Why past land use matters: Learning from the Carpathians

A dissertation proposal submitted by
Catalina Munteanu
Department of Forest and Wildlife Ecology
University of Wisconsin-Madison
cmunteanu@wisc.edu

Advisor
Volker C. Radeloff
Department of Forest and Wildlife Ecology
University of Wisconsin-Madison

Committee
Murray Clayton
Department of Statistics
University of Wisconsin-Madison

Holly Gibbs
Department of Environmental Studies and Geography
University of Wisconsin-Madison

Tobias Kuemmerle
Department of Geography
Humboldt University, Berlin

Anna Pidgeon
Department of Forest and Wildlife Ecology
University of Wisconsin-Madison

Preliminary Examination
18 October 2013, 12:30pm, Room A121, Russell Labs

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Introduction

The mosaic of land covers and land uses , i.e., the land system, both drives and responds to global environmental change (Foley et al., 2005; Turner et al., 2013; Verburg et al., 2013). Changes in land cover and in land use intensity cause changes in climate, biodiversity, ecosystem services and economies, which in turn cause further land change (Ojima et al., 1994; Verburg et al., 2013). Humankinds' relationship with nature is influenced by dynamic drivers, effecting the environment directly or indirectly, and being affected by it as well (Meyfroidt et al., 2010; Turner et al., 2013). Land change has been an active process for millennia, but the pace and intensity of change over the 20th century has been unprecedented (Lambin and Geist, 2006): 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).

The environmental consequences of broad scale land use changes are alarming: forest degradation, increase of pests and pathogens, decrease of carbon sequestration, changes in runoff and groundwater flow, decrease of water quality, loss of plant and animal biodiversity, and alteration of regional climates (DeFries et al., 2004; Foley et al., 2005; Turner et al., 2013). Despite the unprecedented demand on agricultural products and natural resources, it is encouraging though that a potential halt of tropical deforestation (Meyfroidt and Lambin, 2011) coupled with closing yield gaps and increasing cropping efficiency (Foley et al., 2011) may slow down, or even reverse, recent land change trends. However, changing the magnitude or even reversing the direction of change requires a shift in the driving forces across a range of spatio-temporal scales (Verburg et al., 2013). The 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 desired future land use conditions. However, the pace at which land change trends can be altered may also depend on the persistence of legacies from historic land systems – of which a clear spatial assessment is still missing.

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). Depending on the region and the economic, political and institutional settings (Meyfroidt and Lambin, 2011) one or more transition phases can occur (Yeo and Huang, 2013). Furthermore, multiple transitional pathways (such as the forest scarcity pathway, globalization pathway, economic development pathway, smallholder pathway) may occur depending on socio-economic context and socio-ecological feedbacks (Lambin and Meyfroidt, 2010). However, empirical evidence suggests that not all parts of the world move linearly through these transitions: some places may remain relatively constant for a long time, while others may move rapidly through different transitions (Foley et al., 2005). Regions where changes occur at relatively short intervals are particularly interesting to study though, because they may allow comparing different socio-economic, political and demographic components of the change process.

Land use transitions are explained by a series of causal mechanisms (Lambin and Meyfroidt, 2010), i.e., a set of complex factors involved in causing land change. The immediate human activities that affect the environment, usually act at local scale and are the proximate causes of land change, and examples include agricultural expansion, wood extraction or development of infrastructure (Geist and Lambin, 2001). These proximate causes are driven by underlying forces, which are complex social, political, economic, technological, and cultural variables that directly or indirectly affect change (Geist and Lambin, 2001). 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).

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 (D. Foster et al., 2003; Wallin et al., 1994), land use histories and the legacies they create have not been thoroughly considered as important drivers of recent changes. Longitudinal studies addressing questions on land use legacies and time lags are scarce (Lambin and Geist, 2006), partly because of a lack of reliable data for historical time periods. Furthermore, ecosystems may need decades or even centuries to respond to historical changes (D. Foster et al., 2003), making it difficult to identify the right time-frame for analysis. However, the implication is that the ability to understand and predict future change might be limited by the scarce understanding of the past (Lambin and Geist, 2006).

The overall goal of my dissertation is to address existing gaps in land change science regarding the role of past land use legacies in shaping the magnitude and extent of recent land changes. My study will contribute to all dimensions of land change science (Turner et al., 2007): I will map and characterize historic land changes, synthesize them in the context of land transitions, understand causes and impacts of historic land uses for recent land change and identify areas where changes might occur in the future.

My specific research questions are:

1. What are the overall, broad-scale land change patterns and their driving forces over the last 250 years in the Carpathian region?
2. What is the relative role of land use legacies in determining recent land changes?
3. Do past forest uses constrain the timing, extent and magnitude of recent change?

To answer these questions, I will structure my dissertation in three chapters. The first chapter is a comprehensive, broad scale synthesis of published land change studies covering 250 years of land use history and is already completed. The manuscript was shared with the committee and submitted to ‘Land Use Policy’ in July 2013. In this first chapter, I conducted a meta-analysis and literature review to map and characterize historic patterns of land change. I synthesized the results in the context of the forest transition theory and outlined the main drivers of change. The manuscript in its’ submitted form is included below as an in-depth introduction to the study area and the historic land changes that it experienced.

In my second chapter, I will model recent land changes as a function of past land uses across the Carpathian region. I will analyze spatially explicit land cover datasets starting in the 1860s and parameterize logistic regression models to explain the relative role of land use legacies in shaping the magnitude and the timing of recent land changes. By mapping model residuals, I will predict areas where potential future transition may occur.

In my third chapter, I will examine how past forest use practices, especially sudden, and widespread clear-cutting, affect the timing and magnitude of recent forest changes. I will analyze if the effects of historic large-scale clear-cuts manifest themselves with a time lag, approximately coinciding with forest rotation cycles. I will map and characterize forest cover change since the onset of the Cold War, using declassified satellite imagery and Landsat data. I will apply logistic regression to test the significance of past socio-ecological shocks, versus recent political and socio-economic changes in shaping recent forest disturbances.

My dissertation will focus on the Carpathian region in Eastern Europe to study questions related to land use legacies, their timing and potential implications. The study area stretches over two eco-regions and six countries (Figure 1) and provides a unique ‘natural laboratory’ where multiple socio-economic, political, and land management shifts occurred over the past two centuries. These shifts enable me to study several land use legacies and their effects over a relatively short time span. Despite the fact that the Carpathians provide a great ‘natural laboratory’, land change questions at both broad temporal and spatial scales have not been addressed in the Carpathians. However a multitude of long-term, local scale studies (Huzui et al., 2012; Kozak, 2003; Štych et al., 2012) provide valuable insights on the land use history of the region, building a great knowledge pool for a synthesis of land change patterns and processes. Additionally, several collections of historical maps (Timár et al., 2010) as well as Cold War satellite imagery (Peebles, 1997) are available for the region, which facilitate a spatially explicit, long-term analysis of historic land-change.

Another advantage the Carpathians for land use science is the availability of broad scale land change datasets based on remotely sensed data imagery starting in 1985 (Griffiths et al., 2013, in review; Knorn et al., 2009; Kuemmerle et al., 2008). Since the collapse of the Socialism, forests recovered in Eastern Europe, and especially so in Romania and Ukraine (Griffiths et al., 2013; Knorn et al., 2012). Forest succession occurred partly due to widespread farmland abandonment, both in remote areas (Griffiths et al., in review) and in large agricultural fields close to major settlement (Baumann et al., 2011). However, patterns of deforestation and agricultural abandonment vary among countries: even though the socio-economic shocks following the collapse of the Soviet Union was the overall cause, national policies moderated its effects (Kozak et al., 2004; Kuemmerle et al., 2011, 2009b). In addition though, the recent changes, might be modulated by land use legacies and reflect past land use change with time lags. Understanding these past processes is important in the interpretation of recent change, especially in the context of predicting future land use change.

As a biodiversity hotspot, but also a region that provides opportunities for increased and intensified food production, the Carpathian region also provides an interesting study-site in terms of future land management. Land change causes biodiversity loss on high conservation value grasslands (Bezák and Halada, 2010; Biró et al., 2012; Galvánek and Lepš, 2011), habitat fragmentation (Kuemmerle et al., 2012; Rozylowicz et al., 2010), and affects carbon sequestration (Keeton et al., 2013; Kuemmerle et al., 2011). However, due to its agricultural fertility, the region is regarded as potential agricultural intensification area to support global food production (Foley et al., 2011). Thus, future land management that reconciles development and conservation is essential for the Carpathian's sustainable development. To sustain such management, land use planning needs to account for path dependency and ensure that limited understanding of the past does not affect the ability to predict the future.

Within the Carpathian region, I will conduct analyses at two scales to answer my research questions. My chapters one and two will cover most of the Carpathian and Pannonian Ecoregions, including parts of Romania, Poland, Ukraine and the Czech Republic as well as entire Hungary and Slovakia, in total encompassing an area of 350,000km^2. My third chapter will focus on three trans-boundary areas, each with an approximate area of 7,500km^2. These sites capture the diverse socio-economic and political conditions of five countries as well as ecological and environmental diversity of the two eco-regions (Figure 1). The temporal scale of my analyses extends back to the Austro-Hungarian Empire in the 1860s. The broad spatio-temporal scale of my analysis will enable me to answer questions on the role of century-long land use legacies and their timing in shaping more recent land transitions. My findings will contribute to the different dimensions of land change science by revealing the relative role of past land uses in determining current change, identifying the long term implications of land uses in the context of the time-lags they create, and refining the understanding of drivers of land change in the context of land change transition theories.

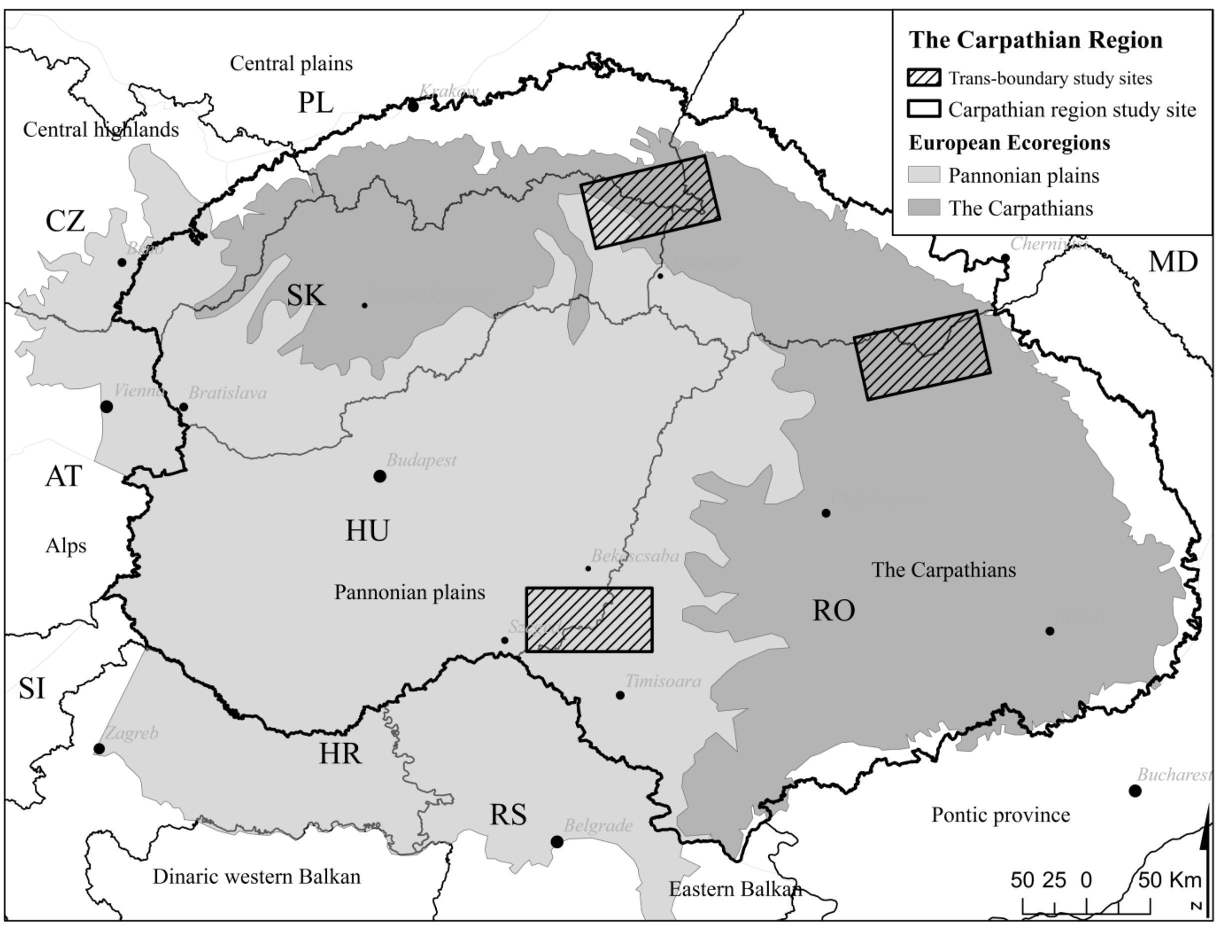


Figure 1: **Carpathian Region in Eastern Europe and approximate delineation of overall study region (Chapter 1, Chapter 2) and selected regions (Chapter 3)**

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

Catalina Munteanu[1]*, Tobias Kuemmerle[2,3], Martin Boltiziar[4,5], Van Butsic[2,6], Urs Gimmi[7], Lubos Halada[4], Dominik Kaim[8], Géza Király [9], Éva Konkoly-Gyuró[10], Jacek Kozak[8], Juraj Lieskovsky[4,7], Matej Mojses[4], Daniel Müller[6,2], Krzystof Ostafin[8], Katarzyna Ostapowicz[1,8], Oleksandra Shandra[11], Přemysl Štych[12], Sarah Walker[13], Volker C. Radeloff[1]

Manuscript submitted to *Land Use Policy, Jul 26, 2013*

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 (D. 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). Furthermore, shock situations, such as rapid shifts in political systems can cause abrupt changes in land cover (Hostert et al., 2011). The question is how long-term land-cover trends vary depending on economic and institutional factors, and how political and economic shocks may affect these trends.

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, in review) 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 2), 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., 2013; Kozak, 2003; 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 distinct historical periods, demarcated by several large-scale shocks: (1) the *Habsburg and Austro-Hungarian Empires (K.u.K. Monarchy)* which had a leading role in the region over the 18th and 19th centuries but ended with World War I (WW I), (2) the *Interwar period*, characterized by the emergence of several nation-states up to World War II (WW II), (3) the *Socialist* period which ended in approximately 1990 in the Carpathian countries, (4) the *Transition* when countries developed market economies, which lasted roughly until 2000, and lastly (5) the *Accession to the EU* of most countries within the study area, in either 2004 and 2007 (except Ukraine). 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.

Based on our prior knowledge of land change in the Carpathians, we formulated a set of expected land change trends for each period. Specifically, we predicted forest cover to decrease for the K.u.K. Monarchy and Interwar periods, and forest recovery for all following periods. For agricultural land, we expected to observe expansion for all historic time periods up to 1990, followed by abandonment for the Transition period and re-cultivation since EU accession (Table 1). We also expected these overall trends to vary considerably among regions due to biophysical and socioeconomic differences.

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*) that (1) were based on spatially-explicit data (historic maps, aerial photographs, and/or satellite imagery); (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 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. 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 2 and Table 1).

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’ and ‘agriculture’. 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 2).

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 3 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 2). 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 3). 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 3).

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 4). 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 4 and Figure 5).

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 4, Figure 6). 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 4).

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 5), while deforestation occurred in lowland areas (e.g., Hungary) as well as in the mining district of southwest 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 (e.g. 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 6). 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 7). 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 7).

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 WW I and WW II, forest cover declines 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 WW II, the observed forest cover increase was in line with our expectations (Table 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, increasings 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., 2012; 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 (K 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., 2013; 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., 2012). 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). 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., 2013; 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. 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 the Socialist regime. 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. The agricultural change was mostly mirrored by forest cover but also involved other land-cover classes, for which data availability was limited. 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.

Acknowledgements

We would like to thank P. Culbert, S. Martinuzzi, H. Gibbs, and J. Alix-Garcia for valuable comments at various stages of this study. We thank all case-study paper authors that shared their data, and provided additional information. We gratefully acknowledge support by the Land-Cover and Land-Use Change Program of the National Aeronautic Space Administration (NASA), the European Commission (Integrated Project VOLANTE, FP7-ENV-2010-265104), the Einstein Foundation, Berlin (Germany) and the Fulbright Scholar Program.

Tables

Table 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 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). 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%	+	-

List of figures

Figure 2: Study area, including spatial extent of case studies (grey) and centroids for 102 case studies (triangles). Country codes: AT: Austria, HU: Hungary, PL: Poland, CZ: Czech Republic, SK: Slovakia, UA: Ukraine, RO: Romania, MD: Moldova, HR: Serbia, SI: Slovenia.

Figure 3: 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 4: 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 5: 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 6: 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 7: 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.

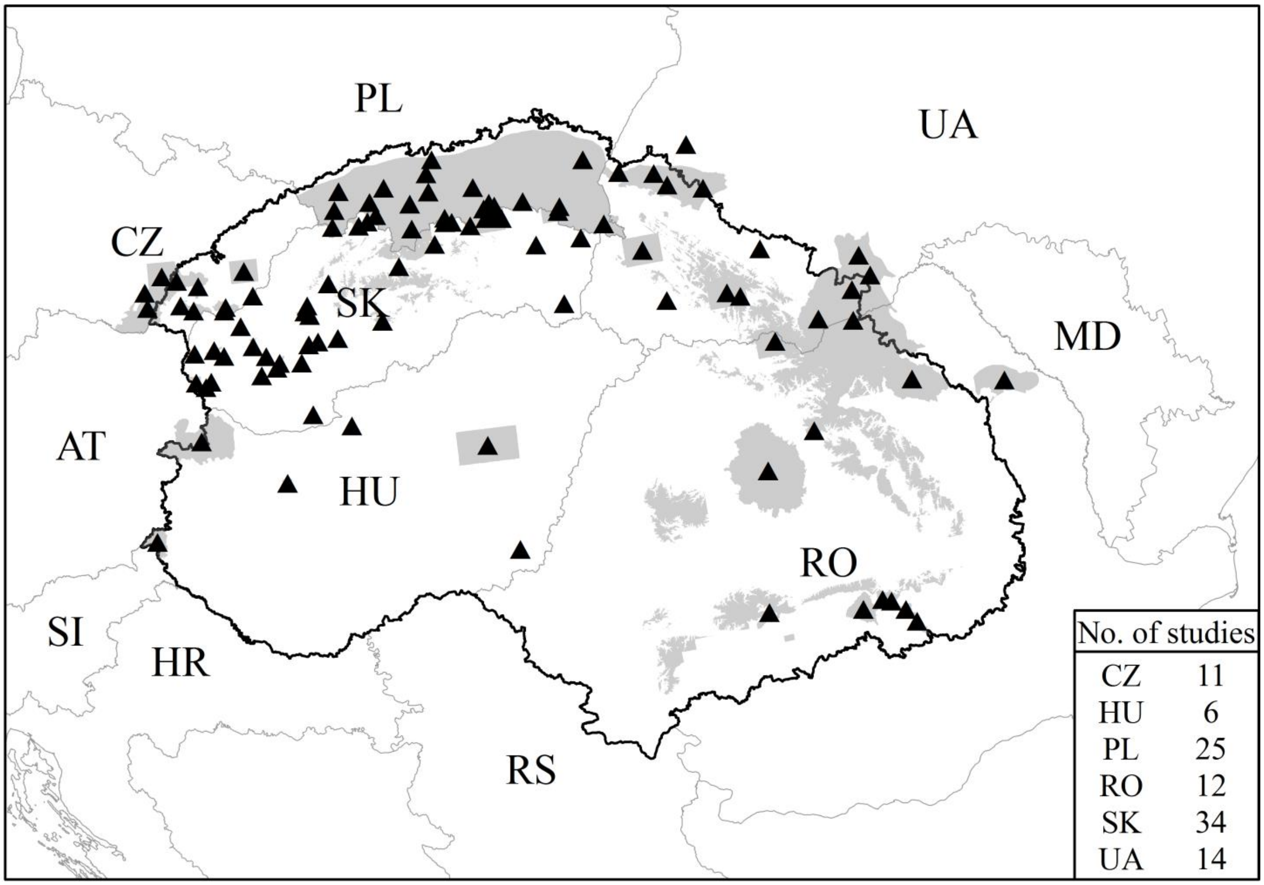

PL
UA
CZ
SK
MD
AT
HU
RO
SI
HR
RS
No. of studies
CZ 11
HU 6
PL 25
RO 12
SK 34
UA 14

Figure 2

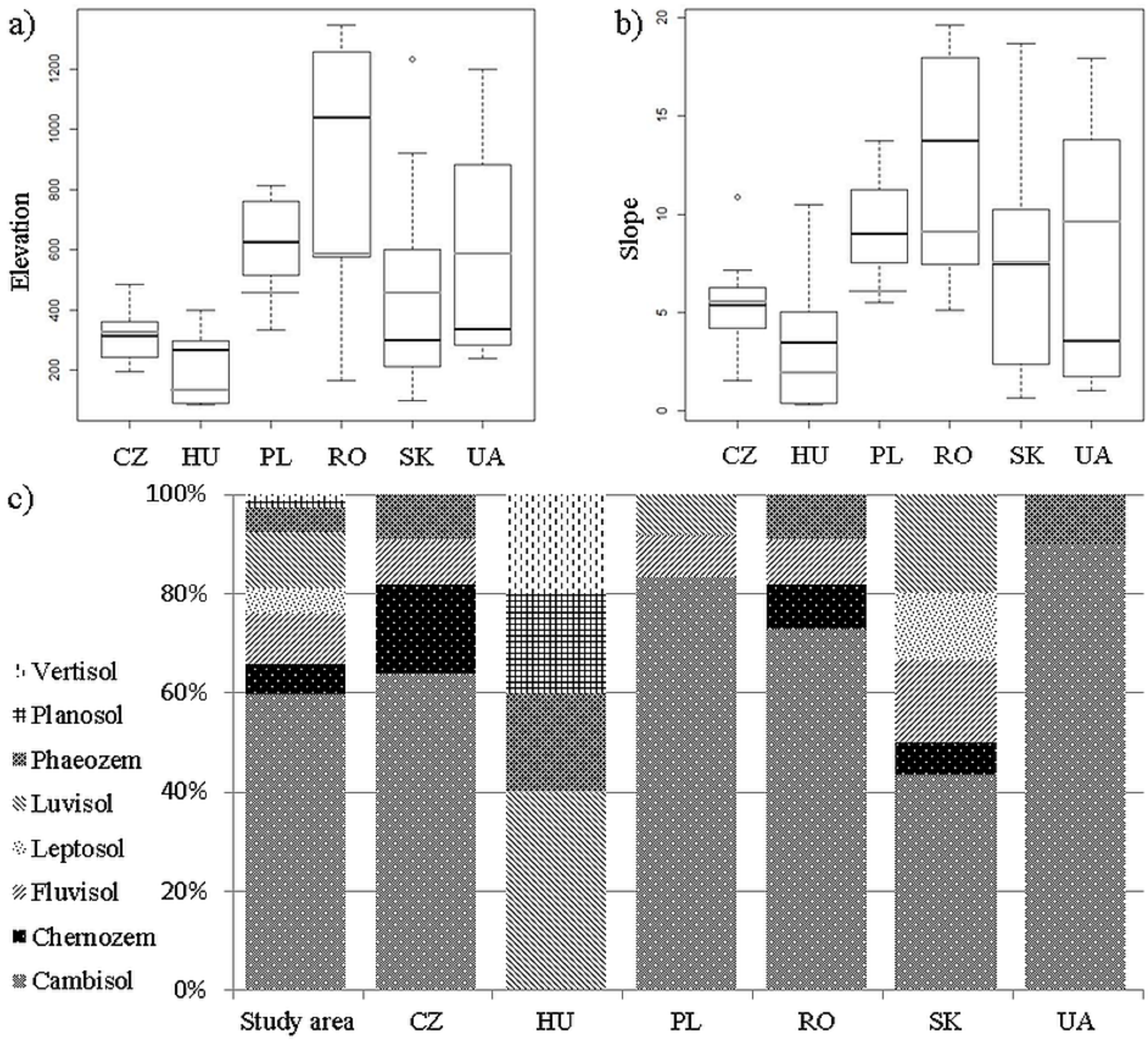
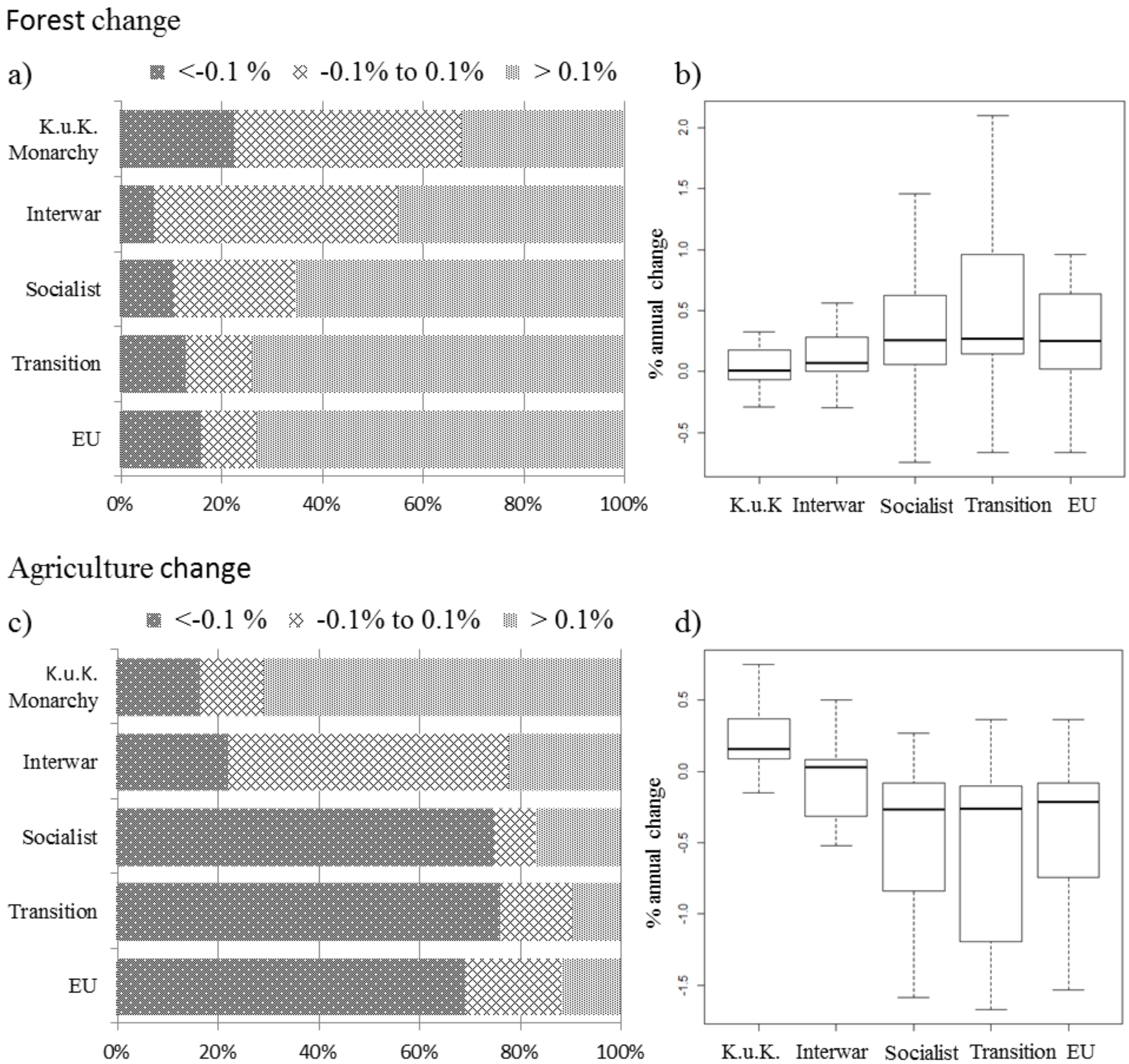

a)
b)
c)
Elevation
Slope
200
400
600
800
1000
1200
0
5
10
15
20
CZ
HU
PL
RO
SK
UA
100%
80%
60%
40%
20%
0%
Vertisol
Planosol
Phaeozem
Luvisol
Leptosol
Fluvisol
Chernozem
Cambisol
Study area
CZ
HU
PL
RO
SK
UA

Figure 3

595



Forest change
a)
<-0.1 %
-0.1% to 0.1%
> 0.1%
K.u.K. Monarchy
Interwar
Socialist
Transition
EU
0%
20%
40%
60%
80%
100%
b)
% annual change
K.u.K
Interwar
Socialist
Transition
EU
Agriculture change
c)
<-0.1 %
-0.1% to 0.1%
> 0.1%
K.u.K. Monarchy
Interwar
Socialist
Transition
EU
0%
20%
40%
60%
80%
100%
d)
% annual change
K.u.K.
Interwar
Socialist
Transition
EU

600 Figure 4

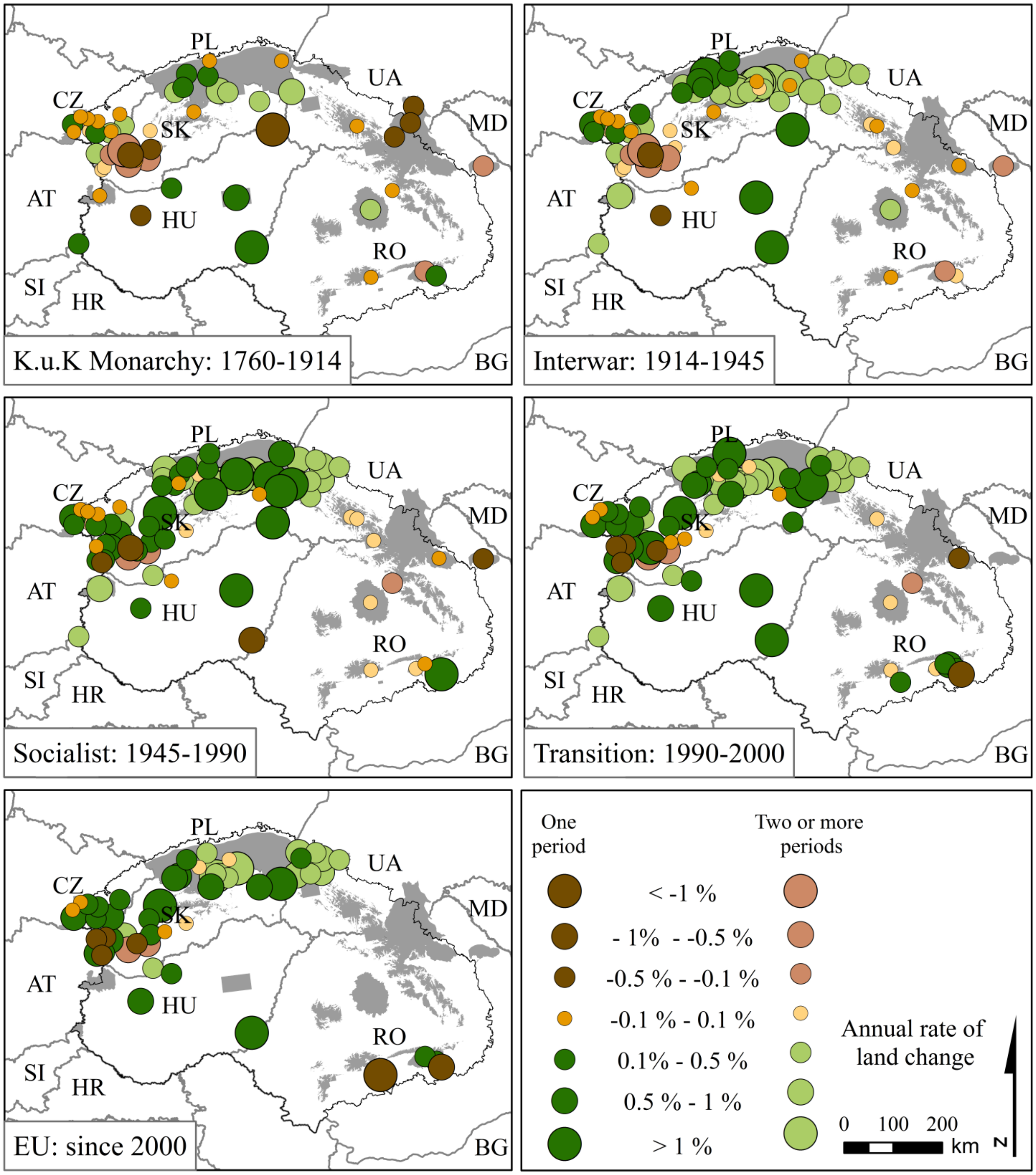

PL
UA
CZ
SK
MD
AT
HU
RO
SI
HR
BG
K.u.K Monarchy: 1760-1914
Interwar: 1914-1945
Socialist: 1945-1990
Transition: 1990-2000
EU: since 2000
One period
Two or more periods
< -1 %
- 1% - -0.5 %
-0.5 % - -0.1 %
-0.1 % - 0.1 %
0.1% - 0.5 %
0.5 % - 1 %
> 1 %
Annual rate of land change
0 100 200
km
N

Figure 5

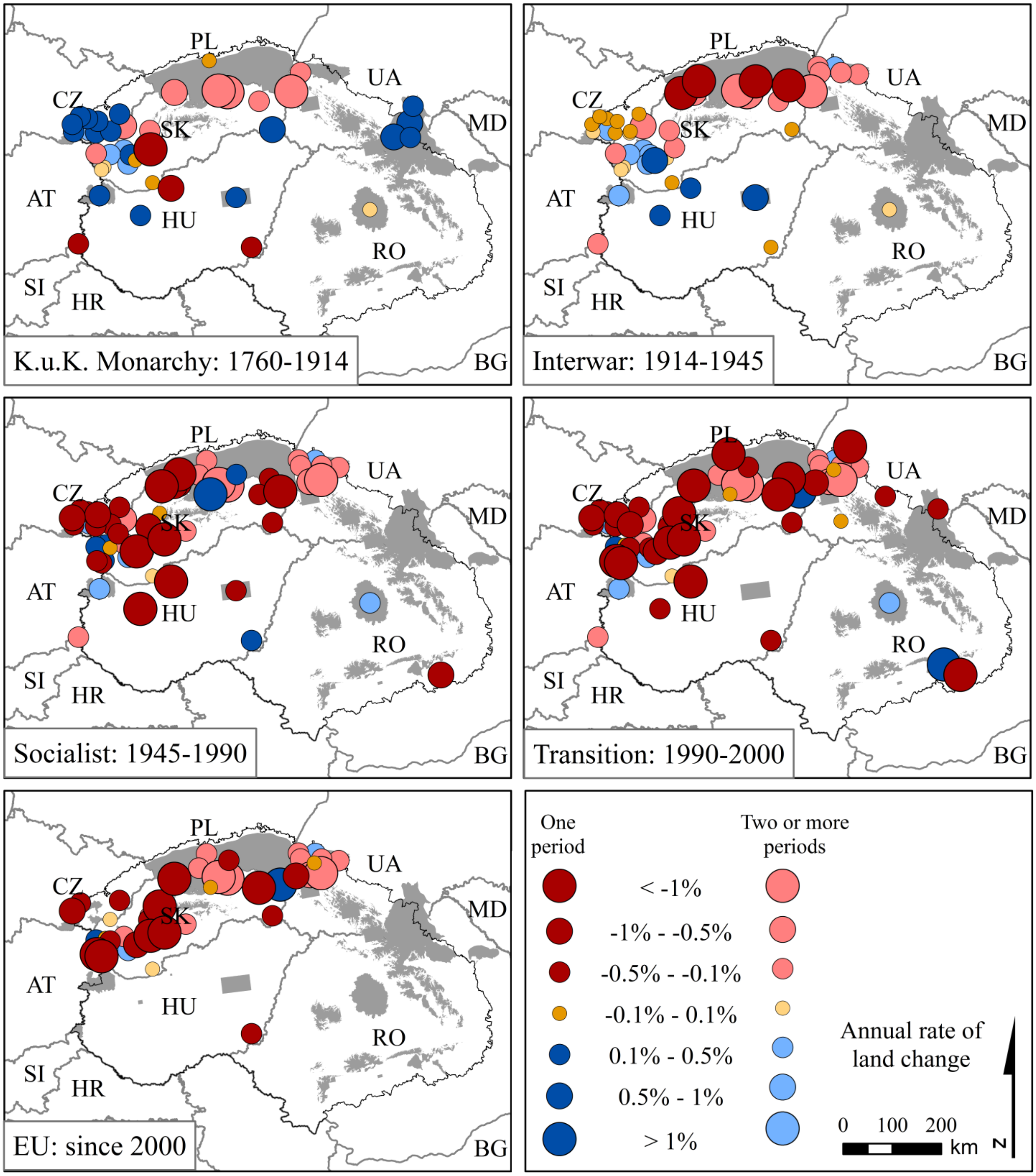

K.u.K. Monarchy: 1760-1914
Interwar: 1914-1945
Socialist: 1945-1990
Transition: 1990-2000
EU: since 2000
PL
UA
CZ
SK
MD
AT
HU
RO
SI
HR
BG
One period
Two or more periods
< -1%
-1% - -0.5%
-0.5% - -0.1%
-0.1% - 0.1%
0.1% - 0.5%
0.5% - 1%
> 1%
Annual rate of land change
0 100 200
km
N

Figure 6

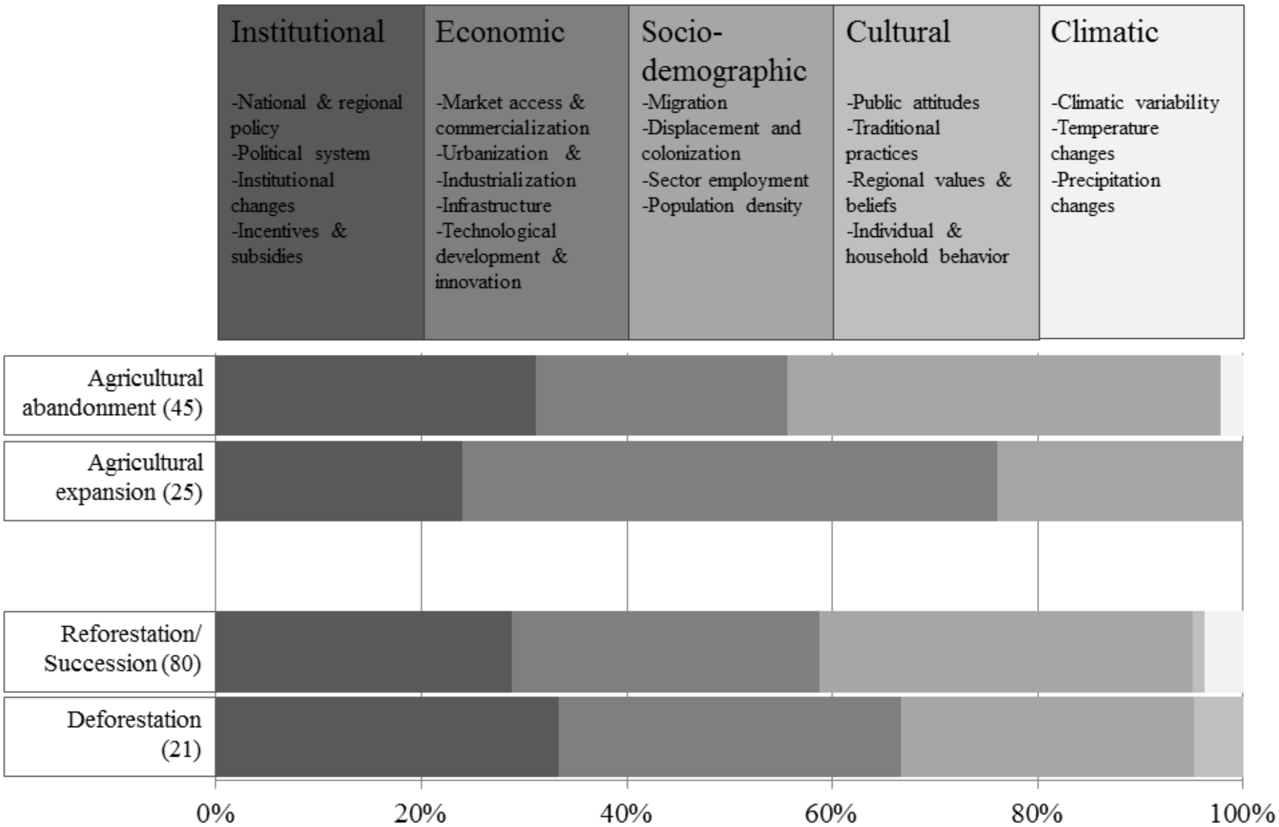

Institutional
-National & regional policy
-Political system
-Institutional changes
-Incentives & subsidies
Economic
-Market access & commercialization
-Urbanization &
-Industrialization
-Infrastructure
-Technological development & innovation
Socio-demographic
-Migration
-Displacement and colonization
-Sector employment
-Population density
Cultural
-Public attitudes
-Traditional practices
-Regional values & beliefs
-Individual & household behavior
Climatic
-Climatic variability
-Temperature changes
-Precipitation changes
Agricultural abandonment (45)
Agricultural expansion (25)
Reforestation/ Succession (80)
Deforestation (21)
0%
20%
40%
60%
80%
100%

Figure 7

Appendix:

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)

Chapter 2: Do land use legacies matter for recent land transitions?

Introduction

The modification of land cover over the past 300 years is one of the most important components of global change, with effects reverberating throughout many ecosystems (Lambin and Geist, 2006). Population increase, mechanization of agriculture, introduction of fertilizers and crop rotations, economic development and globalization have all substantially altered the land cover of the planet (Foley et al., 2011; Lambin and Meyfroidt, 2010). Legacies of these past land uses will persist for a long time into the future (D. Foster et al., 2003), and forest use in Europe (Bellemare et al., 2002) and the eastern U.S. (Thompson et al., 2013) are great examples of how recent forest patterns and composition reflect past human activities. However, it is still unclear in how far the past land uses determine the magnitude and spatial extent of recent land changes and this limits our ability to predict future land change.

Theoretical models of land change, such as forest transition theory, highlight that land cover and land use change follow relatively consistent long-term trajectories, as a function of political and socio-economic change (Lambin and Meyfroidt, 2010; Mather, 1998, 1992; Meyfroidt and Lambin, 2011). The economic and institutional backgrounds of countries, global market dynamics, and social contexts determine the direction and intensity of change (Lambin and Geist, 2006; Lambin and Meyfroidt, 2010; Lambin et al., 2001; Verburg et al., 2009) and may cause a region to experience one (Kozak, 2010) or more (Yeo and Huang, 2013) transition episodes. However, alongside such underlying drivers, land use legacies could be a key component of land transitions, but their role in determining recent change is not well understood (Lambin and Geist, 2006). In order to reveal the role of land use legacies as drivers of change, I will model recent land changes as a function of past land uses. Subsequently, based on observed land use legacies, I will map areas of potential future change.

Global land cover trends include forest loss (Hansen et al., 2010) and agricultural expansion (Foley et al., 2011). However, the 154 million hectares of global agricultural expansion between 1985 and 2005 include both significant increase of agricultural areas in the tropics, and decrease of agriculture in temperate areas, mostly of the Soviet Union and Latin America (Munroe et al., 2013). Abandoned fields are now going through successional stages, associated with possible different change trajectories (Munroe et al., 2013), and their ultimate land use outcomes are still uncertain. To understand their potential future land uses, we need longitudinal land change assessments. Unfortunately, century-long trends in agricultural intensification (Lambin and Geist, 2006), desertification (Geist and Lambin, 2004), agricultural abandonment and forest cover increase (Munteanu et al., n.d.) are usually analyzed either in global studies that rely on spatially coarse statistical assessments, that miss details, or in very local case studies (Munteanu et al., in review). To bridge these temporal and spatial gaps, there is a need for regional scale, spatially explicit studies in order to explore the role of legacies over long time periods. I will thus analyze land use legacies using a regional, spatially explicit record of land change for the past 150 years across the Carpathians.

The reconstruction of historic land use is challenging because of missing, inconsistent, or unreliable data sources. Census data, in particular, is of questionable quality, very poor at subnational levels, and missing explicit spatial information - especially for studies preceding WWII (Lambin and Geist, 2006). However, my study area has two major advantages for studying long term land change and the role of legacies. First, it has experienced several abrupt changes in institutions, economies, socio-political and technological conditions over the past two centuries. These repeatedly affected and changed the land use (Munteanu et al., in review) opening up the possibility to study multiple legacies over a relatively short time span. Second, several collections of historical maps (Timár et al., 2010) and Landsat-based land cover maps (Griffiths et al., 2013) provide a unique opportunity to reconstruct land cover for over 150 years. I will use the Carpathian region of Eastern Europe as a “natural experiment” for studying the relative role of land use legacies for recent land change.

The Carpathian region experienced forest transition around the interwar period (Kozak et al., 2007; Kuemmerle et al., 2011; Munteanu et al., in review). Forest cover started to increase after WWI and this increase continued albeit at varying rates (Baumann et al., 2011; Griffiths et al., 2013; Prishchepov et al., 2012). Despite the overall increase in forest cover since 1985 (4.4%, Griffiths et al., 2013), forest disturbance rates from 1985 to 1995 were high in Poland, Czech Republic, Ukraine and northern Romania, and in the Romanian Carpathians from 1995 to 2000 (Griffiths et al., 2013).

These forest cover dynamics are closely related to changes in agriculture and grassland. Land abandonment and forest succession occurred both in lowlands (Baumann et al., 2011) and in marginal mountain regions (Griffiths et al., 2013; Shandra et al., 2013). Furthermore, some abandonment of agriculture occurred in the form of croplands transitioning to managed grasslands, a process which was most prominent from the collapse of socialism to 2000 (Griffiths et al., 2013; Munteanu et al., in review). After EU accession, 18% of the abandoned fields in the Carpathians were re-cultivated but some new abandonment and forest succession also occurred (Griffiths et al., in review).

Last, but not least, urban sprawl was a prominent and increasing process, starting already during the Habsburg Empire (Munteanu et al., in review), although mountain areas of Poland and Slovakia were depopulated post WWII (Kozak et al., 2004). Wetland loss to agriculture was one a major land cover changes in the Pannonian plains in the 20th century (Schiller et al., 2010).

Using the information on recent change, alongside with data extracted from historical maps, I will model land abandonment and forest disturbance as a function of past land uses, and hence contribute to the understanding of the relative importance of legacies and to the prediction of areas that could be affected by abandonment or forest disturbance in the future.

Objectives

My overall goal is to understand the role of land use legacies in shaping the magnitude and timing of subsequent land transitions. To do this, I will map forest, agriculture, grassland, urban and wetland change over 150 years. I will model recent changes (land abandonment, forest disturbance) as a function of past land uses and quantify the relative importance of legacies for the recent change. My specific goals are to:

1. Map land cover change between 1860 and 2012 to highlight the prominent land transitions as well as the hotspots of change.
2. Quantify the role of land use legacies for recent transitions; specifically test if rates of land change (esp. deforestation and abandonment) are higher on areas with shorter land use legacies.
3. Map areas where change might occur in the future.

Methods

Study area

My study area covers over 360,000 km^2 and includes the two major eco-regions in Eastern Europe, the Carpathian Mountains and the Pannonian plain, including adjacent administrative units at NUTS 5 level (Figure 1). The main land-cover pattern in the Carpathians is a mosaic of forest, small agricultural fields and grassland areas, with scattered settlements (Knorn et al., 2009; Kuemmerle et al., 2008). The Pannonian Plains have historically been dominated by grasslands and wetlands, but due to the fertility of the soils, these were mostly converted to agricultural fields (Schiller et al., 2010), intermixed with planted forests and urban areas. Forest area has increased since the 1920s, with agricultural abandonment being the most important reason for this (Munteanu et al., in review).

Land use data

To map historic land cover, I will analyze a total of 92,000 points, in a regular 2 x 2 km grid. The grid conforms to the 2007 INSPIRE directive (Infrastructure for Spatial Information in the European Community) and LUCAS (Land Use and Cover Area frame Survey) dataset. These are two frameworks aimed at making spatial data infrastructures across the European Union compatible and usable in a trans-boundary context, especially in terms of environmental variables and agricultural practices. For each point, my project partners and I are compiling information on land use for six time points, from a combination of historic military maps and Landsat imagery (Figure 8). The first three time points (1860s, 1930s and 1960s) stem from the digitization of historic maps (thanks to the NASA-funded '200 years of land cover change in the Carpathian Basin' project). I will extract the land cover data for all time layers subsequent to 1985 from wall-to-wall Landsat TM/ETM+ image composites (Griffiths et al., 2013, in review) (Figure 7). I will use seven land use classes: urban, agriculture, grassland and shrubs, forest, wetland, water and other.

The years for which I will have data (Table 3) capture five important time periods in the history of the region (Munteanu et al., in review), i.e., the Austrian and Austro-Hungarian Empires (1805-1918), the period between the two world wars (1918-1945), socialism (1945-1990), the transition to market economies (1990-2005), and the accession to the European Union of most countries (after 2005). Using time intervals with relatively homogeneous policies will enable me to relate land use legacies to each of the respective periods. To map land change transitions, I will employ post-classification comparison for each timestep.

Land change analysis

I will analyze long term land change across six countries of Eastern Europe (Hungary, Slovakia, Poland, Czech Republic, Romania, Ukraine). I will develop land change maps,depicting the spatial extent and hotspots of change (Visser and De Nijs, 2006), change matrixes (Mendoza et al., 2011), depicting the changes for each time step, and land transition graphs (DeFries et al., 2004; Foley et al., 2005).

I will use Map Comparison Kit (MCK) (Visser and De Nijs, 2006) to identify hotspots of land change. MCK has been developed for spatio-temporal land use change analysis and for accuracy assessments of raster maps. It is based on a fuzzy map comparison and resembles human judgment in map comparison (Visser and De Nijs, 2006). I will analyze the spatial distribution of changes per land use category using the cell-by-cell map comparison method (Visser and De Nijs, 2006). I will use fuzzy set theories to depict map similarity on a gradual scale (Hagen, 2003) and identify hotspots of land change (Visser and De Nijs, 2006) (Figure 9). I will correct the maps by the fraction of agreement that can occur by chance (Pontius and Xiaoxiao Li, 2010) and calculate FuzzyKappa, as a measure of agreement corrected by chance occurrence. Small spatial differences will lead to high map similarity, mitigating potential geometrical error in the historic maps (Timár et al., 2010). I will also separate the traditional Kappa value by location and class frequency (Pontius, 2000; Runfola and Pontius, 2013) to account for the amount of change due to slight shifts in point location and to similarity of land cover classes (Visser and De Nijs, 2006). This allows me to distinguish minor changes and fluctuations in the maps from the major land changes of interest (Hagen, 2003). I will obtain information on the direction of land change for each time period by computing change transition matrixes. Change matrixes depict the area that remained unchanged during a time period on their diagonals, while off-diagonals contain estimates of transitions from one class to the other (Mendoza et al., 2011). Furthermore, I will develop land transition graphs (DeFries et al., 2004; Foley et al., 2005) for the region as a whole, and for each country and eco-region (Figure 10) in order to understand the approximate timing of the transitions (Lambin and Meyfroidt, 2010) and their extent. I will interpret the results in context of the forest transition theory and explore it's relation to other land cover classes.

Deviation form uniform intensity analysis

Accuracy assessment and the estimation of omission and commission errors is an important constituent of correct estimates of land change (P. Olofsson et al., 2013). Given the common lack of validation data for historic time periods, accounting for hypothetical errors is essential when estimating change (Pontius and Xiaoxiao Li, 2010). The category similarity matrix (Hagen, 2003; Visser and de Nijs, 2006) and the FuzzyKappa breakdown, which I will obtain from the MCK analysis, will allow me to correct for potential errors (Foody, 2002; Hagen, 2003). The Kappa breakdown will allow me to understand the contribution of two main sources of uncertainty to the final land change product. Furthermore, I will perform intensity analysis for all time periods and land cover classes (Aldwaik and Pontius, 2012), to obtain an estimation of the omission and commission errors. I will analyze land change at the levels of time interval, land cover category, and transition category. For each one of these categories, a measure of uniform intensity is calculated: this represents the observed change distributed for a time period across the entire spatial extent available (Aldwaik and Pontius, 2012). Based on each category's deviation from this uniform intensity, I will compute the minimum hypothetical error that may account for the observed deviation from a uniform intensity (Aldwaik and Pontius, 2013). This deviation represents an estimate for omission and commission errors and will provide a measure of how various levels of errors may influence the change trajectory results.

Land change models

In order to quantify the impact of historic land uses, I will fit multiple logistic regression models (Hosmer and Lemesbow, 1980) to explain two change processes: deforestation and agricultural abandonment. The models will enable me to (i) quantify how much past land changes affect recent change and (ii) identify areas of potential future change. I will use both continuous (elevation, slope, climate and accessibility – i.e. distance to settlements, water bodies and roads) and categorical variables (historic land uses, historic country borders, current countries and districts, soil type, agricultural limitation, eco-region) in the models (Table 4). I will capture the effects of historic changes and their timing either by including interactions terms between historical land uses or by coding additional model variables that allow me to test specific hypotheses about historic land changes. In addition to variables on historic land covers, I will include a set of 'auxiliary' covariates, which will explain environmental, socio-political and accessibility variation. I will check for multicollinearity using the variance inflation factor (VIF) or Spearman's rank-order correlation, as a measure of correlation between explanatory variables I will exclude variables that produce VIF values > 10 or that are correlated more than 0.8. I will also test for the degree of spatial dependence in the point data using semivariograms (Curran, 1988; Griffith, 2003) and will consider model adjustments that might explain spatial correlation, such as including covariates depicting eco-region or agricultural suitability. I will estimate coefficients and test for their significance using likelihood ratio tests (Hosmer et al., 2013). I will perform variable selection using best subset logistic regression (Hosmer et al., 2013). This method selects the parsimonious models which perform best using the leaps-and-bounds algorithm (Furnival and Wilson, 1974). A specified number of best models that include up to a set number of covariates are selected. I will retain the best model.

Additionally, in order to account for the uncertainty in the model selection, I will perform Bayesian model averaging (Hoeting et al., 1999), where the quantities of interest will be expressed as weighted averages of model specific quantities. The weights depend on how much of the data supports each model (Clyde, 2003). I will use Bayesian Information Criterion (BIC) weight approximation (St-Louis et al., 2012) as an alternative to a full Bayesian Model Averaging, because the approach has several advantages. The approach favors parsimonious priors and has an easier and more realistic implementation in environmental sciences (St-Louis et al., 2012). Furthermore, it will account for uncertainty in model selection and result in better predictions than a single model approach (Hoeting et al., 1999; Raftery et al., 1997). The result will consist of an averaged model across a subset of best selected models.

I will compare the performance of the best selected model and a Bayesian averaged model (Hoeting et al., 1999) using receiver operating curve (ROC) techniques (Freeman and Moisen, 2008). I will finally interpret the coefficients of the best performing model (odds ratio). These will provide information related to the relative role of legacies in determining recent change. Furthermore, based on the maps of model residuals, I will verify the model's capability to predict potential future change (see below).

Importance of legacies

I will quantify the importance of legacies and their duration in determining current change. I will use a non-stochastic interpretation of the significance levels (Freedman and Lane, 1983) and rely on odds ratio values extracted from the regression coefficients (Hosmer et al.,

2013) to understand the relative role of legacies for recent change. I will test several hypotheses, related to the duration and timing of the land use transitions:

- Land abandonment is higher in areas that were cleared for agriculture during socialist time then in areas that were in agricultural use since the Habsburg Empire (ie. duration of legacies matter) [F-Ag-Ag-Aband > F-Ag-Aband and For-Ag-Aband>Ag-Ag-Aband]
- Forest succession in areas with historic transitions from grassland to agriculture is higher than in areas only used historically for agriculture [Gr-Ag-Aband>Ag-Ag-Aband].
- Agricultural abandonment on reclaimed wetlands is higher than on converted grasslands [Wet-Ag-Aband>Gr-Ag-Aband]
- Forest disturbance in areas with continuous historic forest cover is lower than forest disturbance in areas harvested for timber during the early 20^{th} century [For-Gr-For-Dist>For-For-For-Dist].
- Forest disturbance in areas converted to agricultural use in their land use history is higher than in areas with continuous forest cover [For-Ag-For-Dist>For-For-For-Dist].
- Recent forest disturbance in areas historically used for agriculture is lower than in areas historically used as grasslands [For-Gr-For-Dist>For-Ag-For-Dist] (Figure 11).

The odds ratio in logistic regression is a measure of association that approximates how much more likely (or unlikely) it is for the outcome to be present, depending on the value of the explanatory variable (Hosmer et al., 2013). I will use odds ratio as a measure of relative importance of historic land uses in determining recent change processes. This measure can be derived from the slope coefficients of the regression line.

Model fit, validation and potential future change

I will assess overall model fit using summary statistics based on deviance residuals. These provide an overall indicator of the agreement between observed and fitted data (Hosmer et al., 2013). I will validate my models with a sub-set of observations that were not included in model building. I will compare model performance using ROC analysis. ROC analysis is a threshold independent method for evaluating logistic models in which true positive rate is plotted against the false positive rate (Freeman and Moisen, 2008). I will use an overall measure of model utility like the area under the ROC curve (AUC) to decide between the single best model or the Bayesian averaged model.

Further, I will map false positive and false negative model predictions based on location information. I will compare these maps with existing land change maps for a subsequent time period. I will attempt to predict abandonment in the subsequent time window, using the model fit to the previous time window, in order to understand if the model might be suitable for predicting future land abandonment or forest disturbance beyond the currently available data.

Expected Results

My results will be (1) a land change analysis for the past 150 years, including land transitions between most important land cover classes and hotspots of change, (2) the quantification of the role of land use legacies in determining current land cover patterns, using a multiple logistic regression model, and (3) identification of areas that will likely experience change in the future. My results will yield several mapped datasets: the first spatially explicit historic land cover data sets for the Carpathian Region (starting 1860s), a set of change maps depicting locations and timing of land use transitions observed over the past 150 years, a set of maps of hot-spots of land change per time period and a map of potential areas of future transitions. Aside from these datasets, I will contribute to the understanding of the relative role of land use legacies in shaping recent change processes and explore land change transitions trajectories for multiple land classes in Eastern Europe.

I expect that land use legacies play an important role in shaping recent transitions, and that longer legacies cause subsequently slower change. For example, I expect that rates of agricultural abandonment will be higher in areas that were converted to agricultural use during the Cold War, compared to those converted to agriculture during the Habsburg Monarchy. I also expect forest disturbance rates to be higher in areas that were harvested or converted to other land uses historically, than in areas with persistent forest. I expect that multiple transitions experienced by the same area are reflected in recent rates of change, in that areas that transitioned from grassland to agriculture to forest will have a higher reforestation rates than areas that transitioned from agriculture to forest. Overall I expect that the longer a land area has been under a certain land use, the slower the subsequent change will be.

In the fuzzy map comparison analysis, I expect to observe several hotspots of change, in the large metropolitan area such as Budapest or Bratislava (due to urban development), along the floodplain of main rivers such as Danube or Tisza (due to wetland reclamation), and along the forest edge of the Carpathians (due to agricultural abandonment and forest disturbances) (**Figure 9**). I will interpret my results in the context of the forest transition theory, which I generally expect to hold true in Eastern Europe (Kozak, 2010; Kuemmerle et al., 2011; Munteanu et al., in review). I expect that transition from decreasing to increasing forest cover occurred between the two World Wars, but I expect to observe regional differences and short term, abrupt changes depending on region and institutional system. In general, I expect a West-East gradient in timing of the transitions. I expect that agricultural land experienced the reversed trend, with abandonment occurring since World War I (Munteanu et al., in review). I expect a slow transition from decreasing to increasing grassland after 2000, potentially related to conservation policies and EU accession. Overall, I expect a shift in the interactions among different land covers types. While historically, agriculture expanded mostly on former grasslands and wetlands (~50% change between 1860s-1950s), forest cover increased since the collapse of the Soviet Union on abandoned meadows and arable land.

Significance

My findings will contribute to land use science by elucidating the relative role of land use legacies in shaping current land change. By making use of the natural experiment that the Carpathian region provides, my study will underline the importance of longitudinal studies in understanding recent land change. The importance of past legacies is also relevant for land management, because it may be possible to plan so that future legacies enhance ecosystem services and conservation. The datasets that I will generate will provide an example of how information on past land uses may be used to inform both science and practice. I will produce a complete set of land cover and land change maps for the period 1860 to 2012 and a set of maps depicting ‘hot-spots’ of land change for each time interval. I expect these results to be directly relevant to land management and planning by supporting the adjustment of management strategies to account for land use legacies. My study will verify if the forest transition theory holds true in the Carpathian countries by using a spatially explicit dataset and I will explore detailed transitional trajectories for all land cover classes. Based on lessons from the Carpathian regions, my study may help predict land change in other parts of the world.

Tables

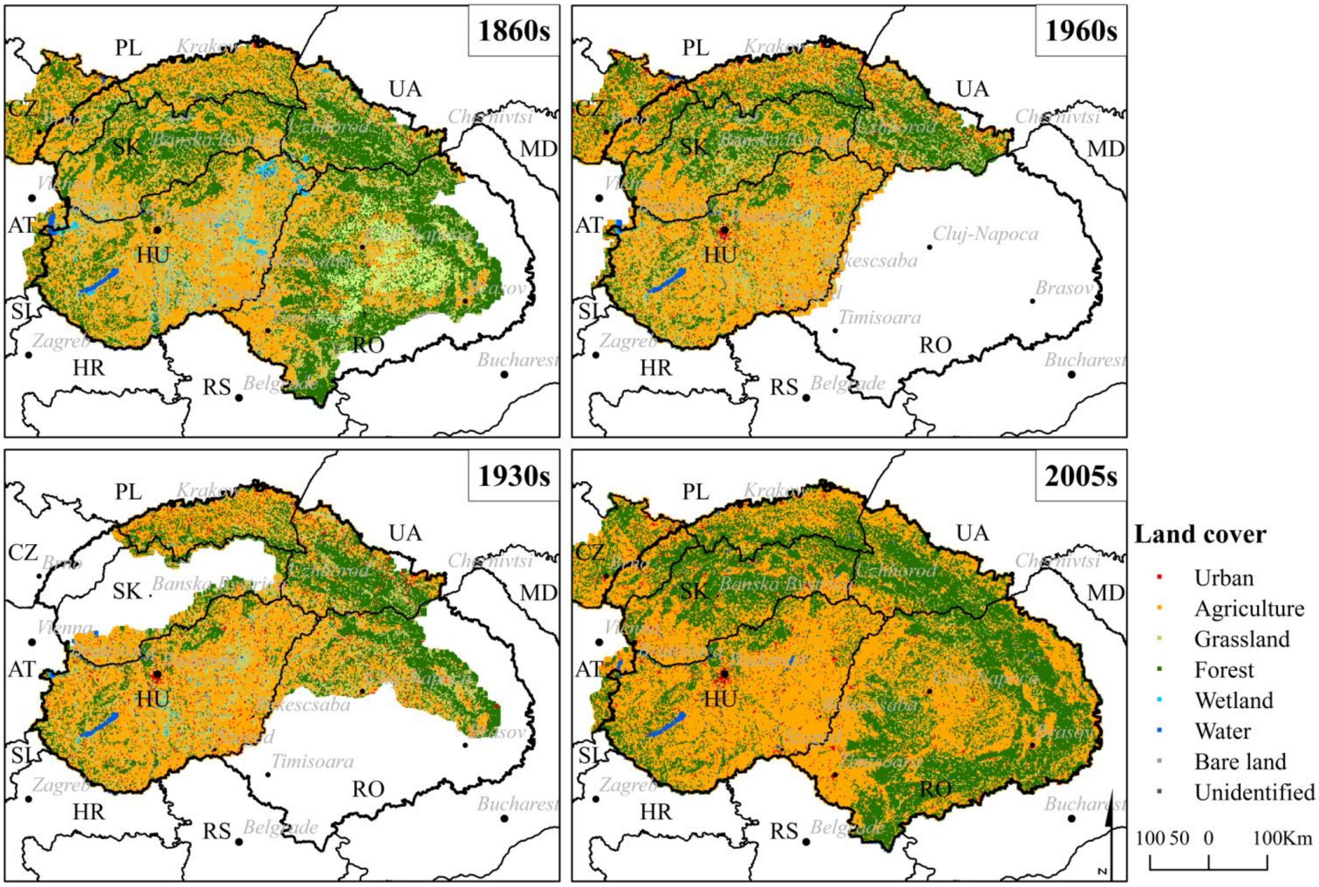
Table 3 Map and remote sensing data sources for mapping land change

Time layer	**Data range of maps**	**Map scale/ resolution**	**Map source/ description**
1860s	1819-1873	1:28.800	Second Austrian Military Survey
1930s	1910-1943	1:50.000 and 1:75.000	National Reambulation of the Third Austrian Military Survey
1960s	1949-1983	1:50.000	Soviet and National Military Maps from the Cold War period
1985s	1982-1987	30m	Landsat TM composite
2000s	1998-2002	30m	Landsat TM/ ETM+ composite
2010s	2008-2012	30m	Landsat TM/ ETM+ composite

Table 4 Possible continuous and categorical covariates to be used in the logistic regression models

Covariate	Type/ Resolution	Source
Elevation	Raster/90m	SRTM Elevation Model for Carpathian Countries CGIAR-CSI void-filled SRTM v4
Slope	Raster/90m	Derived from SRTM Elevation Model for Carpathian Countries, based on CGIAR-CSI void-filled SRTM v4
Soil type	Vector	Soil Group code of the soil unit from the World Reference Base (WRB) for Soil Resources.
Agricultural limitation		Code of the most important limitation to agricultural use of the soil unit, based on World Reference Base (WRB) for Soil Resources.
Rainfall	Raster/0.1º	Maximum 1-day total rainfall monthly/yearly gridded dataset. Climatological grid for the time-frame 1961-2010 from the CARPATCLIM Database, European Commission, JRC
Mean Air Temperature	Raster/0.1º	Mean air temperature monthly/ yearly dataset. Climatological grid for the time-frame 1961-2010 from the CARPATCLIM Database, European Commission, JRC
Number of severe cold days	Raster/0.1º	Number of severe cold days (Tmin < -10°C) monthly/yearly gridded dataset. Climatological grid for the time-frame 1961-2010 from the CARPATCLIM Database, European Commission, JRC
Distance to Waterway	Attribute	Calculated. Distance in meters to nearest waterway based on ESRI 2010 global main rivers layer.
Distance to Road	Attribute	Calculated. Distance in meters to nearest road based on ESRI 2010 road layer.
Distance to Settlement	Attribute	Calculated. Distance in meters to nearest settlement based on CORINE/LANDSAT settlement calculation.
Distance to border	Attribute	Calculated. Distance in meters to neareast country border
Historic land use	Vector/2km	Historic maps and Landsat imagery for 6 time layers according to Table 1.
Country	Vector	NUTS 0 country boundaries. ESRI 2010 administrative later.
District	Vector	NUTS 2 country boundaries. ESRI 2010 administrative later.
County	Vector	NUTS 3 country boundaries. ESRI 2010 administrative later.
Eco-region	Vector	Carpathain Convention for Carpathian Ecoregion. University of West Hungary for Pannonnian Plains.
Historic region	Vector	Euratlas Georeferenced Vector Data for 1900.

List of figures


1860s
1960s
1930s
2005s
PL
UA
CZ
SK
MD
AT
HU
SI
HR
RS
RO
Cluj-Napoca
Timisoara
Brasov
Bucharest
Zagreb
Land cover
Urban
Agriculture
Grassland
Forest
Wetland
Water
Bare land
Unidentified
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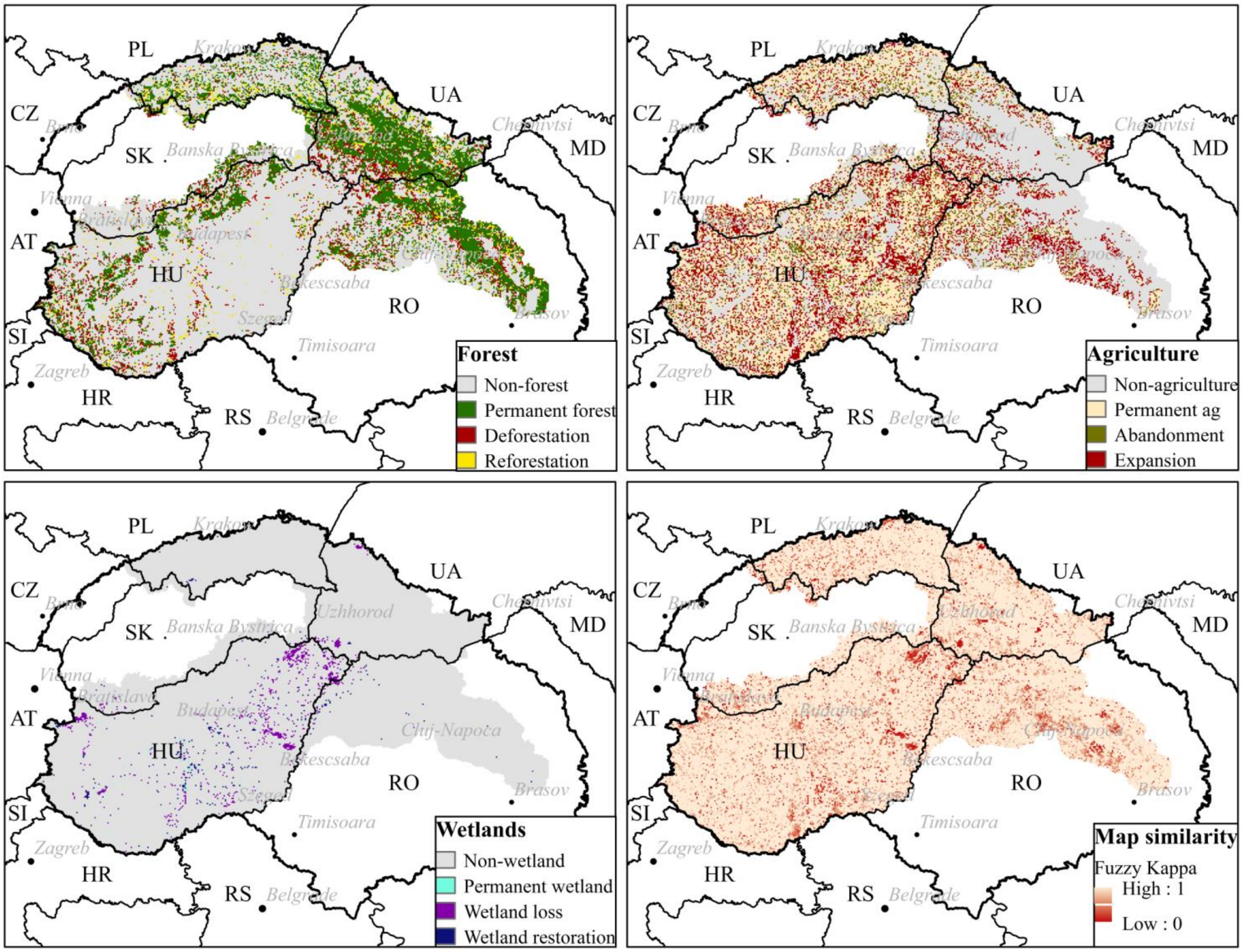
N

Figure 8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HR
RS
Banska Bystrica
Uzhhorod
Cluj-Napoca
Timisoara
Zagreb
Forest
Non-forest
Permanent forest
Deforestation
Reforestation
Agriculture
Non-agriculture
Permanent ag
Abandonment
Expansion
Wetlands
Non-wetland
Permanent wetland
Wetland loss
Wetland restoration
Map similarity
Fuzzy Kappa
High : 1
Low : 0

Figure 9

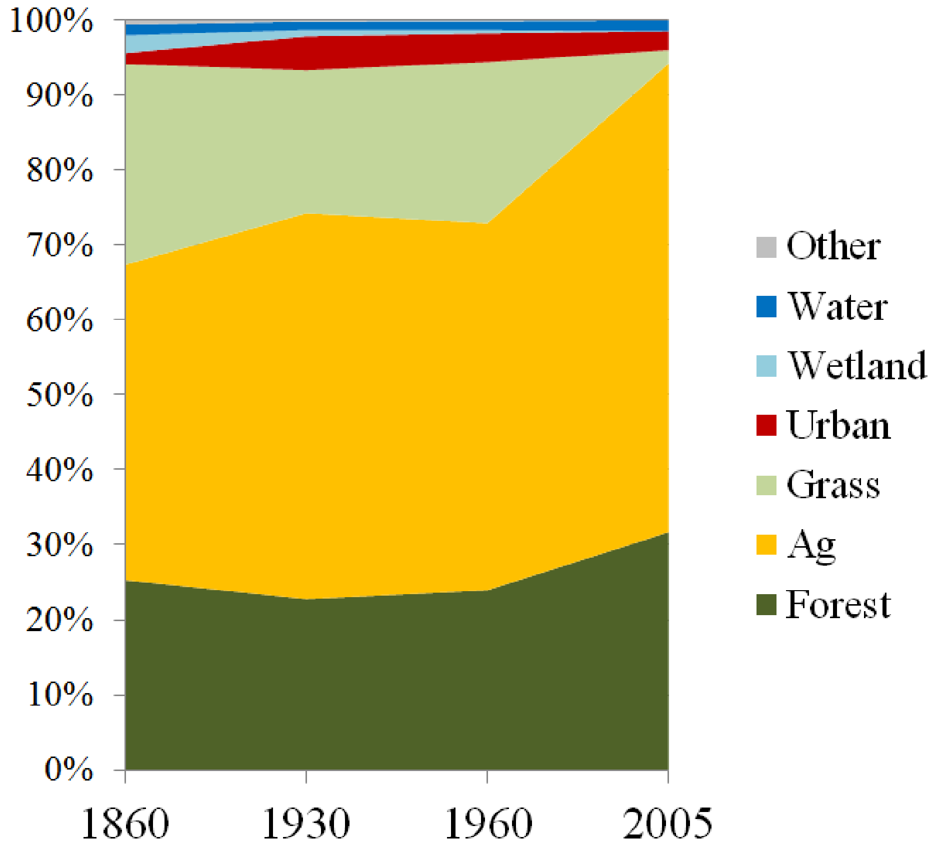

Figure 10

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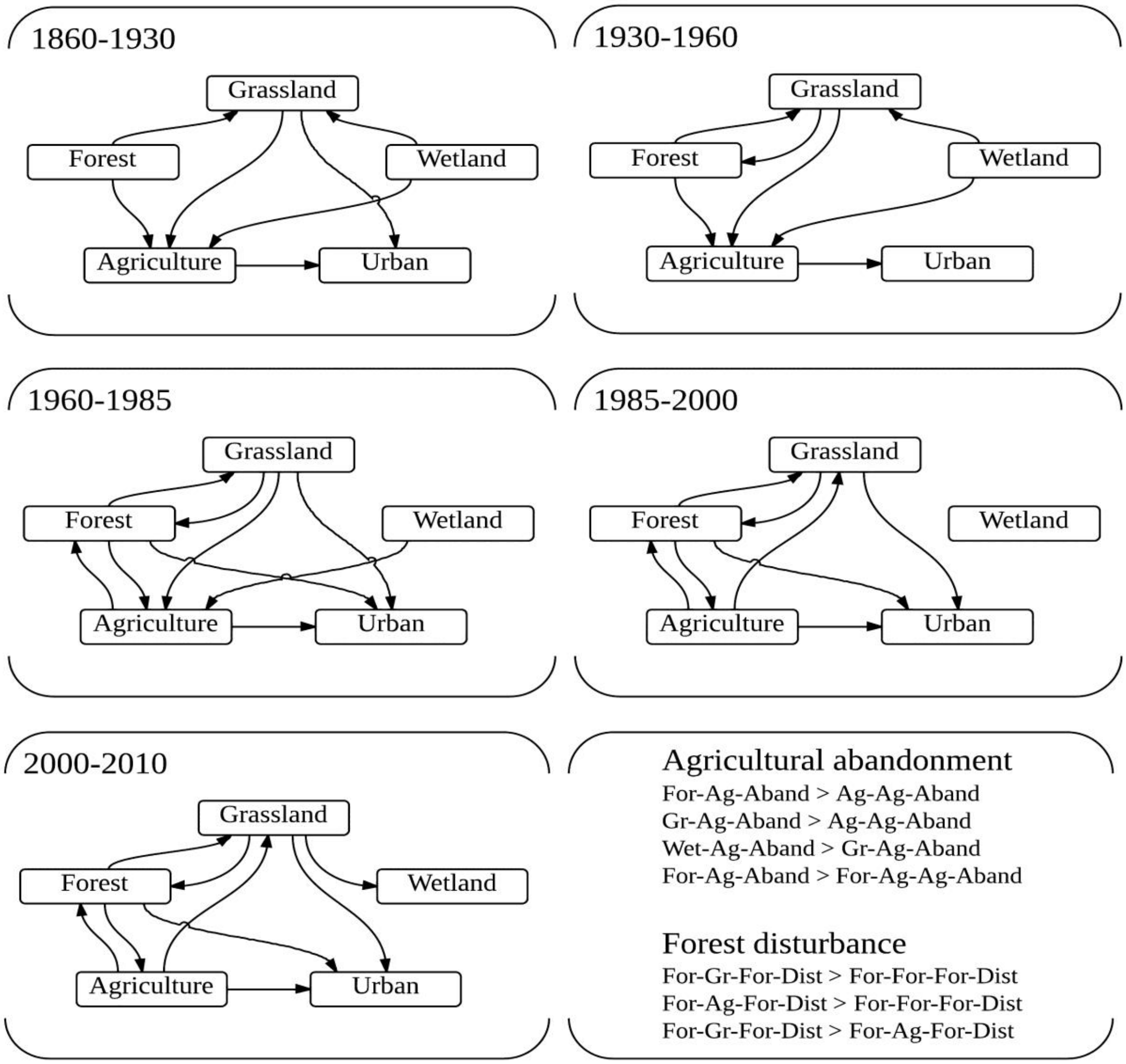

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Figure 11

Chapter 3: Socio-ecological shocks of totalitarian regimes scar the landscape after 50 years

Introduction

Humans have shaped the environment for centuries by interacting with the land and changing its use (Lambin et al., 2001). Such past changes are likely often at the root of more recent land system dynamics, affecting magnitude and extent of recent change (Thompson et al., 2013). When that occurs changes can appear ‘surprising’, because the effects of time lags and past land use legacies may only become apparent after years, decades, or even centuries (J. Liu et al., 2007). For example, scars of past natural resource use policies are still visible today (Brain, 2011; Bramwell, 1989; Uekötter, 2007), but their recent land cover outcomes have not been spatially analyzed or quantified. One response to past land uses can be ecosystem homogenization such as single species dominated forests (Thompson et al., 2013) and even-aged stands (Wallin et al., 1994). Recent socio-economic causes of forest change are clearly important (DeFries et al., 2004; Foley et al., 2005; Meyfroidt and Lambin, 2009; Rudel and Meyfroidt, 2014), but the role of the past uses and the related time-lags are most often not measured. This might lead to erroneous interpretation of the drivers of some of the most prominent land changes, such as broad scale deforestation.

When human alteration of land cover occurs suddenly, and over large scales, it constrains future uses, and I propose here that it causes the ecosystem to experience a socio-ecological shock. Examples of socio-ecological shocks include European settlement in the midwestern U.S., which lead to wide scale deforestation and conversion of grassland to agriculture (White and Mladenoff, 1994), and Soviet dam building along most important Eurasian rivers, which changed the land cover and altered the runoff of large areas (Josephson and Zeller, 2003). The scale and extent of socio-ecological shocks under totalitarian political regimes is often amplified by short-term policies aimed at transformation of natural ecosystems through industrialization, infrastructure development or tourism (Armiero and Graf von Hardenberg, 2013; Brain, 2011; Uekötter et al., 2013). For example, in the 1940s, Stalin’s Great Plan for the Transformation of Nature converted large parts of the Russian and Kazakh steppe into agricultural fields and forested areas (Brain, 2010). Relicts of such past land decisions, are still visible on the landscape in form of large areas of planted forest belts (Brain, 2010). Conversely, in Romania, Soviet forces institutionalized the overexploitation of natural resources to support political goals after WW II (Cioroianu, 2007). As a consequence, large-scale clear-cuts occurred in the Carpathians from 1954 to 1956, and I suggest that resulting changes in forest composition and structure constituted a socio-ecological shock.

Socio-ecological shocks affecting forest cover may in addition to affecting future land change also exhibit time lag effects due to forest rotation cycles. Short-term land use decisions such as large scale forest clear-cuts followed by reforestation projects generate pulses of even-aged forests and uneven age distributions of stands across large areas. As these areas progress through time at similar growth rates, their consequent uses are constrained by the past, and may persist for the duration of one, or even several forest rotation cycles (Wallin et al., 1994) or until natural disturbances occur. The reason for this is that forest plantations have a relatively fixed duration. Following WWII, Eastern Europe experienced multiple socio-ecological shocks, due to Soviet resource exploitation for natural gas, ore and timber (Kligman and Verdery, 2011), mostly following policies on war debt repayment. The Romanian case of the SOVROMs (Soviet-Romanian joint ventures aimed at generating revenue for post-war reconstruction) is an example of rapid timber exploitation to support a political goal (Cioroianu, 2007). According to a law from 1946, Romania was to provide 242500 ha forest and 660000 cubic meters of wood in exchange for Soviet forestry infrastructure and know-how (Banu, 2004). Approximately 3% of the Romania's forest cover was planned for cutting, mostly in areas close to the Soviet border (Banu, 2004). In the following years, centralized land use decisions led to forest plantations mostly consisting of fast-growing non-native species (Munteanu et al., 2008). Norway spruce became the dominant plantation species (Munteanu et al., 2008; Petric, 2009) with rotation cycles being prescribed between 40 and 130 years depending on production class and use (Disescu, 1954). Currently in Romania, fire and pulpwood, with prescribed rotation ages between 40-80 years (Disescu, 1954), makes up for about 40% of the total wood production (INS, 2013). Furthermore timber harvest often occurr prior to the prescribed age (Griffiths et al., 2013). The long-term land use outcomes of such past land use policies are thus likely currently becoming visible on the landscape.

The socio-ecological shocks that Eastern Europe experienced during the early socialistic years after WWII were later followed by two major socio-economic and political shocks: the collapse of socialism in 1989 and EU accession in 2004 and 2007. These changes brought new regulations and policies which affected land cover patterns (Baumann et al., 2011; Kuemmerle et al., 2008; Müller et al., 2013). The collapse of socialism, and the resulting changes in property rights and ambiguous legislation (Kuemmerle et al., 2009b; Munteanu et al., in review; Shandra et al., 2013) resulted in large scale forest disturbances especially in Ukraine and Romania (Baumann et al., 2011; Griffiths et al., 2013; Shandra et al., 2013). The question posed here is whether these disturbances are only the result of recent socio-economic and political changes, or if they are also a consequence of historically cleared forest stands having approximately reached the rotation age. This will be indicated by the degree of overlap between areas of recent deforestation and those that were clear-cut in the early years of the Cold War. Clear-cuts of the Cold War era occurred in the northern part of Romania, as well as in the Eastern Carpathians (Banu, 2004). These areas coincide with areas of high forest disturbances, in the case of the northern Romanian Carpathians for the period 1990-1995 and in the eastern Romanian Carpathians for 1995-2000 (Griffiths et al., 2013). Consequently alongside the political and socio-economic shocks affecting recent change (Griffiths et al., 2013; Kuemmerle et al., 2011) the past socio-ecological shocks experienced by forest in the middle of the 20^{th} century might be important in shaping the recent patterns of forest disturbances observed after 1990.

However, data-availability and reliability from the Cold War period has been a barrier to documenting past patterns and understanding the effects of land management. National statistics are questionable and the existing military maps from the Cold War period (VTU GSh, 1989) do not document land use patterns such as forest disturbance, and thus do not allow to assess the extent or intensity of past land uses. What may remedy this situation though is the availability of a declassified surveillance satellite images from the 1960s (Peebles, 1997), which provide a unique opportunity to extract reliable land use information for the mid 20^{th} century. Argon and Corona reconnaissance missions were flown by the U.S. since the early years of the Cold War (first successful mission on August 18^{th} 1960), largely to detect and prevent nuclear missile use by the Soviet Union (Norris, 2008; Peebles, 1997). The imagery covers large tracts of Europe, Asia, Africa, as well as the Arctic and Antarctic, and provide a detailed account of the Earth's surface prior to Landsat (Cassana and Cothren, 2008). Furthermore, the imagery has excellent spatial resolution (up to 1.5 m) and offers stereoscopic viewing (Sohn, 2004; Zhou et al., 2002), thus providing information on the long term dynamics of ice-sheets in Greenland (Zhou and Jezek, 2002) and Antarctica (Kim et al., 2007), wetland change (Hamandawana et al., 2007), as well as archeological sites (Kim et al., 2007; Sohn, 2004). In terms of land use change, Corona imagery depicts that 97% of Egypt's 1965 tree cover has persisted (Andersen, 2006). However, in Senegal and Mali agricultural land increased from 1963 to 1992 at the expense of brushland and woodlands (Ruelland et al., 2010; Tappan et al., 2000).Similarly, in Burkina Faso and Ghana colonial forestry policies contributed to the reduction of savannah woodlands (Wardell et al., 2003). Overall though, the use of Corona and Argon data for forest assessment is still scarce, partly due to difficulties when geometrically rectifying the data (Sohn, 2004; Tappan et al., 2000). This is unfortunate though because the imagery can be an important and reliable source of information for the mid 20^{th} century, filling a temporal gap in long-term forest dynamics analysis. I will use Corona data to assess forest cover in the 1960s and investigate the effects of past socio-ecological shocks on recent forest disturbance patterns.

Objectives

My overall goal is to explore the extent to which historic socio-ecological shocks – specifically policy-induced, sudden, broad-scale forest disturbances - explain the timing, spatial extent and magnitude of more recent forest harvests and natural disturbances. I will investigate the relation between clear-cuts occurring in the 1960s as a result of Soviet natural-resource exploitation policies and recent (post 1990) disturbances. I aim to understand if the abrupt changes in forest cover since 1990 are related to past forest management and rotation cycles. My specific goals are:

1. Map forest cover during the early years of the Cold War, by rectifying and classifying declassified satellite imagery from the 1960s.
2. Compare forest cover of the 1960s and the post-1990s and explore the overlap between past socio-ecological shocks and recent forest disturbances.
3. Explain the relation between patterns and magnitude of recent forest disturbances and past harvest in the light of forest rotation cycles.

Methods

I will map forest cover right after the establishment of the socialist regime using historic satellite imagery (1960s) and compare it to recent forest cover data (post 1990s) in order to understand how the Soviet ‘socio-ecological shock’ is reflected in recent land use changes in different countries. I will use three trans-boundary areas in the Carpathian region as study areas. I hypothesize that heavy clear-cuts as part of the natural resource exploitation policies of totalitarian regimes of the early 20th century, explain more than a half of the forest disturbances occurring after 1990s: i.e. that past ‘socio-ecological shocks’ have a greater influence on land change patterns than recent socio-economic shocks.

Study areas & sampling design

I will analyze three study areas in the Carpathian region that capture diverse historical and recent socio-economic, political and environmental settings. The Carpathian regions is particularly interesting to study questions related to past ‘socio-ecological shocks’ and recent socio-economic shifts because the fascist and communist regimes of the early 20th century both had extensive plans to transform Eastern Europe into a major natural resource-provider (Josephson and Zeller, 2003) and supported forestry as part of their political ideology (Brain, 2010). However, despite the similarities across the region, each country’s history and political orientation after WWI and especially after WWII determined the extent to which these ideologies and policies were applied on the ground (Brain, 2010; Kligman and Verdery, 2011), and that provides me with a unique opportunity for cross-border comparisons.

I selected study areas that capture both the environmental diversity of the Carpathian Mountains (the Northern, Eastern and Western Carpathians) along with the political and socio-economic diversity among the countries. For example, following WWII, parts of Poland and Slovakia were forcefully depopulated, allowing for forest recovery (Janicki, 2004; Kozak et al., 2007), while Soviet policies on war debts repayment caused heavy exploitation of resources in Romania (Banu, 2004). With the onset of the Cold War, the political decisions in the Eastern Block were heavily influenced by soviet politics. Yet after 1990, development paths diverged significantly, especially with EU accession of most countries in 2004 and 2007.

I will capture differences among countries by using study-sites in trans-boundary regions of the Carpathians. I selected study-sites based on three factors: (1) forest age as reported in national forest inventory data (Figure 11), (2) areas mentioned in the literature as having been harvested in the mid 20th century as part of fascist or communist totalitarian policies (Banu, 2004; Cioroianu, 2007; Kligman and Verdery, 2011), (3) occurrence of forest disturbance following 1990 based on Landsat imagery classification (Griffiths et al., 2013). Histograms of the forest age distribution for each region and their skewness, alongside with forest composition information, provided me with an indicator of tree cohorts that reached the forest rotation age for pulp production (between 40-80 years - Disescu, 1954) after 1990 (Figure 11). Literature on the environmental history of the region, provided me with some indication of the places where both fascist and communist policies resulted in the exploitation of natural resources (Banu, 2004; Josephson and Zeller, 2003; Kligman and Verdery, 2011). Finally, the map of post-soviet forest disturbances (Griffiths et al., 2013) allowed me to select areas that experienced both disturbance and no-disturbance after the collapse of the Soviet Union.

Based on these criteria, I selected three Carpathian trans-boundary regions as test-sites: the Polish-Ukrainian-Slovakian border, the Romanian-Ukrainian border and the Romanian-Hungarian border (Figure 12). Each study region covers an area of approximately 150x50km and together they capture five different socio-economic, political, and environmental contexts of the Carpathians.

Historic satellite imagery rectification and classification

I will use Cold War reconnaissance satellite imagery taken by United States military forces to map historic forest cover. The study areas are covered by approximately 30 Corona images recorded between May 1962 and September 1969. Each scene covers 17 x 230km, and has resolutions ranging from 2 to 10 m on the ground, depending on the mission (Sohn, 2004). Corona data is available through the USGS as scanned pan-chromatic film strips, each strip consisting of four image tiles. Data quality and resolution varies among missions, due to technical differences in camera types, orientation, and satellite altitude (Sohn, 2004; Zhou et al., 2002). For the Carpathian region, images from the Corona Keyhole 4 and Keyhole 4A Missions are available in good image quality, with only minor parts of the images being out-of focus or affected by film static. However, the scanned data need to be geometrically and radiometrically rectified in order to derive a land-use classification from them.

Archival imagery has not been widely used in environmental monitoring (Hamandawana et al., 2005), mainly because of the difficulties related to the rectification and classification of these images (Tappan et al., 2000). However, Corona data has been used in various contexts, reaching from visual interpretation (Tappan et al., 2000) to elaborated models for rectification, that account for panoramic camera distortions and external orientation (Sohn, 2004). The main difficulty lies in the lack of information about the sensor (camera height, interior orientation, exterior orientation) (Hamandawana et al., 2007; Sohn, 2004; Zhou et al., 2003) and the technical differences among missions (Peebles, 1997). Furthermore, the raw images have a high level of spatial distortion, since the original ‘bow-shaped’ image is compressed in a rectangular image frame (Cassana and Cothren, 2008).

Correction using mathematical models that account both for position and orientation changes of camera (Sohn, 2004) perform best in Corona rectification, but they are largely unavailable in commercial software, and photogrammetric frame models have also been applied with good accuracy, as long as a sufficient number of control points is used (Cassana and Cothren, 2008).The most accurate rectification models for Corona images are based on modified collinearity equations and third order polynomial functions. The collinearity equations refer to the alignment of object space and the image space, using the projection through the optical center of the camera. In the case of Corona imagery rectification, modified collinearity equations aimed at removing distortion in panoramic photographs and estimating the exterior orientation parameters (Sohn, 2004) proved to perform well in terms of accuracy (+/-4m). These models use a relatively small number of control points, with accuracies becoming stable around 15-20 points per image strip. The advantage of using modified collinearity equations is the very good accuracy of the rectified image and the reduced number of control points. An alternative and more commonly used approach involves separate rectification of sub-images, mostly using third order polynomial transformations (Cassana and Cothren, 2008; Lorenz, 2004). Using photogrammetric frame models, each sub-image is treated as an individually captured photograph of aprox. 5000x5000 pixels. This approach requires aprox. 20 control points per image tile and achieves accuracies of minimum +/- 15m (Cassana and Cothren, 2008).

Another approach that takes the exterior, interior, and orientation parameters as unknowns is the block bundle adjustment, which ties overlapping images together without the absolute need for ground control points in each image (Zhou et al., 2002). Potential issues in the referencing of historic data relate to the clustering of control points and low number of points in a single image. In such situation, tie-points (identifiable features measured only in image coordinates) can help increase the number of usable points/ image (Kim et al., 2007; Zhou et al., 2003). Leica Photogrammetry Suite (Cassana and Cothren, 2008), ERDAS (Cassana and Cothren, 2008; Tappan et al., 2000; Zhou et al., 2002) and Arc (Zhou and Jezek, 2002; Zhou et al., 2002) software all provide algorithms for image rectification.

Following the geometric rectification, radiometric discrepancies among images in the mosaicking process are minimized by using seamless functions (Zhou et al., 2003, 2002), hermite based functions for weighting of pixels along blending areas (Zhou et al., 2003, 2002), or linear stretching (Kim et al., 2007). After the geometric rectification, image filtering, bright strip removal and radiometric balancing are essential before automated classifications can be attempted. Radiometric correction of historic satellite imagery has not been wide-spread though because automated classifications have rarely been performed on this type of data. However, adaptive filtering to remove noise and grain based on region growing algorithms were successfully applied to Argon data to remove noise of various spatial extents (Zhou et al., 2003, 2002).

I will rectify and pre-process Corona images using ENVI 4.8 software (Canty, 2007) because of its' capability to deal with multiple, stacked raster datasets. ENVI provides the possibility to mosaic images pre- and post- geometric rectification, but has – to my knowledge – not yet been tested for Corona imagery. Each Corona film strip consists of four overlapping tiles. I will first mosaic these tiles based on the overlapping areas, disregarding other spatial references, just to reconstruct each film strip. I will then reference each strip using the corner coordinates provided by USGS. Because fiducial marks are not available on Corona imagery, these coordinates are only an approximation and further registration is required. I will perform image registration using ENVI 4.8 based on national sets of rectified military topographic maps for the time period 1950-1970s. Because the spatial distortion of the Corona imagery is large, and depending on the selected transformation, I will use a minimum of 60 control points/ image and aim to obtain accuracies of 5-15 meters on the ground (Cassana and Cothren, 2008; Sohn, 2004). I will include elevation information in the rectification process in order to account for spatial distortion in mountain areas (Kim et al., 2007; Zhou et al., 2002). Finally, I will produce three image mosaics, one for each of the study areas. I will test post-referencing mosaicking techniques using seamless functions and rubber sheeting to adjust discrepancies and match the original image to the selected map projection (Doytsher and Hall, 1997; Doytsher, 2000). After the geo-rectification, I will run radiometric filters in ENVI in order to remove film grain, corona effects (over-exposed film areas) and film static (Sohn, 2004). Following image rectification, I will use a subset of control points to calculate average accuracy and confidence interval for spatial accuracy (Zhou et al., 2002).

For the land use classifications, I will test semi-automated object based classification and image segmentation techniques to map forest cover. Object based classification uses not single pixels as classifiers, but groups of pixels that represent objects to be classified (Blaschke, 2010; Walter, 2004). Image segmentation techniques identify homogeneous parts of the image with respect to some characteristic such as grey tone or texture (Haralick and Shapiro, 1985). In addition to the original image, I will apply several morphological filters on the original image (edge detection, sharpening, opening) and I will incorporate these in the segmentation process, to improve the performance of the algorithm. I will perform image segmentation using eCognition software (Chen et al., 2009; Flanders et al., 2003). I will test segmentation for different spectral and neighborhood thresholds and will perform a supervised classification of the segments for 3 land cover classes: forest, non-forest and harvested. I will validate my classification with a set of military topographic maps of the 1960 (VTU GSh, 1989).This is particularly relevant for the 'harvested' class, because non-forest areas could easily be miss-classified as non-forest in the automated classification. The comparison with topographic maps will indicate if such areas are included in the forest inventory, thus supporting my classification of the 'harvested' class. I will use a randomly generated set of points to assess classification accuracy. Land cover at these points will be hand-digitized using military topographic maps of the 1960 and on-screen visual interpretation of the Corona imagery. I am optimistic that my automated approaches will be successful, but I realize that this task is challenging (Tappan et al., 2000). If the automated classifications fail, I will use a set of 1000 randomly generated points in each of my three study areas. At each point I will hand-digitize land cover visually, on-screen. This will allow me to model change and explain the relation between past and recent forest cover (see below).

Recent land cover and land change analysis

I will analyze forest disturbance patterns after 1990 using wall-to-wall Landsat forest disturbance maps of the study region (Griffiths et al., 2013). These maps provide information on annual forest disturbance rate in five-year intervals and will allow me to assess post-soviet forest change relative to the disturbances mapped from Corona data. I will use post-classification comparison to highlight the extent of post-soviet forest disturbances that overlap Cold War 'socio-ecological shocks'. I will use Map Comparison Kit (MCK) (Visser and De Nijs, 2006) to identify three land change processes: a) post-soviet forest disturbance in areas that were not disturbed around 1960s, b) post-soviet forest disturbance in areas that were disturbed in the 1960s and c) post-soviet forest recovery in areas that were disturbed around 1960s. In addition, I will produce maps of areas that did stay under continuous forest or non-forest cover and maps of forest regrowth on 1960s non-forest areas. I will compare the extent of the recurring forest disturbance over 1960s harvested land to the other two change classes. This will indicate the importance of past ‘socio-ecological shocks’ in determining the location and extent of recent forest disturbance, as well as their relative relation to areas harvested due to recent socio-economic shocks in political and economic situations. The MCK algorithm will allow to control for small differences due to mapping method and data source differences, by reporting fuzzy kappa values (Pontius, 2000; Runfola and Pontius, 2013)

Explaining post-soviet disturbances by Cold War land uses

I will use a logistic regression model (Hosmer and Lemesbow, 1980) to explain to what extent the recent disturbances are a result of past socio-ecological shocks. I will analyze significant variables that may explain post-soviet deforestation and will test the hypothesis that more than half of the post-soviet forest disturbances occur due to forest disturbances prior to 1960s, rather than post-soviet socio-economic shifts.

Within each of the 3 test areas, I will generate a set of 1000 stratified random points, with a minimum distance between points of 1 km and parameterize logistic regression models including continuous and discrete variables as indicators of environmental conditions, political regimes, accessibility and historic land use (Table 5). The response variable will be presence-absence data of post-1990 forest disturbance.

I will check for coefficient significance using likelihood ratio tests and will perform best subset logistic regression to select the most parsimonious model that explains change. I will consider model adjustment to eliminate spatial correlation (based on semivariograms) and multicollinearity. I will derive the odds ratio from the slope coefficients of the regression (Hosmer et al., 2013) and interpret this in context of my land change hypothesis. I will test hypothesis related to the relative contribution of socio-economic contexts (EU membership, country etc.) and the 1960s forest disturbances to recent deforestation patterns.

Expected results

My main result will to elucidate the relation between post-soviet forest disturbances and post WWII ‘socio-ecological shocks’. My analysis will generate several mapped datasets: 1) the first spatially explicit and reliable forest cover map for the early years of the Cold War period; and 2) land change maps for the 1960s and post 1990s depicting the overlap of forest harvest in the two periods. Aside from mapped datasets I will explain recent disturbances in relation to past socio-ecological shocks and will quantify the extent to which past disturbances drive recent deforestation.

I expect that the forest disturbances after the collapse of the Soviet Union will be partly explained by the widespread clear-cuts conducted in the 1950s in Eastern Europe. I expect to demonstrate that past socio-ecological shocks due to abrupt land use decisions have at least as dramatic effects on the forest ecosystem as more recent the socio-economic and political shifts.

My results will establish an important link between the drivers of historic land change and those of recent changes, and will underline the importance of considering legacies and time-lags in land change science.

Methodologically, I expect to develop a reliable and efficient method to use declassified surveillance satellite imagery for historic land cover change assessment. I expect that by using a combination of object based classification techniques and image segmentation approaches I will be able to automatically detect forest cover in a variety of panchromatic images.

Significance

My study contributes to land change sciences by advancing the understanding of land use legacies and time lag effects as drivers of recent land change. It underlines the importance of longitudinal studies in analyzing change and highlights the potential problems deriving from short-term studies, such as erroneous or incomplete interpretation of change-drivers. The comparative analysis of past disturbances with recent forest cover will contribute to explaining some of the recently observed deforestation patterns, while relating them to the land cover legacies from Soviet times. My methodological contributions consist of the first land cover assessment using Corona imagery in temperate forest ecosystem, and the development of an image segmentation approach for the automatic detection of forest cover from panchromatic satellite imagery. The method is applicable for the entire coverage of the Corona Mission, including Asia, northern Africa and parts of the Arctic and Antarctica, and will allow land cover assessments based high-resolution imagery for a time-period that has not previously been mapped at broad scales. My results will be relevant in guiding future forest management in terms of where plantings should be concentrated and what age composition should be aimed for. Current harvest patterns may affect future land uses after more than 50 years in the future and this is important in the context of forest management. My study is also relevant to other related disciplines, because it produces reliable forest cover information over a time-span that has long been characterized only by questionable statistics. For example, researchers in economics, environmental history, and other social sciences, may benefit from the data I generate on natural resource exploitation. Furthermore, my results may be important for predicting future land change both in and outside the region.

Tables

Table 5 Variables to be used in logistic regression

Covariate	Type/ Resolution	Source
Elevation	Raster/90m	SRTM Elevation Model for Carpathian Countries CGIAR-CSI void-filled SRTM v4
Slope	Raster/90m	Derived from SRTM Elevation Model for Carpathian Countries, based on CGIAR-CSI void-filled SRTM v4
Soil type	Vector	Soil Group code of the soil unit from the World Reference Base (WRB) for Soil Resources.
Distance to Waterway	Attribute	Calculated. Distance in meters to nearest waterway based on ESRI 2010 global main rivers layer.
Distance to Road	Attribute	Calculated. Distance in meters to nearest road based on ESRI 2010 road layer.
Distance to Settlement	Attribute	Calculated. Distance in meters to nearest settlement based on CORINE/LANDSAT settlement calculation.
Distance to border	Attribute	Calculated. Distance in meters to nearest country border
Country	Vector	NUTS 0 country boundaries. ESRI 2010 administrative later.
District	Vector	NUTS 2 country boundaries. ESRI 2010 administrative later.
County	Vector	NUTS 3 country boundaries. ESRI 2010 administrative later.
Eco-region	Vector	Carpathian Convention for Carpathian Eco-region. University of West Hungary for Pannonnian Plains.
1960s forest cover	Vector	Derived from classified corona imagery. Classes: forest, non-forest, disturbed forest.

List of figures

Figure 12: Forest age distribution by age-class, summarized for administrative regions of Poland, Slovakia and Romania. Most data was mapped in the interval 1999-2008.

Figure 13: Carpathian region, coverage of 32 Corona film strips in trans-boundary areas and approximate location of three study areas of 50x150km.

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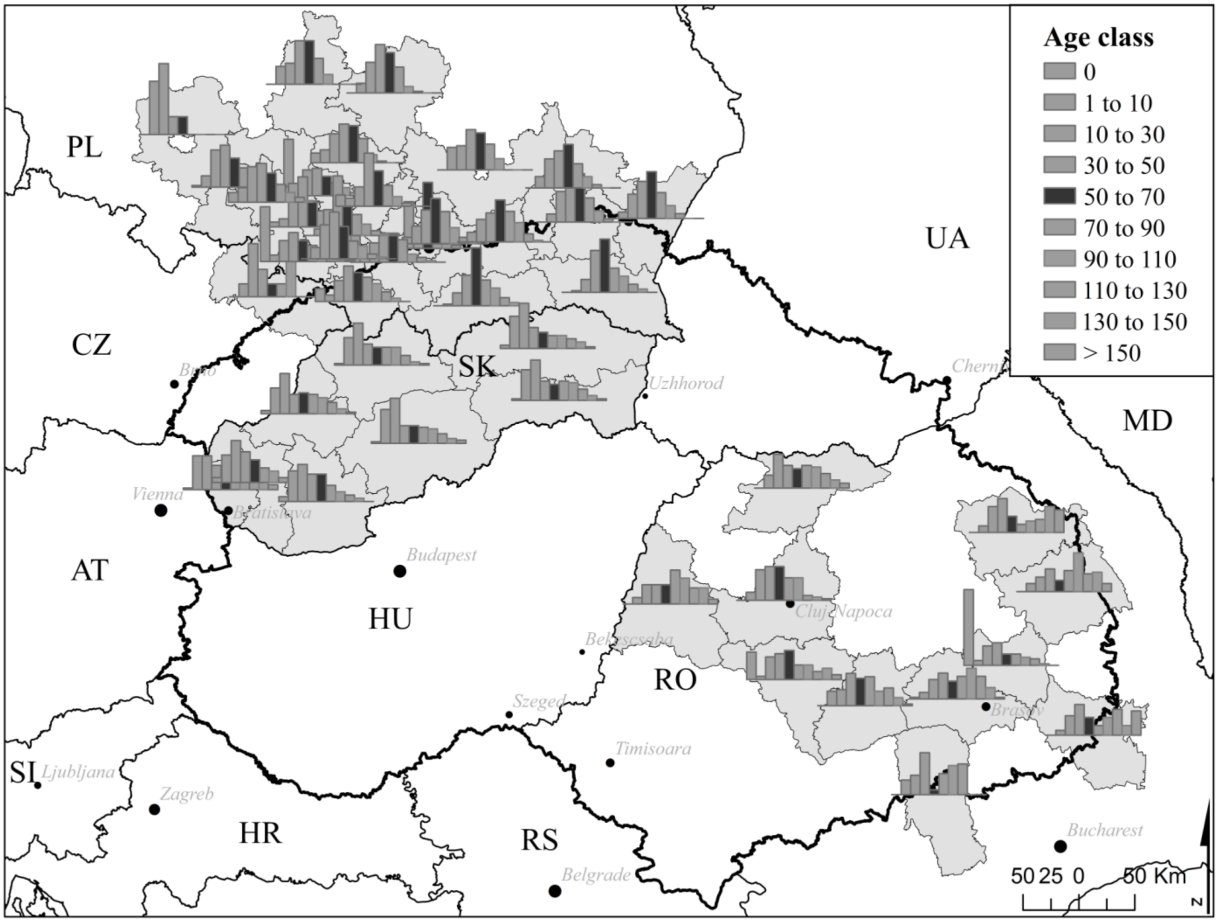

Figure 12

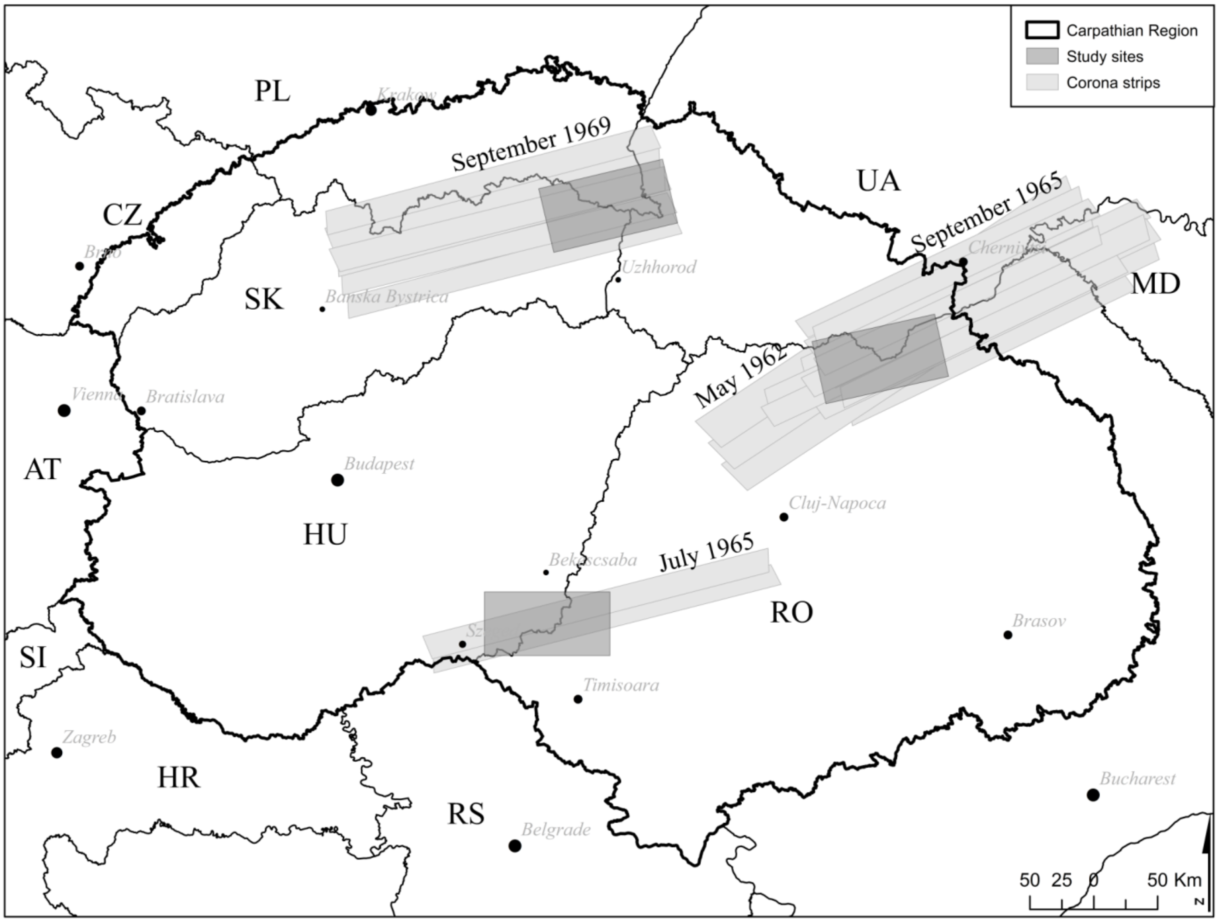
Carpathian Region
Study sites
Corona strips
PL
CZ
SK
UA
MD
AT
HU
RO
SI
HR
RS
September 1969
September 1965
May 1962
July 1965
Krakow
Uzhhorod
Banska Bystrica
Vienna
Bratislava
Budapest
Cluj-Napoca
Brasov
Timisoara
Zagreb
Belgrade
Bucharest
50 25 0 50 Km

Figure 13

Overall significance of the dissertation

My research will be - broadly speaking - relevant to land change science, remote sensing, and land management. The Carpathian Basin enables me to analyze effects of land use legacies over broad temporal and spatial scales. The environmental diversity of the region combined with the multiple political and socio-economic shocks that Eastern Europe experienced over a relatively short time span, both influenced land management and land use decisions, providing a great ‘natural experiment’ to investigate the relation between past land uses and recent change. Ultimately, the results of my research will be broadly relevant to many landscapes, because they will elucidate the role of land use legacies in determining the magnitude, spatial extent and timing of subsequent transitions. Similarly, my methods have the potential to be applied to other regions with long land use histories and extrapolated to continental scales.

My first chapter functions as a broad review of change processes in the Carpathians and their drivers. The results demonstrate that for the same land use type, the direction of change is influenced by different underlying drivers. For example agricultural abandonment is driven by socio-demographics, while agricultural expansion is mostly driven by institutional and economic factors. This first chapter also sets the stage for the further analysis of the role of land use legacies. My second chapter examines in depth the complex interactions of historic land uses and the relative role of legacies and their timing in determining recent change. The main contribution of this chapter will be the quantification of the role of legacies and hence demonstrate the need to incorporate legacies into analysis of drivers of land change. In addition to assessing legacies *per* se, I will examine how the duration of a given land use affects the magnitude of subsequent changes. In my third chapter, I will analyze in detail the drivers of forest change, and in particular potential time-lag effects of past socio-ecological shocks for recent forest transitions. I expect to demonstrate that some ecosystems might need several decades to display effects of past disturbances, and thus underline the need of incorporating time-lags when interpreting land change.

Within the scope of my dissertation, I plan to publish three peer-reviewed journal articles relevant to the fields of land use science, remote sensing and land use policy (Table 6). My project will also derive a variety of new datasets, mostly consisting of land cover maps and land change maps (Table 7), and I will make these available to the scientific community, and land management agencies and conservation groups alike. Overall my research will contribute land change science and practice in terms of theoretical scientific advancements, methodologies as well as practical land management and conservation.

Scientifically, my work will elucidate the role of land use history, legacies, and their driving forces in different land change processes (Chapter 1). By modeling change over long time periods, I will advance the scientific understanding of the relative role of land use legacies in determining current change. I will assess how much land use persistence determines the speed and magnitude of subsequent changes and I will advance the theoretical understanding of land system dynamics as a function of the past (Chapter 2). Overall, I expect that my results will indicate that past land uses determine where transitions occur and that a longer duration of a given land use type, results in slower subsequent land transitions. Furthermore, my results will highlight the extent to which the study of long-term dynamics is important to understand land changes, especially when studying forests or pastures, where effects of past socio-ecological-shocks may exhibit a time-lag (Chapter 3). In the case of forests, I expect that time lag effects of past uses occur at intervals approximately matching forest rotation cycles.

In addition, my results will test the applicability of forest transition theory in an area that experienced multiple socio-economic and political shifts and will elucidate if such shocks change the magnitude or direction of change, causing multiple transitions. My research will also contribute more broadly to the understanding of land change dynamics of regions affected by multiple socio-economic and socio-ecological shocks and thus be relevant to any regions that are currently hot-spots of human pressure on the environment due to wars and political unrest (e.g., the Middle East) or large development projects (e.g., China). For the Carpathian region itself, I will produce 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**, I will develop technical approaches to study long-term land change. Specifically, I will develop a strategy for the automated detection and classification of historic land cover maps from panchromatic data. My analysis of Corona satellite imagery will exemplify this approach for high resolution (1-10meters) remotely sensed data and will provide land cover maps for one of the time periods of modern history for which other data are most questionable in terms of data reliability, i.e., the Cold War. This contribution is significant, because U.S. reconnaissance satellite missions from the Cold War period covered most of Europe, northern Africa, all of Asia, as well as the Arctic and Antarctic. Having a method to assess land change based on these high resolution images provides great new opportunities for scientific inquiry related to historic land change across a large part of the world. After the collapse of the Soviet Union, the development paths of former Soviet republics, and hence their land use trends, diverged. It is likely that these trends were influenced by past land use patterns, but data that could capture those patterns is limited. My study will open up new possibilities to study land use and land cover questions in the early Soviet Union and its satellite states. It will also facilitate a series of comparative studies related to the effects of past land uses across regions. Last but not least, my method to classify panchromatic data automatically will be applicable to any other type of aerial photography, thus enabling the automated analysis of land cover as far back as World War I.

In addition to new remote sensing methods, I will develop a set of logistic regression models that will explain the role of land use legacies and time lags in determining the extent and magnitude of recent change. My models will be applicable to any area for which there are spatially explicit long term datasets of land cover and can be used to reveal the relative importance of past uses for recent changes, and to predict areas of future change based on past transitions. The fuzzy-set map comparison approach can be used in conjunction with these models to spatially explain the distribution of hotspots of change. The method of fuzzy map comparison is particularly relevant in the context of historic data where no validation is possible and data sources may vary across time. Areas where the implementation of my models and fuzzy set analysis would be particularly interesting include regions which underwent multiple transitions in the past, driven by changes of political, socio-demographic, economic or even 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 will also be relevant in the context of **land management and conservation**. My results will inform stakeholders on the importance of past land uses, so that they can consider these legacies in their current planning. For the Carpathian region, my datasets will elucidate the spatial and temporal extent of land change for over a century and across two eco-regions. These datasets are relevant both in a land management (forestry and agricultural planning) and in a conservation context. My results will support management decisions, such as identifying priority areas for conservation, and can help to mitigate effects of recent legacies. As such, my study provides an important basis for the emerging cross-border conservation and management efforts for the Carpathians, because it generates the first long term comprehensive, spatially explicit land change assessment that is consistent and comparable across six countries. The data resulting from my dissertation will be publicly and freely available both to practitioners and to the science community. The project is highly interdisciplinary and scientists in other fields may benefit from this data in their analyses on social, political, economic or conservation questions related to changes in land use. My research will therefore provide valuable information for other research disciplines.

Tables

Table 6 : Planned publications, targeted journal and planned submission dates

Topic	Targeted journal	Submission to journal
Forest and agricultural land change in the Carpathian region – a meta-analysis of long-term patterns and drivers of change	Land Use Policy	July 2013
Do land use legacies matter for recent land transitions?	Annals of the Association of American Geographers	May 2014
Socio-ecological shocks of totalitarian regimes scar the landscape after 50 years?	Remote Sensing of Environment	December 2014

Table 7 : Datasets resulting from the dissertation

Dataset	Extent
Map of existing case-studies of forest and agricultural change (meta-analysis)	Carpathian Basin ~ 350,000 km^2
Map of historic land uses for 1860, 1930, 1960	Carpathian Basin ~ 350,000 km^2
Map of land change for the periods 1860-1930-1960-1990-2000-2010	Carpathian Basin ~ 350,000 km^2
Map of hotspots of land change between 1860-2010	Carpathain Basin ~ 350,000 km^2
Map of potential future land changes	Carpathain Basin ~ 350,000 km^2
Map of forest cover and deforestation for 1960s	Three test areas of ~ 7500 km^2 each, for border regions RO-UA, UA-SK-PL, RO-HI
Forest change maps between 1960s – post 1990s	Three test areas of ~ 7500 km^2 each for border regions RO-UA, UA-SK-PL, RO-HI

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