fischer et al., 2014; Grau et al., 2013; Phalan et al., 2011). Areas where low-intensity agriculture has been practiced for extended periods of time are considered ideal for wildlife-friendly farming (Hartel et al., 2013; Mikulcak et al., 2013; Plieninger et al., 2006), because these landscapes preserve high levels of farmland diversity (Kleijn et al., 2009; Tscharntke et al., 2012). On the other hand, if high-yield farming in one place can facilitate the protection of remaining natural habitats such as contiguous tracts of forest elsewhere, conservation benefits may he high (Phalan et al., 2011). In most regions where land use is intensifying, a combination of these strategies may be most appropriate.

Overall, in landscapes with decreasing land use intensity, it may be beneficial for conservation to pay farmers to forgo intensive land use practices, and retain traditional farming practices. However, retaining such practices may not be best for conservation when the alternative is natural succession and rewilding (Navarro and Pereira, 2012). Indeed, remote regions of Europe, such as the Carpathian Mountains, have been suggested for rewilding, due to their high rate of land abandonment, contiguous forest ecosystems, high mammal and avian biodiversity and unique presence of large carnivore and herbivore species (Ceaușu et al., 2015a, 2015b; Navarro and Pereira, 2012). The question is though whether rewilding, which could greatly benefit forest species, should be the goal for conservation given the trade-off of a likely loss of habitat for farmland species.

The question of what conservation goals are effective in places with decreasing land use intensity is not theoretical. The European Union supports substantial programs for biodiversity conservation, and they include both preserving low-intensity, high-natural-value farmland via agri-environmental payments (€4.44 bln/ year between 2007-2012) (European Court of Auditors, 2011) and protecting species and habitats under the Natura 2000 conservation program (estimated €5.80 bln/ year in 2012) (The European Comission, 2014). Yet these efforts are rarely allocated considering long-term habitat dynamics for species of high conservation responsibility in a given geographical region (Keller and Bollman, 2004; Schmeller et al., 2012, 2008). Historical land uses can affect ecosystem structure, functioning and ultimately biodiversity levels (Brudvig et al., 2013; Dullinger et al., 2013; Plue et al., 2009). Furthermore, land use legacies can restrict the pace at which contemporary land change is possible (Munteanu et al., 2015b), which may reduce the effectiveness of agri-environmental payment schemes. Given a species' proportional distribution, population trends, available habitat and conservation status, certain regions may carry higher conservation responsibility than others for conserving the species' global population (Keller and Bollman, 2004; Keller and Bollmann, 2001). This information is essential for making conservation decisions, such as allocating agri-environmental payments towards regions which carry high conservation responsibility for farmland species.

Empirical evidence suggest that bird populations in Eastern Europe are declining at slower rates than in Western Europe (Gregory et al., 2007; Skorka et al., 2010; Verhulst et al., 2004), likely due to lower intensity land uses compared to the rest of Europe (Gregory et al., 2007). This means that Eastern Europe may be a future hotspot for bird diversity conservation. However, the historical landscape context and the conservation responsibility of the Carpathians at broad spatial scales remain largely unexplored, leading to potentially ill-informed conservation actions.

Our overarching goal was to provide conservation recommendations for the Carpathian Mountains, based on historical and recent habitat trajectories for species of highest conservation responsibility at the European level. Specifically, we asked:

1) How did habitat for different bird species change in the Carpathian Mountains over the past 150 years?

2) For which of the bird species do the Carpathians carry the highest conservation responsibility at the European level?
3) What bird conservation strategies should be pursued, and what future land use trends would be most desirable for bird conservation in the Carpathians?

Methods

Study area

We studied the Carpathian Ecoregion (207,309 km^2) which is the largest mountain range and a conservation hotspot in Europe due to its valuable forest ecosystems (Knorn et al., 2012a), diverse cultural landscapes (Kozak et al., 2013b) and high levels of biodiversity (Akeroyd and Page, 2011; Kuemmerle et al., 2010; Pereira and Navarro, 2015). The Carpathians are part of six European countries, and experienced numerous shifts in land use over the last century, due to major changes in socio-economic and political conditions (Munteanu et al., 2015b). Increasing forest cover and agricultural abandonment were the most prominent changes over the past century (Munteanu et al., 2014). The contemporary land cover consists of forests (58%), agricultural fields (9%), grasslands (30%), and scattered settlements (Figure 5.1 A). Historically, forest cover experienced its lowest extent during the 1930s (46% of the Carpathians) and agricultural use was highest during the 1960s (27% arable land). The main agricultural crops are cereals (wheat, corn, barley) and legumes (potatoes, sugar beets), and they are mostly scattered across the landscape as small subsistence farms (Griffiths et al., 2013b). Grasslands consist mostly of pastures, hay meadows and wooded pastures, and preserve a high level of biodiversity due to their low intensity use (Akeroyd and Page, 2011; Halada et al., 2008; Hartel et al., 2013). Despite high forest disturbance followed by spruce plantings during and after the Socialist regime (Griffiths et al., 2014; Munteanu et al., 2015b), tree species diversity is high in the

Carpathians. At low elevation, deciduous woodlands (Quercus sp, Fagus sylvatica, Carpinus betulus, Populus sp, and Robinia pseudoaccaia) are common. At high elevations, coniferous forests are dominant (Pinus sp, Picea abies, Abies alba) (Munteanu et al., 2015b). The Carpathians have an increasing network of protected areas, some of which are aimed at conserving habitat for bird species (Natura 2000), with highly variable effectiveness (Butsic et al., 2015b).

Data

We analyzed species range maps for 252 bird species (BirdLife International and NatureServe, 2014), and their attributes including IUCN Red List status, population trend at European level from 1990 to 2000, European level threats to the populations survival, and major habitat (i.e., the primary habitat used by the species for breeding or feeding; Birdlife International 2016). Habitat data was available for 170 species. We reconstructed available forest, grassland and agricultural land use throughout the Carpathian Ecoregion for six points in time: 1860, 1930, 1960, 1985, 2000 and 2010. We used a regular 2-km point sampling grid (Gallego and Delince´, 2010; Munteanu et al., 2015b) and assigned one of the three cover types to each point for each year. We obtained land use data for the 1860s, 1930s and 1960s from historical topographic maps (Munteanu et al., 2016a, 2015b) and land cover data for the years 1985, 2000 and 2010 from classified Landsat TM/ETM+ image composites (Griffiths et al., 2014, 2013b). In total, we had 51,648 data points. Due to low accuracy of historic maps in parts of Romania and Hungary, for a total of 3,409 points, we could not distinguish agricultural from grassland land use for the 1860s. For these points, we assigned the 1930s land use class for the 1860s as well (Munteanu et al., 2016a). For comparability, we reclassified the major habitat data for each species (BirdLife

International and NatureServe, 2014; Birdlife International, 2016) into three categories that matched our long-term land cover data: agriculture, grasslands and forests.

Analysis

To determine the change in available habitat for each bird species, we analyzed data points that matched the spatial extent of each species' range with the species major habitat types. For each of the 170 species, we mapped available habitat for the years 1860, 1930, 1960, 1985, 2000 and 2010 (Figure 5.2, A, B) Although several species use other habitats as their major habitat (such as wetlands or open water), this land use data were not available for all time periods, which is why we did not include these habitat types in our spatial analysis, and assumed they do not influence the overall trend because they only make up a small part of the landscape.

To determine the conservation responsibility of the Carpathians for each species, we considered three criteria: a) if a species had a high proportion of its European range in the Carpathians, b) if a species had an IUCN conservation status of vulnerable (VU), near threatened (NT), endangered (EN) or critically endangered (CR) and c) if a species' population declined at the European level from 1990 to 2000. We assumed that the proportional distribution of a species is a proxy for the relative importance of the region for the species viability (Keller and Bollman, 2004; Schmeller et al., 2008). Because the Carpathian Mountains make up 3.106% of the total European landmass (excluding European Russia), we considered values less than 3.106% as low and values higher than 3.106% as a high proportion of the species European range being located in the Carpathians (Figure 5.1. B,C,D,E). We gave special consideration to species with more than 6.212% of their range in the Carpathians, following prior studies for the Alps (Keller and Bollman, 2004; Keller and Bollmann, 2001). We checked if the range distribution captures well the species use of habitat within its range and calculated proportional distribution stratified by land use types, but found no substantial differences (Appendix 5.1) By combining the proportion range information with the IUCN conservation status and the population trend at European level, we defined classes of conservation responsibility for the Carpathians (Appendix 5.2). Species with high percentage of their range in the Carpathians, IUCN status of concern, and/or declining population at European level, represent species of high conservation responsibility in the Carpathians Ecoregion.

To understand which habitat types are important for the high conservation responsibility species, we analyzed the percentage of the species' European range within the Carpathians by major habitats types, in relation to the 3.106% and 6.212% thresholds. If a species used more than one habitat type, we included it in the analysis of both habitats. For the species of high conservation responsibility we summarized all data points representing available habitat within their range, and analyzed changes in habitat over time.

To understand what conservation strategies could be pursued to ensure the conservation of high responsibility species in the Carpathians, we reviewed the species threats at European level in relation to species historic available habitat. Descriptions of the major threat classes for each species were available from the IUCN Red List and Birdlife International (BirdLife International and NatureServe, 2014). If a listed threat affected the species habitat at European level, but was not present in the Carpathians, we assumed that the region could make a substantial contribution to the conservation of that species. Finally, we identified land management options that could minimize the number of threats for the high conservation responsibility species in the Carpathians.

Results

We found that available forest and grassland habitat increased substantially since 1860 within the ranges of all Carpathian species, and that agricultural habitat declined after 1960. We also found that of all species present there, the Carpathians carry high conservation responsibility for forest and grassland birds and no conservation responsibility for birds that rely on agriculture. The main threats at European level for the species of high conservation responsibility were agricultural intensification and natural system modification. Because agricultural land declined substantially in our study region since the 1960s, we suggest that there is a high potential for conservation of these species in the Carpathians.

When analyzing the changes in available habitat for all 170 species between 1860 and 2010, we found that 39% of all species used forest as their major habitat, 27% grasslands, and only 2% (4 species) agriculture (Figure 5.2). Overall, we observed a general increase in grassland and forest habitats, and a decrease in agricultural habitat (Figure 5.2). For example, the Ural owl (*Strix uralensis)* is a forest specialist, and the available habitat within its Carpathian range increased from 48% of its range in 1860 to 58% of its range in 2010 (Figure 5.2. A). Similarly, the Pallid harrier (*Circus macrourus*) is a grassland specialist, for which despite an initial decline, the available grassland habitat increased from 25% in 1860 to 33% in 2010 (Figure 5.2. B).

To identify for which species the Carpathians carry high conservation responsibility, we compared the proportion of the species range in the Carpathians with the proportion of the Carpathians in European territory (3.106%). Our results indicated that for 67% of the species, the proportion of their Carpathian range is higher than the 3.106% threshold. Furthermore, for 7% of all species (19 species) the Carpathians made up more than 6.212 % of their European range. Most of these species were either forest or grassland specialists, and none relied on agricultural fields (Figure 5.3).

Of the 252 bird species present in the Carpathians, 16 species were IUCN Red listed as either vulnerable (VU), near threatened (NT), critically endangered (CR), or endangered (EN). When analyzing the European level population dynamics between 1990 and 2000 for the 252 species, we found that 33.7% (85 species) declined at European level. Of these, 55 had a high percentage of their range in the Carpathians, and 12 were of conservation concern (VU or NT) (Table 5.1).

Overall, we identified 29 species of high conservation responsibility according to the proportion of their habitat in the Carpathians, their population trend, and their IUCN red list status (Table 5.1 and Appendix 5.3). Most of the 29 high conservation responsibility species require forest habitats (13 species), followed by grasslands (11), and other habitats (including wetlands, water and settlement areas, 9 species). Because we could not reconstruct wetland change over the entire period, and water areas were relatively stable, these were excluded from our further analysis, as were species with unknown habitat (total of 9 species).

When analyzing the dynamics of available habitat for the species of high conservation responsibility, we found for all species an overall increase in available habitat since 1860, and particularly after 1960. The grassland species registered small declines in available habitat since 2000, due to grassland conversions (Figure 5.4). Of the species of high conservation responsibility in the Carpathians, the Eastern imperial eagle *(Aquila heliaca)* the lesser spotted eagle (*Clanga pomarina*), collared flycatcher (*Ficedula albicollis*), ring ouzel (*Turdus torquatus*), and red kite (*Milvus milvus*) require forest and grassland habitat for their survival, the rest were either forest (8 species) or grassland specialists (7 species).

When analyzing the major threats at the European level to the species of high conservation responsibility, we found that the most frequent threats were related to agriculture and aquaculture, and natural system disturbance (Figure 5.5). Farming, grazing and wood extraction were the most frequently cited threats. Of 29 species, twelve were threatened by agricultural intensification and herbicide use, two by wood harvesting, and for thirteen species, no information on threats was available. Lesser grey shrike (*Lanius minor*), snow bunting (*Plectrophenax nivalis*) and ring ouzel were more affected by climate change than by habitat change.

Discussion

Regions where land use intensity is decreasing, such as the Carpathians, may offer opportunities for conservation. But, the question is whether conservation efforts should aim for restoring forest habitats or for the maintenance of low-intensity land use, and traditional agricultural practices. The answer to this question requires the consideration of long-term habitat dynamics and the conservation responsibility of a given region for the populations at large (Keller and Bollmann, 2001; Schmeller et al., 2012). Here, we assessed long-term habitat dynamics for bird species in the Carpathians, and identified high conservation responsibility species. We found that the species of highest conservation responsibility were those that require forest and grassland habitat for their survival, not agriculture. For these species, available habitat increased since the 1860s, despite the European level threats, suggesting that the region could become a conservation stronghold for these species as long as other threats remain in check.

Our results suggest that conservation action should be directed towards forest specialists and forest generalist species, including several woodpeckers, the Ural owl, and the hazel grouse. We caution though that the conservation of forest birds will depend greatly on the type of forests, and their structure. Most forest species require structurally heterogeneous forests for survival. For example, the Oral owl requires contiguous forest with a high proportion of deciduous and old trees (Kajtoch et al., 2015), the hazel grouse require dense understory and alder (Åberg et al., 2003; Schaublin and Bollmann, 2011) and most woodpeckers prefer old trees and snags (Lõhmus, 2003; Roberge et al., 2008). Because woodpeckers are great indicators for forest bird diversity in Eastern Europe (Mikusiński et al., 2001), conserving these high responsibility species will likely benefit many other species in the Carpathians.

Although the Carpathians are one of the last strongholds of old-growth forests in Europe (Kozak et al., 2013b; Munteanu et al., 2015b), and available habitat for forest species has increased since 1860s, intense forest harvest has diminished old-growth forests (Knorn et al., 2012a; Munteanu et al., 2016b). Forest composition shifted towards coniferous forests since the 1860s due to large-scale clear-cuts and spruce and pine monocultures (Griffiths et al., 2014; Munteanu et al., 2015b). These changes likely affect the use of available habitat for high conservation responsibility species. Forest management should thus aim not just at restoring forest cover, but also tree species and structural diversity.

Four species in our analysis require both woodland plus either grassland or wetlands. The increase in habitat availability that we found since 1860s for the Eastern imperial eagle, coincides with population recoveries in Slovakia, Hungary, and the Czech Republic (Demerdzhiev et al., 2011) after the late 19th and early 20th century (Salmen, 1980). The biggest European-level threats to the Eastern imperial eagle are agricultural intensification and natural habitat loss, which caused substantial population declines in Greece (Hallmann, 1996). But, we suggest that the region is well suited for the protection this species because in the Carpathians, agricultural abandonment is widespread and large-scale agriculture is uncommon. Red kites, lesser spotted eagles, and collared flycatchers have similar habitat requirements and threats as the imperial eagle. In our study region, the Transylvanian plain could represent highly suitable landscape for these species due to it being a mosaic of woodlands and open grasslands (Fischer et al., 2012; Hartel et al., 2013).

Our results suggest that grassland birds should also be a focus of conservation actions in the Carpathians. Although grassland species like the corn crake, lesser grey shrike, and ring ouzel are declining across Europe, their available habitat in the Carpathians increased since 1860. The historic changes we found in available habitat for these species are confirmed by historic population trends. For example, the corn crake uses managed and unmanaged grasslands and riverine floodplains (Elts, 1997), and its populations declined in the Carpathians after early 1900s, when agricultural expansion started in Transylvania (Salmen, 1980). The decline persisted until the middle of the 20th century (Salmen, 1980) consistent with our available habitat trends. The ring ouzel uses grassland and shrubby vegetation for nesting (Sim et al., 2007).

One reason why the Carpathians provide more habitat for so many forest and grassland species is the agricultural abandonment that followed the collapse of the collective farming system and the removal of subsidies received under socialist regimes (Griffiths et al., 2013b; Hartvigsen, 2014; Kuemmerle et al., 2008). At the European level, the majority of the threats to the Carpathians' species of conservation responsibility are related to agricultural intensification, and herbicide use. But agricultural expansion, intensification or pesticide use are not widespread in the Carpathians, despite some re-cultivation in the lowlands (Griffiths et al., 2013b).

Overall, three broad conservation messages emerge from our analysis: 1) The Carpathians carry great conservation responsibility for forest and grassland species, and hence, conservation efforts should focus on these species and their habitats. 2) The conservation responsibility of the Carpathians for agricultural species is very low, which is why we suggest that cropland abandonment is a positive trend in the Carpathians, as long as grasslands persist. 3) The observed increase in potential habitat provides a great opportunity for conservation, but conservation efforts must ensure that forest diversity and structural elements such as dead wood and snags are maintained.

Ultimately, we suggest that maintaining both forested areas and grasslands in the Carpathians would be best for bird conservation in the Carpathians, but supporting row-crop agriculture is not (Appendix 5.4). Forested areas could be mostly located at higher elevations and would benefit other species in isolated regions (Pereira and Navarro, 2015). Grasslands could be maintained in Transylvania and in the larger river valleys, where wildlife-friendly livestock grazing could contribute to the conservation of grassland species (Hartel et al., 2013; Mikulcak et al., 2013). In addition to birds, grassland conservation would benefit other taxa with high species richness in the Carpathians, like plants and butterflies (Cremene et al., 2005; Loos et al., 2014; Schmitt and Rákosy, 2007). We see the current land change trends in the Carpathians as a positive one, and see little justification for EU subsidies for row-crop farming from a bird conservation perspective. Decreasing land use intensity provides great opportunities for conservation in the Carpathians, but the approach that we developed here could easily be applied for other regions and other taxa to inform conservation action.

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Tables and figures

Table 5.1 Species of high conservation responsibility in the Carpathians, and their selected species characteristics. Only species marked (y) in the habitat dynamics column were considered in our available habitat dynamics. For the rest of the species, habitat information was missing.

Scientific name	Common name	Order	Family	European trend*	% range in Carpathians	IUCN Red List Status	Major habitat*	Habitat dyna-mics
Bombycilla garrulus	Bohemian Waxwing	Passeriformes	Bombycillidae	SF	6.54%	LC	F	y
Nucifraga caryocatactes	Spotted Nutcracker	Passeriformes	Corvidae	SF	10.13%	LC	F	y
Miliaria calandra	Corn Bunting	Passeriformes	Emberizidae	D	20.56%	LC	NA	n
Plectrophenax nivalis	Snow Bunting	Passeriformes	Emberizidae	SF	6.60%	LC	G	y
Lanius minor	Lesser Grey Shrike	Passeriformes	Laniidae	D	6.82%	LC	G	y
Ficedula albicollis	Collared Flycatcher	Passeriformes	Muscicapidae	I	11.73%	LC	FG	y
Tichodroma muraria	Wallcreeper	Passeriformes	Sittidae	SF	11.62%	LC	NA	n
Acrocephalus paludicola	Aquatic Warbler	Passeriformes	Sylviidae	D	5.37%	VU	O	n
Sylvia nisoria	Barred Warbler	Passeriformes	Sylviidae	NA	6.30%	LC	F	y
Turdus torquatus	Ring Ouzel	Passeriformes	Turdidae	SF	9.45%	LC	FG	y
Aquila heliaca	Eastern Imperial Eagle	Accipitiriformes	Accipitridae	SF	8.09%	VU	FG	y
Circus macrourus	Pallid Harrier	Accipitiriformes	Accipitridae	D	6.16%	NT	G	y
Clanga pomarina	Lesser Spotted Eagle	Accipitiriformes	Accipitridae	NA	6.78%	LC	FG	y
Milvus milvus	Red Kite	Accipitiriformes	Accipitridae	D	6.13%	NT	FG	y
Anser erythropus	Lesser White-fronted Goose	Anseriformes	Anatidae	D	6.39%	VU	O	n
Aythya nyroca	Ferruginous Duck	Anseriformes	Anatidae	D	5.31%	NT	O	n
Gallinago media	Great Snipe	Charadriiformes	Scolopacidae	D	4.36%	NT	G	y

Scientific name	Common name	Order	Family	European trend	% range in Carpathians	IUCN Red List Status	Major habitat*	Habitat dyna-mics
Limosa limosa	Black-tailed Godwit	Charadriiformes	Scolopacidae	D	3.42%	NT	G	y
Numenius arquata	Eurasian Curlew	Charadriiformes	Scolopacidae	D	3.20%	NT	O	n
Coracias garrulus	European Roller	Coraciiformes	Coraciidae	D	5.70%	NT	G	y
Falco cherrug	Saker Falcon	Falconiformes	Falconidae	D	3.74%	EN	O	n
Falco vespertinus	Red-footed Falcon	Falconiformes	Falconidae	D	4.85%	NT	NA	n
Bonasa bonasia	Hazel Grouse	Galliformes	Phasianidae	I	8.22%	LC	F	y
Crex crex	Corncrake	Gruiformes	Rallidae	SF	6.85%	LC	G	y
Dendrocopos syriacus	Syrian Woodpecker	Piciformes	Picidae	D	8.53%	LC	NA	n
Leiopicus medius	Middle Spotted Woodpecker	Piciformes	Picidae	NA	6.77%	LC	F	y
Picoides tridactylus	Three-toed Woodpecker	Piciformes	Picidae	NA	8.01%	LC	F	y
Picus canus	Grey-faced Woodpecker	Piciformes	Picidae	SF	7.27%	LC	F	y
Strix uralensis	Ural Owl	Strigiformes	Strigidae	SF	12.84%	LC	F	y

** D=decline, I=increase, SF = stable or fluctuating, NA = unknown*
***F=forest, G=grassland, FG=forest and grassland, O=Other, NA=unknown*

Figure 5.1 A. The Carpathian Ecoregion in Eastern Europe and land cover types in year 2010. Country codes AT: Austria, PL: Poland, SK: Slovakia, HU: Hungary, UA: Ukraine, RO: Romania. B. European range map of Ural owl (Strix Uralensis). As much as 12.84% of the owl range falls within the Carpathians (D), making this a high responsibility species. C. European Range map of great bustard (Otis tarda). Only 1.03% of the bustard range falls within the Carpathians (E), making this a low responsibility species.

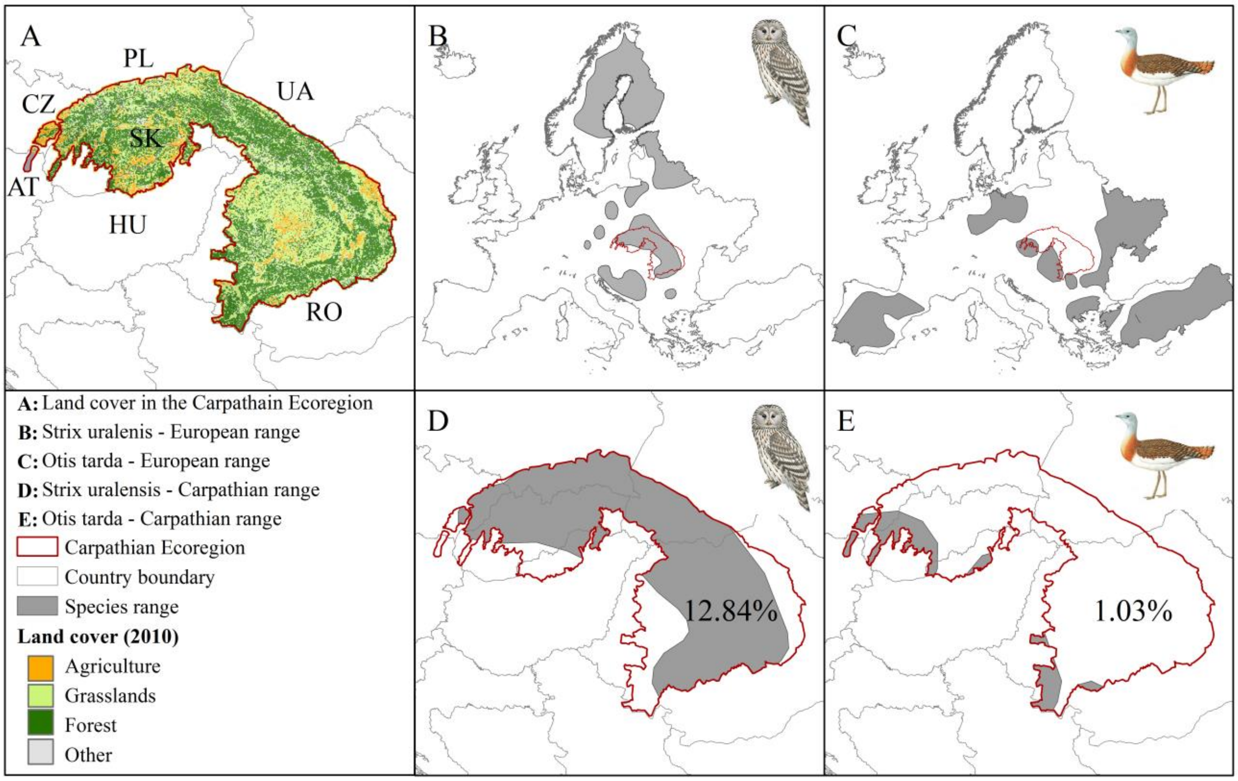


Figure 5.2 A. Change in available habitat (dark greu) for the Ural owl (Strix uralensis) between 1860 and 2010. Species range is shown in light gray. B. Change in available habitat (dark grey) for the pallid harrier (Circus macrourus) between 1860 and 2010. Species range is shown in light gray. C. Change in agriculture, grassland and forest available habitat for all species present in the Carpathians, by major habitat used. Double counting is possible if a species uses more than one habitat. Dynamics of other habitat types such as wetland or water are excluded.

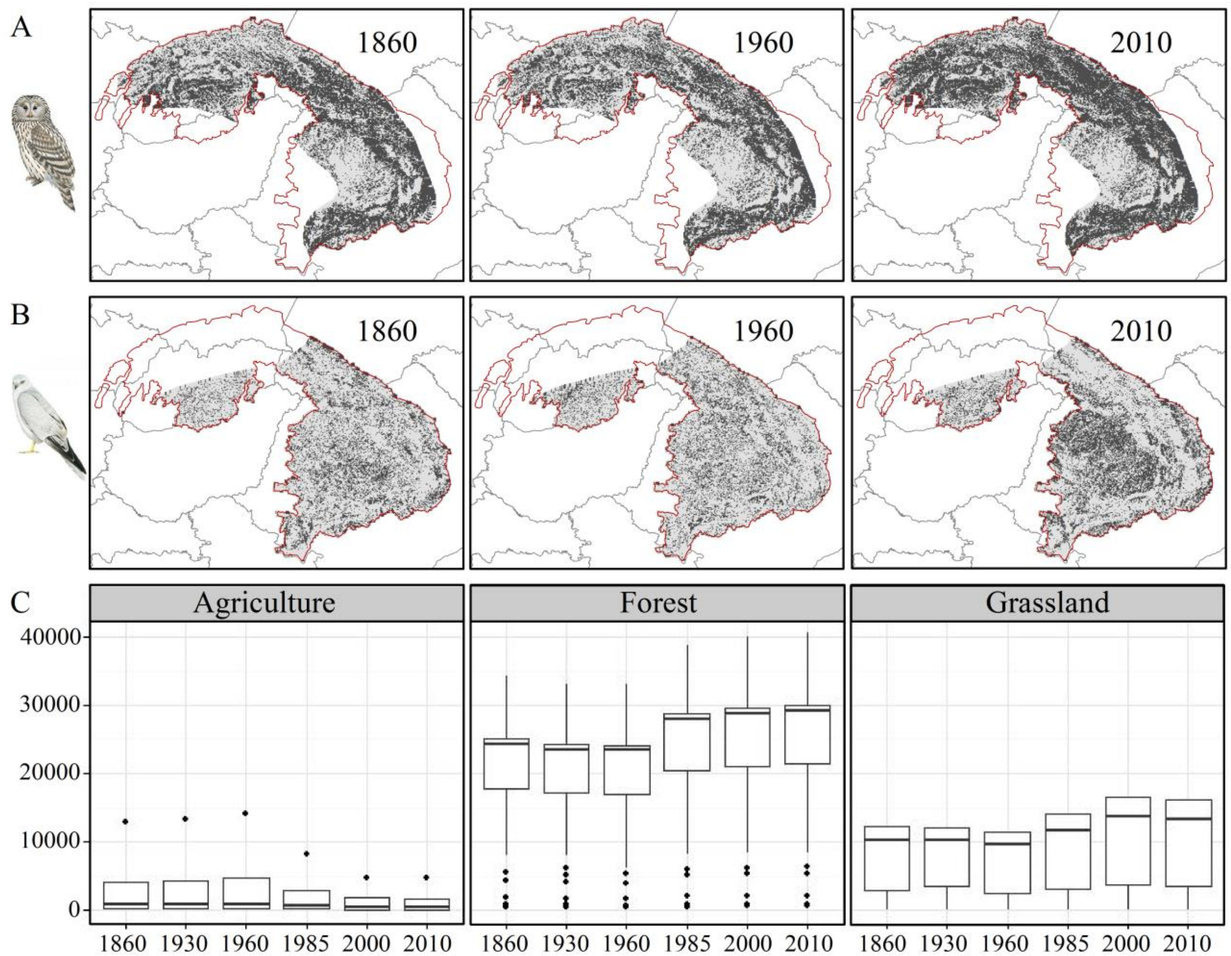


Figure 5.3 Percentage of European range (x-axis) in the Carpathians for 170 species, by different habitat types (y-axis). Each dot represents a species associated with the respective habitat type. If a species used more than one habitat type, double counts are possible. Percentages are shown in relation to the 3.1% threshold (proportion of Carpathians from total European territory) and the doubled value (6.2%).

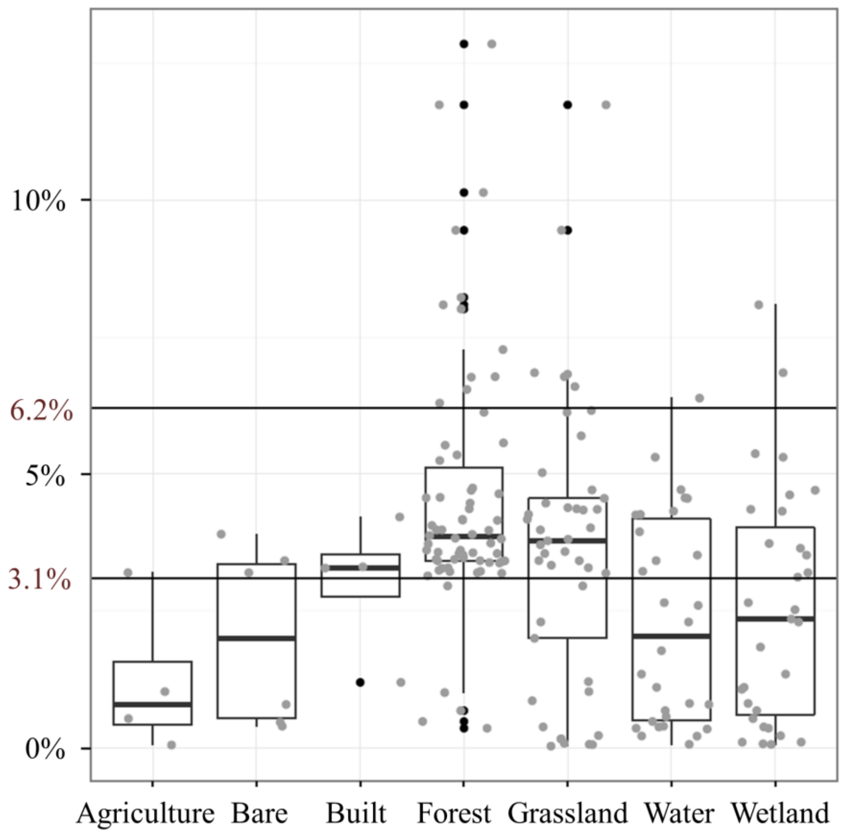


Figure 5.4 Changes in available habitat for species of high conservation responsibility, by major habitat used.

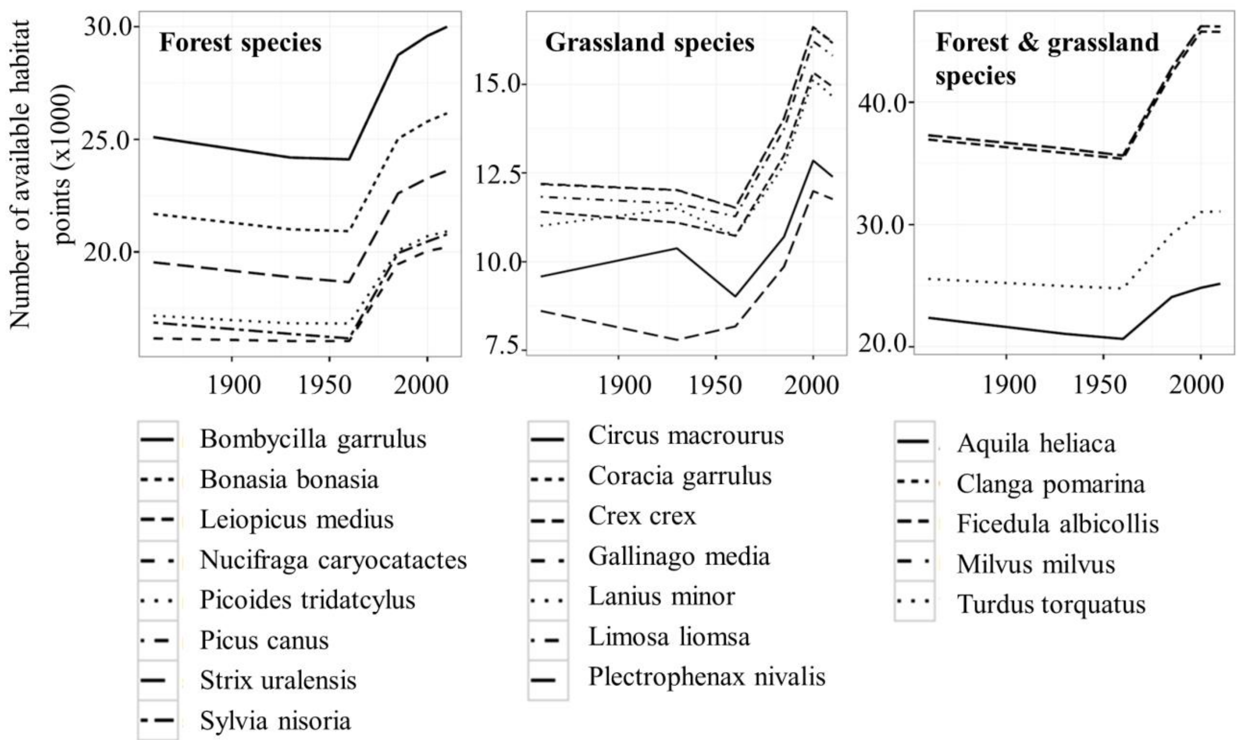
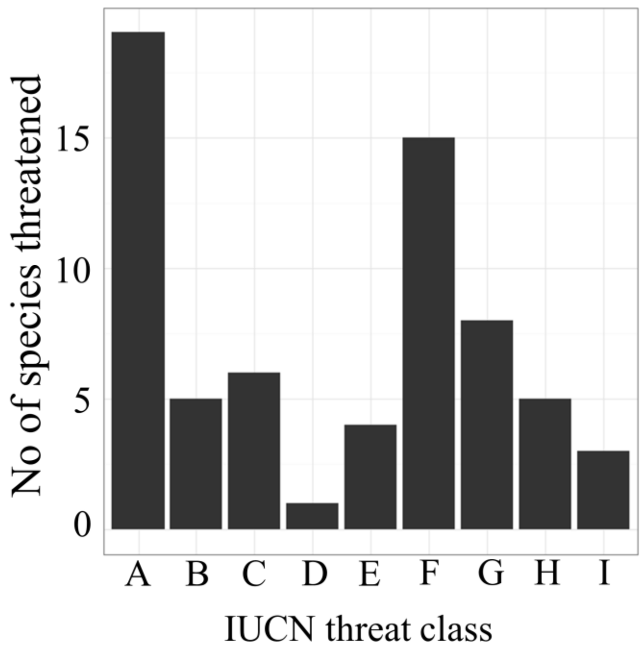


Figure 5.5 Major threats to the species of high conservation responsibiltiy as listed by IUCN. The x-axis represents how many species of high conservation responsibility in the Carpathians are affected by each threat class.



A: Agriculture
B: Biological resource use
C: Climate change and weather
D: Energy production and mining
E: Invasive species and disease
F: Natural system modification
G: Pollution
H: Residential and commercial development
I: Transportation

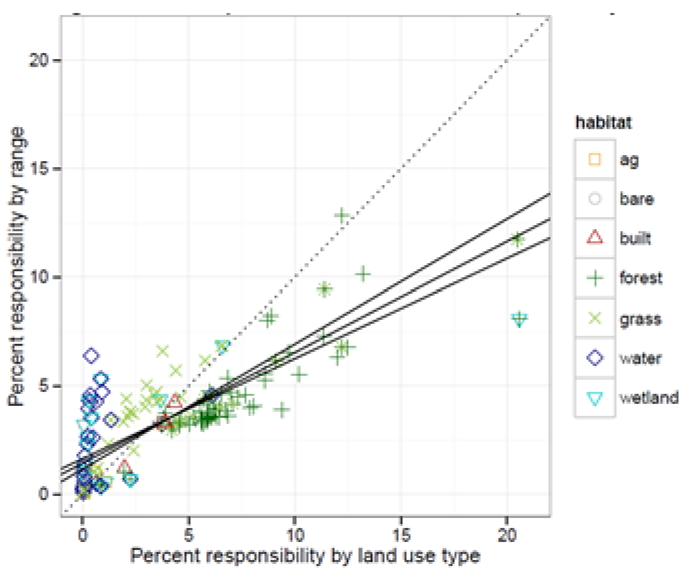
Appendix

Appendix 5.1 Conservation responsibility comparison

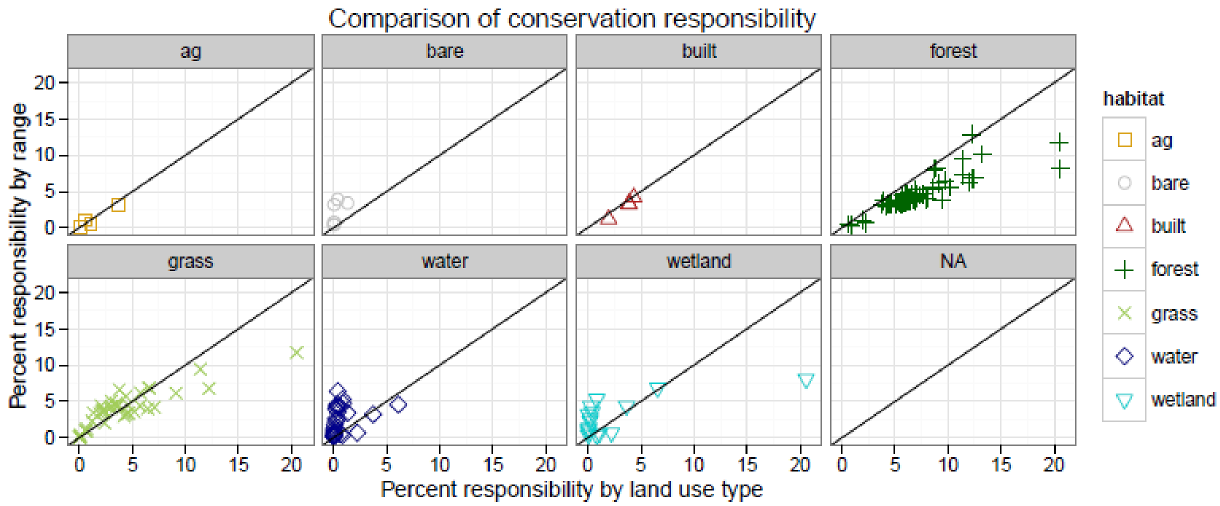
To calculate conservation responsibility *based on range distribution*, for each species we calculated the percent range located in the Carpathians.

To calculate conservation responsibility *based on major land use types*, we first determined the major habitat type for each species (ag, forest, grass, wetland, water, bare) and calculated the percentage of all Carpathian habitats that a species uses from the total used habitats in the European range of the species.

We plotted the relationship of percent responsibility based on the range against the percentage responsibility based on habitat types. We found a correlation of 0.78 between datasets and that overall the percentage responsibility based on range would underestimate the importance of the Carpathians for the species (if using land use stratification). This means that estimates of responsibility based on range are overall conservative.



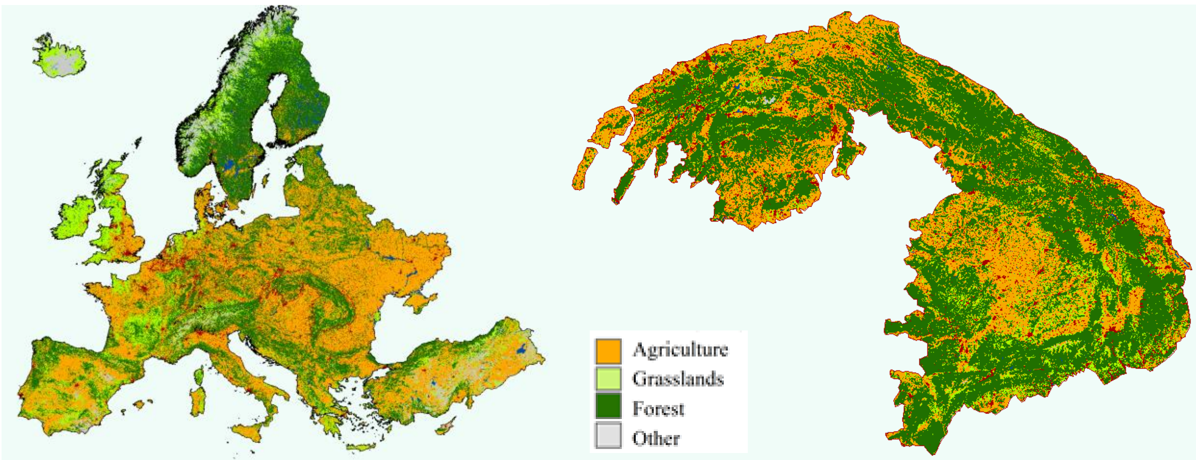
When analyzing how well the range responsibility is indicative of major habitat we found that for that for agricultural and built areas, the relationship is strong. For forest species, the range estimates are conservative while water and wetland species importance in the Carpathians may be overestimated when using range estimates. Estimates for grassland species when using range distribution and habitat stratification are similar.



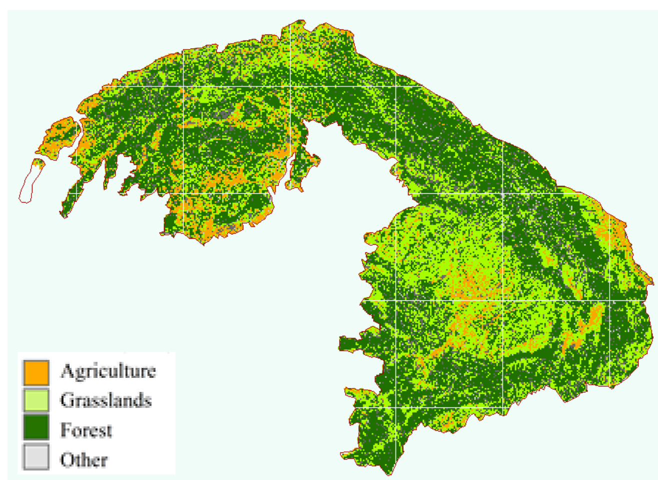
For species located below the 1:1 line, using the range responsibility is a conservative measure, which underestimates the conservation responsibility of the Carpathians. For species located above the line, the conservation responsibility is mostly overestimated when using range distribution. This is mostly the case for water and wetland birds, but because accurate wetland data is missing for our historic dataset, we did not consider these species in the further analysis.

Appendix 5.2 Land use datasets comparison

For the estimation of responsibility based on *based on major land use types* we used Climate Change Initiative Land Cover (CCI Europe) 2010 dataset (map below) available at http://maps.elie.ucl.ac.be/CCI/viewer/index.php.

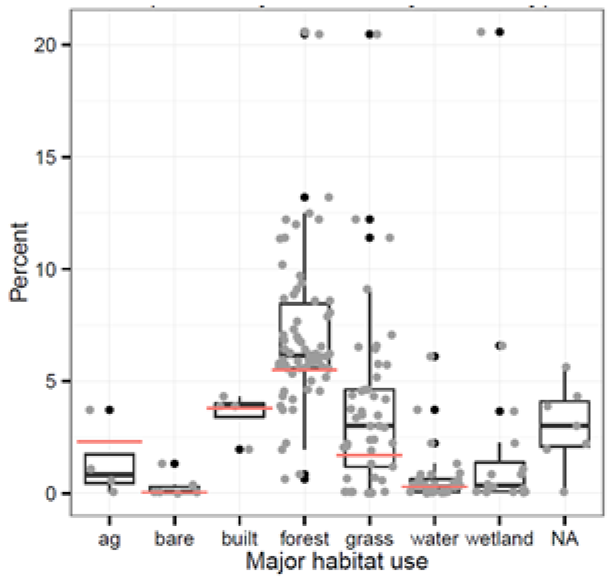


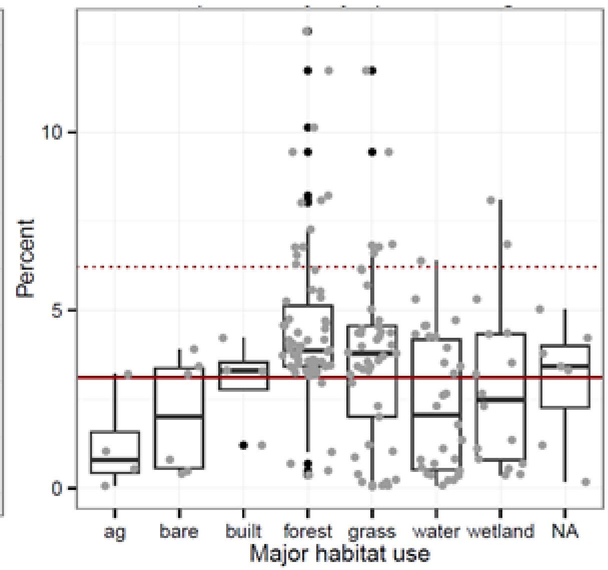
One of the major disadvantages of this dataset is that underestimates the amount of grassland cover in the Carpathian mountains (15.58%), compared to the more accurate Landsat estimates (Griffiths et al 2014) (31.83%) (map below). This underrepresentation of the grassland cover, could mean than potentially the Carpathians carry more conservation responsibility that estimated based on the stratification by land use types.



Due to this disagreement in the amount of grassland cover, our final analysis was based on estimate of conservation responsibility *based on range distribution* and *land cover estimates based on Griffiths et al 2014.*

However, we ran the analysis with both datasets, and overall, the results are the same when comparing responsibility using *major land use types* (left) to using *species range* (right). The Carpathians in both cases carry high conservation responsibility for forest and grassland species (values above red lines).


Percent
Major habitat use
ag
bare
built
forest
grass
water
wetland
NA
0
5
10
15
20


Percent
Major habitat use
ag
bare
built
forest
grass
water
wetland
NA
0
5
10

Appendix 5.3: Classes of conservation responsibility for the Carpathians

Based on the percentage of a species range in the Carpathians, its IUCN conservation status and European Level population dynamics we defined four classes of conservation responsibility in the Carpathians.

HHCD: High conservation responsibility for the Carpathians because the species has: **h**igh percentage of the species range in the Carpathians (> 6.212%), IUCN status of **c**oncern (VU, NT, EN, CR) and population at European level in **d**ecline or fluctuating between 1990 and 2000.

HHLC: High conservation responsibility for the Carpathians because the species has: **h**igh percentage of the species range in the Carpathians (> 6.212%), IUCN status of **l**east **c**oncern (LC) and population at European level either in decline or increasing.

HMCD: **H**igh conservation responsibility for the Carpathians because the species has: **m**edium percentage of the species range in the Carpathians (>3.106 and < 6.212%), IUCN status of **c**oncern (VU, NT, EN, CR) and population at European level in **d**ecline.

LLLC: Low conservation responsibility for the Carpathians because the species has: **l**ow percentage of the species range in the Carpathians (<3.106%) or medium percentage of the species range in the Carpathians (>3.106 and < 6.212%) and IUCN status of **l**east **c**oncerned (LC).

We define species of high conservation responsibility all those species that fall in the classes HHCD, HHLC and HMCD. Based on this classification, we identified 29 species of conservation responsibility (classes HHCD, HHLC, HMCD). The HHCD responsibility class included two species with IUCN status of concern and a high percentage of their range in the Carpathians: the Eastern imperial eagle and the lesser white-fronted goose. The HHLC responsibility class included a total of 17 species with varying population trends and the HMCD responsibility class included 10 species of conservation concern that had a moderate proportion of their range in the Carpathians (Appendix 5.1 and Table 5.1).

Carpathian contribution to European range	IUCN concern status	European population trend	No. species	Conservation responsibility class
high	C	decline	1	HHCD
high	C	stable/fluct	1	HHCD
high	LC	decline	3	HHLC
high	LC	stable/fluct	8	HHLC
high	LC	increase	2	HHLC
high	LC	NA	4	HHLC
medium	C	decline	10	HMCD
medium	LC	decline	41	LLLC
medium	LC	stable/fluct	66	LLLC
medium	LC	increase	23	LLLC
medium	LC	NA	10	LLLC

Carpathian contribution to European range	**IUCN concern status**	**European population trend**	**No. species**	**Conservation responsibility class**
low	C	decline	2	LLLC
low	C	stable/fluct	1	LLLC
low	C	NA	1	LLLC
low	LC	decline	28	LLLC
low	LC	stable/fluct	24	LLLC
low	LC	increase	12	LLLC
low	LC	NA	15	LLLC
Total number of species			252	
% in classes of high conservation responsibility			67.06%	

Appendix 5.4: Potential future habitats in the Carpathians

The conservation goals that arise from our results, i.e., to focus on forest and grassland bird species, could be achieved by allowing for natural succession on all land that was forested in 1860s or thereafter, and allowing the remaining agricultural lands to convert to grasslands. If such management was implemented, the Carpathians would consist of 66% forest cover and 32% grassland, which would benefit all species of conservation concern. Furthermore, this management plan would require a 8% increase in forest cover and a 2% increase in grasslands, rates of change well within historic ranges of change in the Carpathians, and consistent with recent land use trends (see map below for visualization of this landscape). The current trend of agricultural abandonment in the Carpathian Mountains is positive for avian diversity, and we see little justification for EU subsidies for row-crop farming from a conservation perspective. The Transylvanian plains were historically mostly un-managed grassland landscapes. We suggest that in those areas, low-intensity livestock management could enhance conservation outcomes. The left map depicts habitat distribution in 2010. The right map shows potential future habitat distribution if all agricultural land would be abandoned, and forest succession would occur in all areas that were forested at any point after 1860s. Map legend: dark green=forest, light green=grassland, yellow=agriculture.