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Legacies of 19th century land use shape contemporary forest cover

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ABSTRACT

Historic land use can exert strong land-use legacies, i.e., long-lasting effects on ecosystems, but the importance of land-use legacies, alongside other factors, for subsequent forest-cover change is unclear. If past land use affects rates of forest disturbance and afforestation then this may constrain land use planning and land management options, and legacies of current land management may constrain future land use. Our goal was to assess if and how much land-use legacies affect contemporary forest disturbance, and the abundance of different forest types in the Carpathian region in Eastern Europe (265,000 km^2, encompassing parts of Poland, Slovakia, Ukraine, Romania, Hungary, and Czech Republic). We modeled contemporary forest disturbance (based on satellite image analysis from 1985 to 2010) as a function of historic land use (based on digitized topographic maps from 1860 and 1960). Contemporary forest disturbance was strongly related to historic land use even when controlling for environmental, accessibility and socio-political variation. Across the Carpathian region, the odds of forest disturbance were about 50% higher in areas that were not forested in 1860 (new forests) compared to areas that were forested then (old forests). The forest disturbance in new forests was particularly high in Poland (88% higher odds), Slovakia (69%) and Romania (67%) and persisted across the entire range of environmental, accessibility and socio-political variation. Reasons for the observed legacy effects may include extensive plantations outside forest ranges, predominantly spruce, poplar, and black locust, which are prone to natural disturbances. Furthermore, as plantations reach harvestable age of about 70 years for pulp and 120 year for saw-timber production, these are likely to be clear-cut, producing the observed legacy effects. Across the Carpathians, forest types shifted towards less coniferous cover in 2010 compared to the 1860s and 1960s likely due to extensive historic conifer harvest, and to recent natural disturbance events and clear-cuts of forest plantations. Our results underscore the importance of land-use legacies, and show that past land uses can greatly affect subsequent forest disturbance for centuries. Given rapid land use changes worldwide, it is important to understand how past legacies affect current management and what the impact of current land management decisions may be for future land use.

1. Introduction

Land use and land cover change are major components of global change, causing daunting sustainability challenges (Foley et al.,

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

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

Forests are particularly likely to exhibit land use legacies, because they are persistent elements in landscapes due to the long lifespan of trees. Land use legacies can affect both forest structure and management decisions. For example, forests that were farmed during Roman times in Western Europe have a different seed bank than those that were always forested, including higher abundance of species that colonize abandoned land, and fewer seeds of poor dispersers (Dupouey et al., 2002; Plue et al., 2009). Historic land use leads to the occurrence of fruit tree species in oak forest systems (Plieninger et al., 2010) and affects both forest structure and composition including basal area, tree density, and woody plant richness (Plieninger et al., 2010; Rhemtulla et al., 2009). Even in cases in which forest composition is similar to that of historic forests, for example after agricultural abandonment in the Northeastern US, the relative importance of tree species is

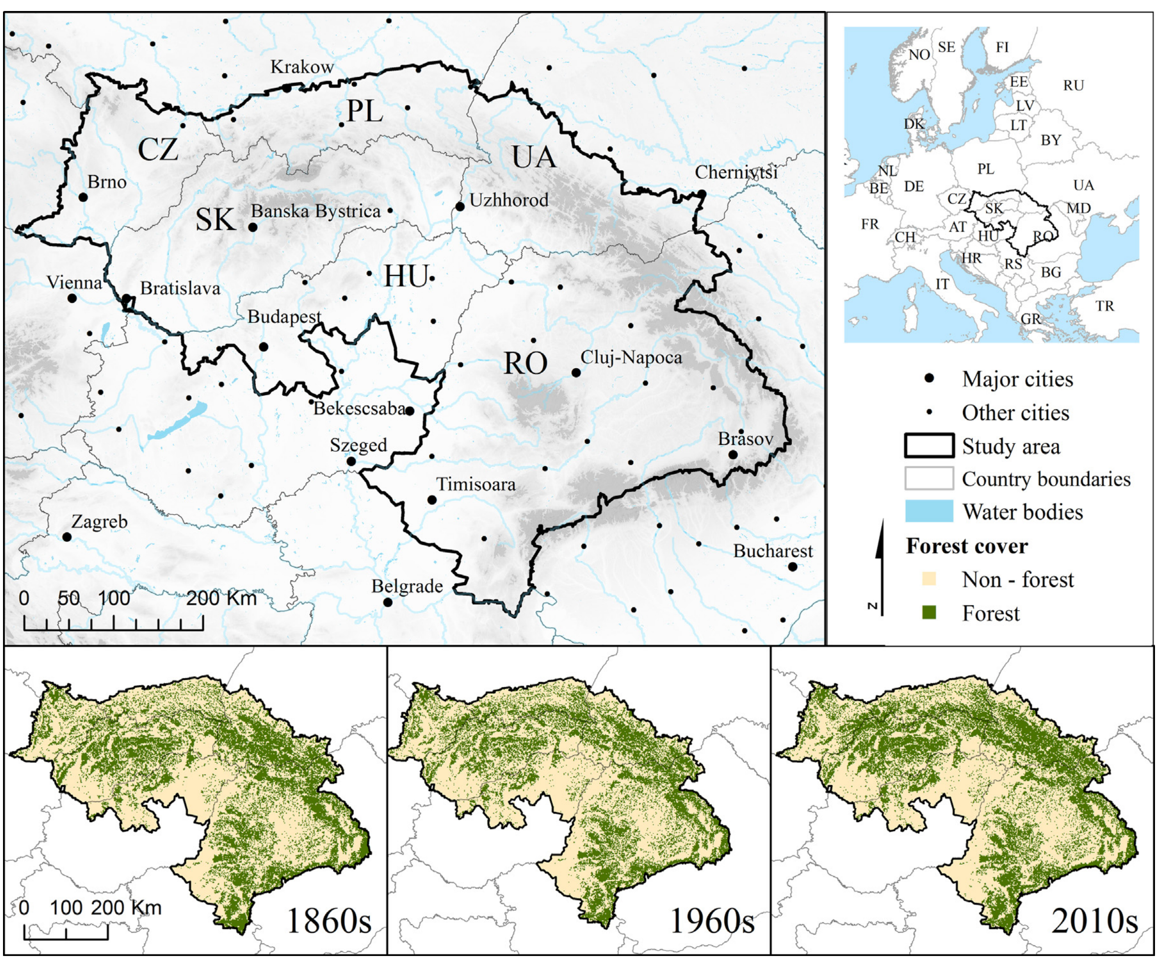

Fig. 1. Study area in Eastern Europe and forest cover maps for the 1860s, 1960s and 2010s. CZ: Czech Republic, HU: Hungary PL: Poland, RO: Romania, SK: Slovakia, UA: Ukraine.

different and depends on the historic use (Thompson et al., 2013). Similarly, Mayan overexploitation of forests affects forest structure until today, due to changes in micro-topography, soil moisture, nutrient content and the location of ancient settlements (Foster et al., 2003). However, while past land uses clearly affect current forest patterns, their impact is difficult to predict, especially if land management is constrained by such legacies.

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

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

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

2. Material and methods

2.1. Study area

We studied the Carpathian region in Eastern Europe (~265,000 km^2), because the region experienced multiple socio-economic, political, and land management shifts over the past two centuries, providing an ideal 'natural experiment' for the study of land-use legacies (Munteanu et al., 2014). The study area includes parts of two major eco-regions, the Carpathian Mountains and the Pannonian plains, and parts of Romania, Slovakia, Ukraine, Poland, Czech Republic and Hungary (Fig. 1). Our study period from 1860 to 2010 captured a century and a half of land-use history, starting with the peak of the Habsburg Empire in the mid-19th century.

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

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

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

2.2. Historic and contemporary land use and land cover data

We reconstructed historic forest area and historic forest types for the region in 1860s and 1960s from several collections of historical maps (Table 1), most of which were available in digital, georeferenced format (Arcanum Adatbázis Kft, 2015). We verified point location accuracy by a back-dating approach that associates the location of the digitized point with nearby landmarks in all available maps. From the historic maps we extracted forest cover information at two points, first during the Habsburg Empire (1805–1918) and second, during Socialism (1945–1990). We labeled 92,000 points arranged in a regular 2×2 km grid as either forest or non-forest for each time point (roughly 21% of the points being forested in each time slice). Where possible, we also mapped forest types as coniferous, mixed, or deciduous. Depending on the time period, forest type information was available for 62–96% of the data points. Our point grid matched that of the 2007 INSPIRE directive (Infrastructure for Spatial Information in the European Community) and LUCAS (Land Use and Cover Area frame Survey, (Gallego and Delince', 2010).

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

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

2.3. Land use legacy models

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

We fitted multiple logistic regression models (Hosmer and Lemesbow, 1980) to explain contemporary forest disturbance and to estimate the role of historic forest extent for contemporary disturbances. We fitted an overall model using the full dataset (19,947 data points), and country-specific models (Müller et al., 2009) to capture socio-economical and institutional diversity (Table S1, Supplementary material). We performed variable selection using an exhaustive search (Hosmer et al., 2013) based on the Akaike Information Criterion (AIC) and retained the best performing model. Because we were interested in estimating the effect of historic land uses on contemporary change, we refitted the best model including the legacy variable for those countries where the best performing model did not include land use legacies (Ukraine, Hungary and Czech Republic). We found no changes in the signs of the model coefficients and also no major changes in coefficient values. The changes in AIC values were always less than 3 for the model including legacies. We tested for interactions between historic forest cover and two environmental variables (slope and elevation) to assess whether contemporary forest disturbance occurred in topographically marginal areas with historic forest cover (Müller and Zeller, 2002), but found that interaction terms were not significant and coefficients were close to zero (results not shown). We checked the degree of spatial autocorrelation of the dependent variable using semivariograms of

Table 1
Maps and satellite images used for forest cover mapping.

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

Table 2
List of predictors used in the forest disturbance models (n = 19947), including data sources, measurements in units (Unit), their spatial resolution (SpRes), mean values (Mean), standard deviation (SD), range (Min, Max).

	Variable	Description	Source	Unit	SpRes	Mean	SD	Min	Max
Response	dist_8510	Forest disturbance 1985–2010	Griffiths et al. (2014)	Yes/No	30 m	Factor	N/A	N/A	N/A
Historic land use	FNF1860	Forest cover 1860	(Arcanum Adatbázis Kft, 2015)	Yes/No	Vector	Factor	N/A	N/A	N/A
Environmental	elev	Elevation	Farr et al. (2007)	m	90 m	693.83	327.22	77.00	1598.00*
	slope	Slope	Farr et al. (2007)	m	90 m	12.79	7.25	0.00	54.09
	temp	Annual Mean Temperature in C*10 from WORLDCLIM	Hijmans et al. (2005)	C * 10	~1 km	67.86	18.17	6.00	114.00
	precip	Annual Precipitation in mm from WORLDCLIM	Hijmans et al. (2005)	mm	~1 km	767.21	118.94	524.00	1481.00
	crop_si	Crop suitability index	GAEZ v 3.0	%	~8 km	3466.58	2221.02	0.00	10000.00
	grow_ss	Length of growing season	GAEZ v 3.0	days	~8 km	205.21	19.93	143.00	253.00
Accessibility	acc_50k	Accessibility to nearest 50k inhabitants town, time in minutes	Nelson (2008)	min	~1 km	175.24	131.42	1.00	869.00
	dist_city	Euclidean distance to nearest major city in km	Calculated (ArcGIS)	km	Vector	44.36	19.55	1.10	96.77
	dist_settl	Euclidean distance to nearest settlement in km	Calculated (based on EEA, 2013)	km	Vector	2.97	2.51	0.00	17.87
	dist_road	Euclidean distance to nearest road	Calculated (based on CIESIN and ITOS (2013))	km	Vector	7.97	6.64	0.00	50.10
	dist_border	Euclidean distance to nearest current border in km	Calculated (based on ESRI (2014))	km	Vector	52.72	49.64	0.00	213.81
	dist_rail	Euclidean distance to nearest railroad in km	Calculated (ArcGIS)	km	Vector	13.94	11.76	0.01	70.46
	dist_river	Euclidean distance to nearest main river in km	Calculated (based on Vogt et al. (2007))	km	Vector	5.28	3.43	0.00	19.97
Socio-political	cntry	Country delineation	ESRI (2014)	N/A	Vector	factor	N/A	N/A	N/A
	pop90	Population count for year 1990	CIESIN, FAO and CIAT (2005)	pers	~5 km	1081.45	1927.00	0.00	38026.50

*The maximum elevation was truncated at 1600 m, the average timberline for the Carpathian Mountains (see Section 2).

model residuals (Curran, 1988; Griffith, 2003) and did not find significant spatial autocorrelation.

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

To address our second objective regarding the relationship between land-use legacies and other spatial determinants of forest disturbance, we compared the proportion of forest disturbance in old and new forests along a gradient of environmental and accessibility values (variables described in Table 2). We split our data into two groups (old and new forests), computed the proportion of disturbance in each group along gradients of other continuous variables in our data, and plotted partial dependence of the disturbance proportion.

To address our third objective of the effect of legacies on the forest types, we estimated the proportion of forest types at four time points. These estimates were based on historic land use maps for the 1860s and 1960s (Table 1) and forest-type classifications for 1985s and 2010s (Griffiths et al., 2014). For each time slice (Table 1) where forest type information was available, we calculated the percentage of each forest type in the overall forest. Forest type data was complete for the time layers 1960, 1985 and 2010, but was absent for approximately 15% of the whole area in 1860, and 49% of contemporary Poland. We assumed that forest types in areas with no forest type information followed the same pattern as in areas where forest type information was available (Table S5, Supplementary material). Here, we considered the legacy effects of past management by assessing changes in forest types and shifts in the proportion of coniferous, mixed and deciduous forest over time. We also analyzed the historic forest types of recently disturbed forests, the 2010 forest types of new forests for each country as well as the 1860 and 2010 forest types of old forest. When we calculated the percentage of each forest type in 2010 for areas not forested in 1860, we compared our results with the 1960s forest types in new forests to check for consistency between the two time periods.

3. Results

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

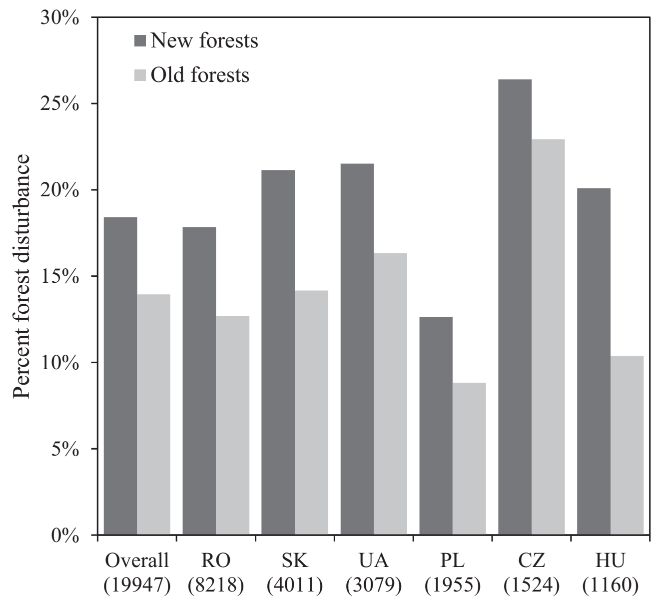

Fig. 2. Percentage forest disturbance in the Carpathian Region (overall) and by country (RO: Romania, SK: Slovakia, UA: Ukraine, PL: Poland, CZ: Czech Republic, HU: Hungary) in old forests and new forests. Old forests refer to areas that were forested throughout 1860s–1985, new forests to areas not forested in 1860s, but forested in 1960s. The graph indicates consistently more forest disturbance in new forests. Number of observations per country in brackets.

3.1. Forest disturbance legacies

Across all Carpathian countries, forest disturbance was more likely in areas that were not forested in 1860s (new forests), compared to forested areas in 1860s (old forest) (Fig. 2). From the total set of 19,947 points, 73% were forested in 1860s and still forested in 1960s, 1985s and 2010s. Observed forest disturbance between 1985 and 2010 in old forests was 13% (of forested area), but 18% in new forest (Fig. 2, Table S1, Supplementary material). The ratios of forest disturbances in new relative to old forests, were consistently higher in all countries, with the maximum percentage of observed disturbance in old forests in the Czech Republic and Ukraine (22% and 16%, respectively) and the maximum percentage of observed disturbance in new forest in Czech Republic (26%), Slovakia (21%) and Ukraine (21%) (Fig. 2).

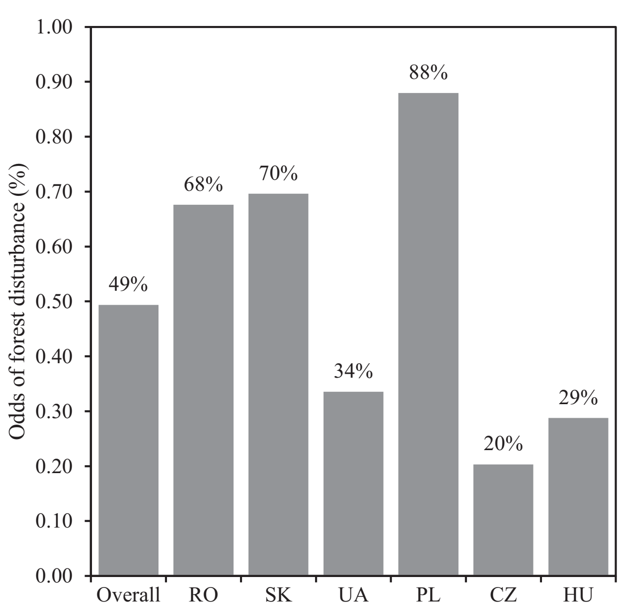

Fig. 3. Odds of forest disturbance (in%) in new forests (not forested in 1860s) compared to old forests (forested in 1860s), overall and in country models (RO: Romania, SK: Slovakia, UA: Ukraine, PL: Poland, CZ: Czech Republic, HU: Hungary).

The logistic regression results suggested that even when controlling for environmental, accessibility and socio-political factors, the odds of forest disturbance were 49% higher for new forests than for old forests (Fig. 3). However, legacies varied by country: they were strongest in Poland (odds 88% higher), weakest in Ukraine (odds 34% higher), and not important in the Czech Republic and Hungary (Fig. 3, Table S2, Supplementary material). The AUC for the seven models varied from 0.62 (Czech Republic) to 0.78 (Poland). The overall model had an AUC value of 0.66. Our findings suggest that even after controlling for the environmental, accessibility and socio-political differences in the study region, the historic land uses played an important role in determining the location of contemporary forest disturbance.

3.2. Spatial determinants of disturbance

Our models confirmed the importance of environment (topography, temperature, length of growing season) and accessibility (distance to cities and settlements) for forest disturbance in all Carpathian countries. In the overall model, slope, annual mean temperature, and the length of the growing season were important predictors, alongside our country dummy variable, which captured at national level, processes not captured by other variables, such as land reforms, strength of institutions, or accessibility differences (Levers et al., 2014; Müller and Sikor, 2006). In all countries, areas with steep slopes were less likely to be disturbed, and areas afar from major cities, and close to human settlement were more likely to be disturbed (Table S3, Supplementary material). Our models did not show strong quantitative evidence for a relationship of forest disturbance with population density in the 1990s or distance to railroads (Table S3, Supplementary material).

Our comparison of the proportion of disturbance in old and new forests across the full range of slopes, temperatures, precipitations, and accessibilities, indicated that the proportion of disturbance was consistently higher in new forests both when we summarized our data (Fig. 4) and when modelling disturbance while controlling for other spatial determinants of change (Fig. S4, Supplementary material). Disturbance decreased with increasing slope, temperature, crop suitability, and length of the growing season in both old and new forests, but the consistently higher proportion of disturbance in new forests remained. The shorter the growing season, the more new forests were disturbed. Within 15 km of roads, new forests were more likely to be disturbed, and although at distances higher than 20 km, older forests were more likely to be disturbed, we had only few observations in this data range. Forests closer to settlements were also more likely to be disturbed.

3.3. Changes in main forest types abundance

We analyzed forest type abundance in the Carpathian region for four time points (1860s, 1960s, 1985s, and 2010s). We found that coniferous forest cover declined in all countries except Romania and Hungary. Slovakia and Czech Republic reached their peak coniferous forest cover in the early socialist period (1960s) while Hungary, Romania and Ukraine reached a peak in the late 1980s. The forests of most countries were mainly coniferous and mixed in 2010 (65–98% in Ukraine and Romania respectively). Only Slovakia and Hungary had over 50% deciduous forests in 2010. Overall, coniferous cover in 2010 was 24%, roughly 5% lower than in 1860.

When we analyzed the 1860s forest types of areas that were disturbed after 1985, we found that over 50% of the disturbance occurred in 1860s coniferous stands, except for Romania and

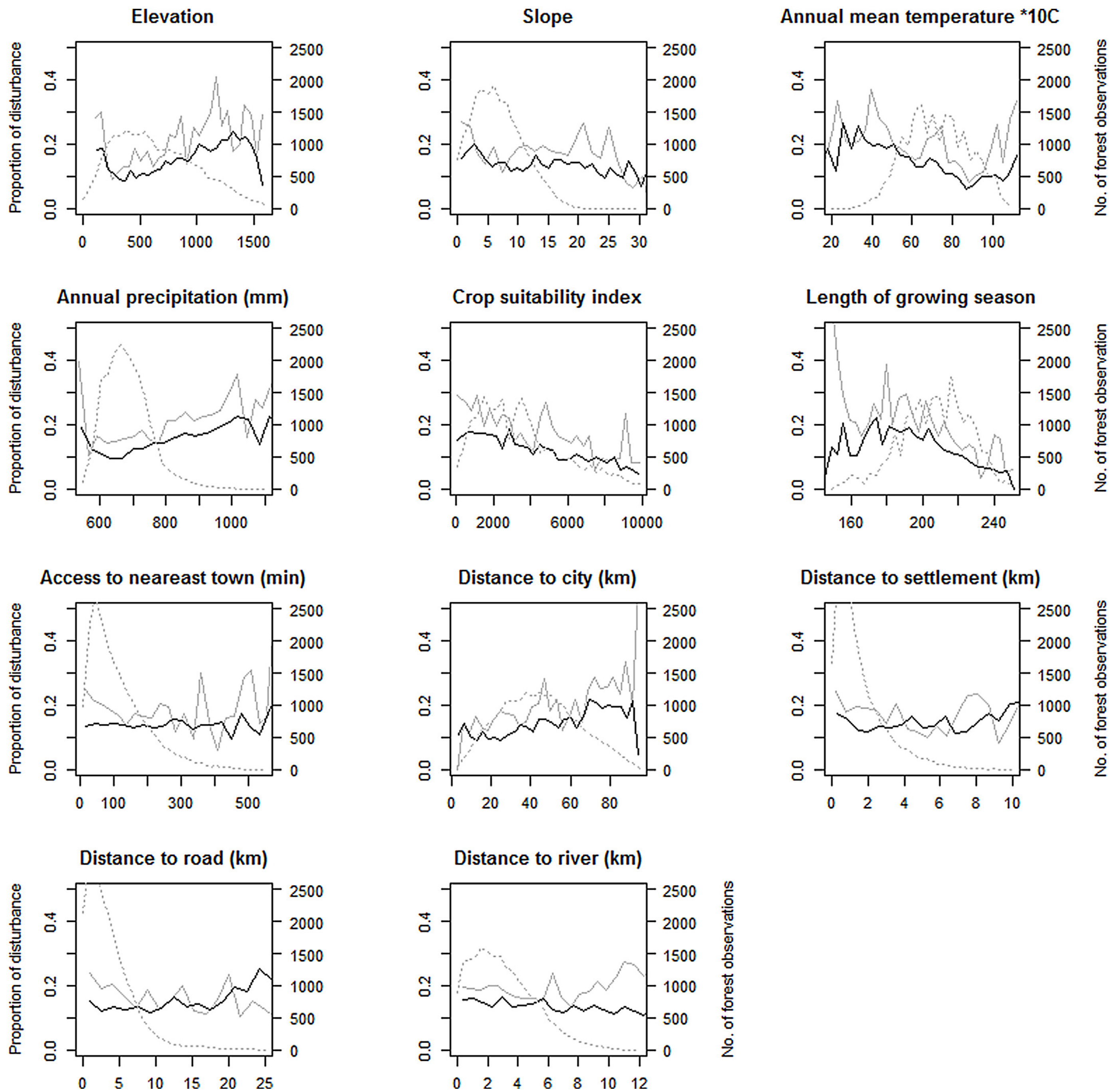

Fig. 4. Proportion of forest disturbance (left *y* axis) in old forests (black line) and new forests (grey line) in relation to elevation, slope, annual mean temperature, annual precipitation, crop suitability, length of growing season, accessibility, distance to cities, settlements, roads and rivers. The graph represents a data summary of all observed disturbance. The dotted line represents number of forest observations in 1985 (right *y* axis). Continuous variables were divided in 30 equal interval data bins and the proportion of disturbance as well as the mean number of forest observations was plotted for each bin. For model based results please see Supplementary material Fig. S4.

Hungary where the proportion of coniferous forest was low in the 1860s (Fig. 5a). Overall, the 2010s forest types in new forests were 28% coniferous, 27% mixed, and 40% deciduous, but there were marked differences among countries: in Romania, Hungary and Slovakia, over 50% of the forests were deciduous and mixed, while Ukraine and Czech Republic had an approximately equal proportion of deciduous, coniferous, and mixed forests (Fig. 5d). The proportion of coniferous and deciduous new forests was very similar in 1960 and 2010. Most contemporary disturbances (1985–2010) occurred in 1860s coniferous stands, less Hungary, where there were few coniferous to start out with (Fig. 5b). The proportion of forest types in old forests shifted toward less coniferous in all countries except Romania and Hungary (Fig. 5c and e). Generally, there was a higher proportion of coniferous in new forests than in old forests across countries (Fig. 5d and e). Forest disturbances between 1985 and 1995 also affected forest types in 2010. Of all disturbed points that were initially coniferous, only 37% remained coniferous after disturbance. Conversely, 90% of the disturbed deciduous and mixed forests retained their composition.

4. Discussion and conclusions

Our results showed that land-use legacies were an important spatial determinant of forest disturbance in the Carpathian region.

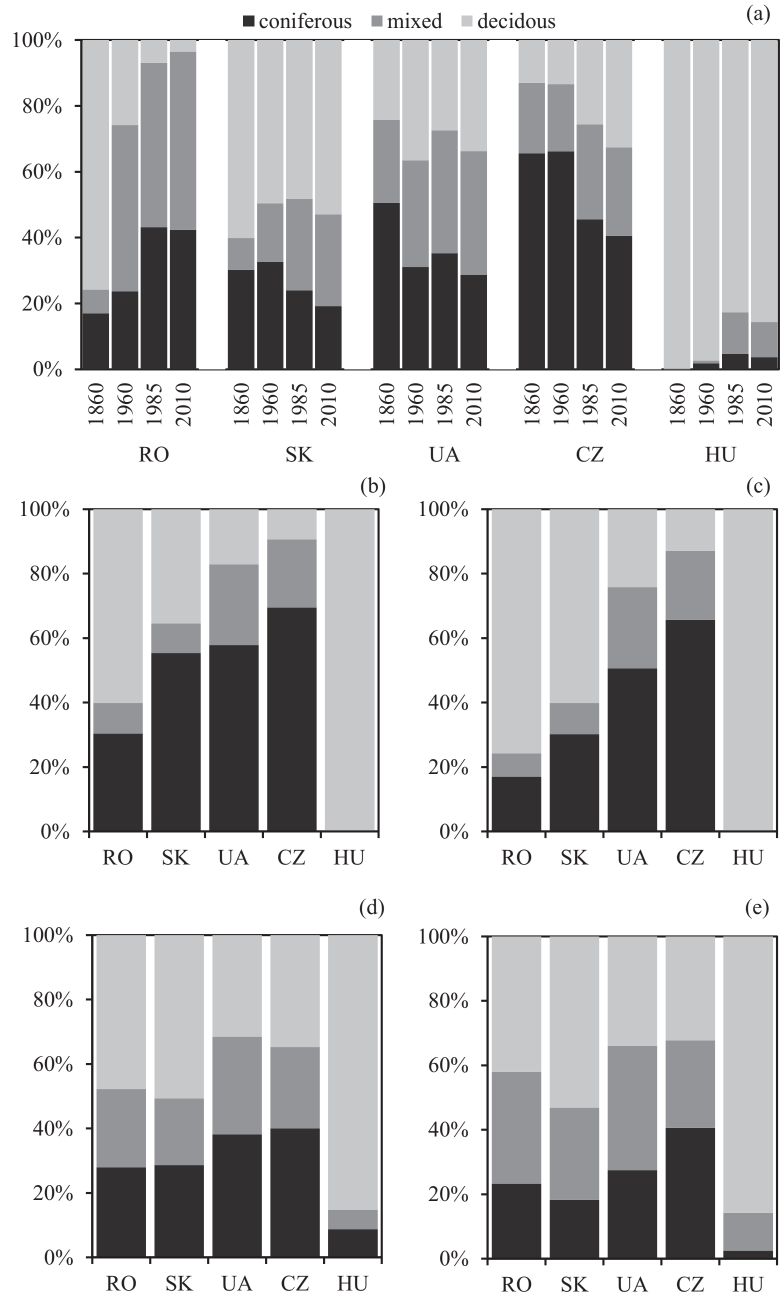

Fig. 5. (a) Forest types by year and country since 1860s, (b) 1860s forest types of disturbed forests between 1985 and 2010, (c) 1860s forest types of old forests, (d) 2010s forest types of new forests, and (e) 2010s forest types of old forests. RO: Romania, SK: Slovakia, UA: Ukraine, CZ: Czech Republic, HU: Hungary. Poland has been excluded from this graph due to scarcity of forest type data. Note: figures are not for entire country territory but for the study region depicted in Fig. 1. Forest type distribution in (a) is not identical to Griffiths et al. (2014) because the data presented here is restricted to 1960 forest cover.

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

4.1. Forest disturbance legacies

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

4.2. Spatial determinants of disturbance

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

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

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

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

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

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

4.3. Changes in forest types

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

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

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

4.4. Conclusions

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

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2015.06.015.

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