Accepted Article

Received Date : 25-Nov-2014
Accepted Date : 27-Jan-2015
Article type : Primary Research Articles

Forest transitions in Eastern Europe and their effects on carbon budgets

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/gcb.12897

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Running head: *Carbon dynamics in Eastern Europe*

Paper type: Primary Research Article

Submitted to *Global Change Biology*, November 2014

ABSTRACT

Forests often rebound from deforestation following industrialization and urbanization, but for many regions our understanding of where and when forest transitions happened, and how they affected carbon budgets remains poor. One such region is Eastern Europe, where political and socioeconomic conditions changed drastically over the last three centuries, but forest trends have not yet been analyzed in detail. We present a new assessment of historical forest change in the European part of the Former Soviet Union and the legacies of these changes on contemporary carbon stocks. To reconstruct forest area, we homogenized statistics at the provincial level for AD 1700 to 2010 to identify forest transition years and forest trends. We contrast our reconstruction with the KK11 and HYDE 3.1 land change scenarios, and use all three datasets to drive the LPJ dynamic global vegetation model to calculate carbon stock dynamics. Our results revealed that forest transitions in Eastern

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Europe occurred predominantly in the early 20th century, substantially later than in Western Europe. We also found marked geographic variation in forest transitions, with some areas characterized by relatively stable or continuously declining forest area. Our data suggests extensive deforestation in European Russia already prior to AD 1700, and even greater deforestation in the 18th and 19th centuries than in the KK11 and HYDE scenarios. Based on our reconstruction, cumulative carbon emissions from deforestation were greater before 1700 (60 Pg C) than thereafter (29 Pg C). Summed over our entire study area, forest transitions led to a modest uptake in carbon over recent decades, with our dataset showing the smallest effect (<5.5 Pg C) and a more heterogeneous pattern of source and sink regions. This suggests substantial sequestration potential in regrowing forests of the region, a trend that may be amplified through ongoing land abandonment, climate change, and CO_2 fertilization.

Keywords: Long-term land-use change, carbon flux, forest transition, post-Soviet land-use change, reforestation, afforestation, agricultural abandonment.

INTRODUCTION

Forests play an essential role in the global carbon cycle, storing and sequestering the bulk of carbon in the terrestrial biosphere (Bonan, 2008, Luyssaert et al., 2008). Major shares of the world's forest have historically been converted to agriculture (MA, 2005), and while deforestation continues in some tropical regions (Baccini et al., 2012, Hansen et al., 2013), forests in much of the temperate latitudes are regrowing as a result of the abandonment of marginal farmland (Kauppi et al., 2006, Meyfroidt and Lambin, 2011). Understanding how land-use changes have affected forests in different world regions is critical to understanding both past emissions of land-use change and the potential of land-based climate change

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mitigation (Kaplan et al., 2012, Smith et al., 2013). Yet, major uncertainties prevail in our understanding of how changing forest cover has affected the terrestrial carbon budget (Houghton, 2010, Erb et al., 2013).

A major reason for this lies in uncertainty about the rates, spatial patterns, and pathways of past forest change. The onset of substantial agricultural expansion, and thus widespread deforestation, remains highly speculative in many regions of the world. For example, different assumptions about the intensity at which people used land translates into vastly different scenarios of preindustrial anthropogenic land cover change (Ellis et al., 2013). Most land change scenarios are in agreement that, following the establishment of agricultural societies, global deforestation increased continuously until the modern era, with the exception of minor, regional fluctuations related to disease, war, changes in technology and geopolitics (Yeloff and van Geel, 2007, Hostert et al., 2011, Pongratz et al., 2011). With the Industrial Revolution however, agricultural and pasture lands have undergone widespread abandonment and conversion to other forests in those regions with suitable climate. Such a forest transition (i.e., shift from net deforestation to net forest gain) is characteristic of many parts of the world as a result of a variety of causes (Lambin and Meyfroidt, 2010), including urbanization, industrialization, and agricultural intensification (Mather, 1992, Aide and Grau, 2004), emerging forest scarcity (Rudel et al., 2005), land-use displacement (Meyfroidt et al., 2010), and forest plantations (Rudel, 2009). Whereas forest transitions are well documented for some parts of the world, the timing and geographic patterns of forest transitions are poorly understood for most world regions (Rudel et al., 2005, Meyfroidt and Lambin, 2011).

Because forest transitions and subsequent reforestation can have marked effects on carbon budgets, including shifting regions from source to sink modes (Kuemmerle et al.,

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2011, Kaplan et al., 2012, Erb et al., 2013), understanding forest transitions is important. Given the potentially strong legacy effects of forest transitions on carbon budgets, incomplete knowledge on the timing and geographic patterns of forest transitions remains a large source of uncertainty when attempting to quantify the current state of the carbon cycle and assessing potential land use-based strategies for climate change mitigation.

Eastern Europe provides an archetypical example of a region with a poorly understood, yet dynamic land-use history that translates into considerable uncertainty when estimating the region's carbon budget. Agricultural intensification occurred substantially later in Eastern Europe than in Western Europe, with three-field rotation and shifting cultivation prevailing in parts of Russia until the 20th century (Darby, 1956, Treivish, 1999). Eastern Europe also experienced multiple socio-economic and institutional shocks in the 20th century, including revolutions, wars, and the rise and fall of the Soviet Union, which all resulted in widespread land-use change (Lyuri et al., 2010, Schierhorn et al., 2013). Whether and when forest transitions occurred across Eastern Europe remains unclear though, especially for the European part of the former Soviet Union (Meyfroidt and Lambin, 2011). Whereas forest transitions in Western Europe occurred mainly in the 18th and 19th centuries (Meyfroidt and Lambin, 2011), studies on Eastern Europe suggest that forest transitions may have occurred later, if at all (Kauppi et al., 2006, Kuemmerle et al., 2011). Moreover, forest transition patterns in Eastern Europe varied markedly, even within smaller regions (Kozak et al., 2007).

Reconstructing land-use histories for Eastern Europe is challenging, in part because data on historic land use are scarce and heterogeneous, and in part due to major political border changes following the two World Wars and the breakup of the Soviet Union. Yet it is important to improve our understanding of forest change in Eastern Europe, not in the least

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because the state of contemporary carbon stocks is influenced strongly by the legacies of land-use changes on centennial timescales (Kuemmerle et al., 2011, Olofsson et al., 2011, Kaplan et al., 2012). Thus potential future responses of ecosystems to climate change, and opportunities for land-based climate change mitigation largely depend on current conditions, which in turn may be strongly influenced by past forest transitions.

The goals of this study were to improve our understanding of forest dynamics in Eastern Europe over the past three centuries and to quantify the impact of forest area change on carbon stocks. Because quantifying the impacts of forest change on carbon stocks relies on having spatially detailed land-use histories, we first set out to create a new reconstruction of forest cover in the European part of the Former Soviet Union that covers the past 300 years. We used forest area statistics from a wide range of sources to reconstruct forest cover for the European part of the Soviet Union at the provincial (i.e., *oblast*) level. Using this dataset, we then estimated land-use effects on the carbon budget and quantified the spatial pattern of legacies of past land-use change on today's carbon budgets. Specifically, we investigated the following questions:

1. How did forest trends and forest transitions vary across the European part of the Former Soviet Union?
2. What was the effect of land-use change during the last 300 years on carbon budgets and how do estimates based on a spatially detailed forest history differ from previous estimates?
3. How do legacy effects of past land-use change affect today's carbon budgets across the region?

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MATERIALS AND METHODS

Study region

Our study region was the European part of the Former Soviet Union, including contemporary European Russia up to the Urals, and including Ukraine, Moldova, Belarus, Armenia, Azerbaijan, Georgia, and the three Baltic States: Estonia, Latvia, and Lithuania. The region is environmentally heterogeneous, with boreal and cool-temperate mixed forests in the north, temperate deciduous forests in the center, forest steppes and semi-deserts in the south, and temperate and mountain forests in the Caucasus (Olson et al., 2001, Blinnikov, 2011).

While the region has a long land-use history, slash-and-burn agriculture was the main agricultural system until the late 17th century, when population growth and trade led to intensifying agricultural and forest use (Riasanovsky, 2000). A marked wave of agricultural expansion occurred in the second half of the 18th century, when the abolishment of serfdom in 1861 led to widespread agricultural expansion and deforestation in European Russia (Rylsky, 2000). Already during this time, socio-economic differences translated into markedly different regional forest trends, with lower levels of agricultural expansion in European Russia compared to the Baltic States, Belarus, and Ukraine, despite similar agro-climatic conditions (Chirot, 1991, Blinnikov, 2011).

The 20th century was characterized by a series of socio-economic and institutional shocks, each of which affected land management and thus forest extent. The Russian Revolution in 1917 eventually led to the formation of the Soviet Union in 1922, in turn triggering a phase of

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collectivization and industrialization in agriculture with the goal to increase agricultural production and self-sufficiency. World War II (WW-II) led to a drastic disruption of agriculture, followed by the westward expansion of the Soviet Union and its land-management paradigms into much of contemporary Belarus, Ukraine, and the Baltic States. Agricultural land use across the Former Soviet Union expanded substantially in the 1950s and 1960s, whereas agricultural intensification and concentration, along with abandonment of marginal areas, characterized the period 1965-1980 (Blinnikov, 2011).

The breakup of the Soviet Union in 1991 and the subsequent transition to market economies affected agriculture in the region markedly. Formerly guaranteed markets and state subsidies disappeared, agricultural institutions were overhauled, and agricultural land was privatized in most successor countries (Ioffe and Nefedova, 2004, Lerman et al., 2004, Rozelle and Swinnen, 2004), together resulting in drastic production declines and widespread agricultural abandonment (Prishchepov et al., 2012; Schierhorn et al., 2013). While some of these abandoned lands were recultivated after 2000, in part due to growing support for agriculture and rising commodity prices, much of the former agricultural land remains abandoned and is gradually returning to forest (Hansen et al., 2013; Sieber et al., 2013).

Datasets

We acquired forest cover estimates for the entire European part of the Russian Empire at the level of governorates (i.e., *guberniyas*). Estimates for the time period 1700 until 1914 were based on the major land-use and forest surveys carried out by ground surveyors across the European part of the Russian Empire (i.e., contemporary European Russia up to the Urals, Ukraine, Moldova, Belarus, Estonia, Latvia, Lithuania, Armenia, and Georgia, see Fig. S1) for the years 1780, 1796, 1861, 1868, 1881, 1887, and 1914 (Tsvetkov, 1957). To increase

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the temporal resolution of the forest area time series, forest area was estimated for years around which major population censuses were carried out in the Russian Empire (i.e., 1700, 1710, 1722, 1742, 1762, 1782, 1796, 1812, 1815, 1835, 1851, and 1858). This was done by first estimating the farmland (i.e., cropland and pasture) area used per person for each governorate for periods in which forest surveys and population censuses had been carried out approximately at the same time. These ratios where then used to interpolate the farmland per person for years where only population data was available and thus to delineate forest area per governorate. We did not employ a population-based method for estimating forest cover beyond the mid-19th century, as an increasing orientation towards agricultural exports resulted in a decoupling of farmland area and population in European Russia from then on (Rylsky et al., 2001). Whenever possible, additional maps and/or fine-scale forest and population surveys where incorporated to adjust forest area estimates for each governorate. Finally, the resulting forest area time series were scaled proportionally to match the detailed cartographic survey of the Russian Empire conducted in 1889 in cases where area estimates differed (Tsvetkov, 1957). Some regions in contemporary western Ukraine were outside the Russian Empire and we used forest area estimates from surveys of the former Kingdom of Galicia and Lodomeria for the years 1872 and 1876 (Table S1). For Georgia, pre-WWI forest area estimates were taken from national forestry statistics (Table S1).

Forest area estimates for the period 1914 – 1991 were taken from Soviet statistics at the provincial level (Table S1). For the time period 1914 – 1991, we used a harmonized dataset of forest area estimates for all years in which major Soviet land-use and forest surveys were implemented (i.e., 1927, 1940, 1944, 1949, 1958, 1966, 1973, 1978, 1983, and 1988) (Rylsky et al., 2001). To account for changes in oblast boundaries during that period, forest area statistics at district level (i.e., *rayon*) were aggregated to the provincial (i.e., oblast) level,

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because district boundaries remained relatively stable after 1927 (Rylsky, 2000). For western Ukraine, forest estimates for the interwar period were available from surveys of the Second Polish Republic for the years 1923, 1928, and 1937 (Table S2). For Belarus, Estonia, Latvia, Lithuania, Moldova, Ukraine, and Armenia, we complemented Soviet forest censuses with ancillary datasets (e.g., national reports, fine-scale forest survey; see Table S2). For the time period after 1991, Russian forest surveys were available for the years 1993, 1998, 2003, and 2008 (Rylsky et al., 2001) complemented by official statistics from 2010, 2011, and 2012 (Table S2). For Ukraine, official forest area estimates were available for the years 1993, 1996, 2003, and 2009 (Table S2). For Belarus, official estimates were available for the years 2000-2010 (Table S2). For Estonia, Lithuania, Latvia, Moldova, Armenia, Azerbaijan, and Georgia, national-scale forest cover estimates after 1991 were taken from the countries statistical yearbooks or FAOSTAT (Table S2).

We linked the forest area time series before 1914 to a geodatabase of governorates digitized from the Atlas for the European part of the Russian Empire at a scale of 1:2,000,000 (Shokalsky, 1910). Contemporary administrative boundaries (i.e., national boundaries and oblast boundaries for Russia, Ukraine, and Belarus) were taken from the ESRI Data and Maps Kit 2009. All datasets were reprojected to the Albers Equal Area coordinate system (Fig. S1).

To compare our dataset to alternative, well-established land-use reconstructions for the last centuries, we used the HYDE 3.1 and KK11 databases. HYDE 3.1 uses estimates of historical population, statistics of cropland and pasture extent, satellite-based land-cover maps, and ancillary data on cropland suitability (agroecological zones, topography) to allocate cropland and pasture area for the period 10,000 BC to AD 2000 (Klein Goldewijk et

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al., 2010).The KK11 dataset is based on simulating historic land cover/use based on population data and maps of agricultural suitability (Kaplan et al., 2009, Kaplan et al., 2011). Both dataset differ strongly, however, in their assumptions about land-use intensity. Whereas HYDE assumes that land-use area per capita remained approximately constant before AD 1961, the KK11 model assumes that per capita land use was itself a function of population density (Kaplan et al., 2009) and therefore changed over time, consistent with Boserup's land-use intensification theory (Boserup, 1965), resulting in higher land area used per capita in historic times. Differences in this assumption lead to strikingly different land-use reconstructions (Ellis et al., 2013).

Methods

Reconstructing forest trajectories

To merge the time series before 1914 (at the level of governorates) and after 1914 (at the level of states and autonomous republics), we disaggregated the pre-1914 dataset and re-aggregated it to the contemporary administrative boundaries (Fig. S1). First, we intersected both geodatabases and calculated the area of each resulting segment. We then calculated the weighted mean forest area for each post-1914 administrative unit (i.e., countries or states) from all segments falling within such a unit. As weights, we used the relative area of these segments. This was done for each year for which pre-1914 forest cover estimates were available, resulting in a combined time series spanning the entire study period 1700 - 2012. Missing data were omitted in all calculations. City-states (i.e., St. Petersburg, Moscow, Kiev) were excluded.

The forest area estimates were unequally dense in time and contain outliers due to the heterogeneous data sources we relied on. We therefore interpolated and smoothed the forest

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area trajectories using the full time-series of forest-area estimates to generate a complete time series for each administrative unit. We employed scatterplot smoothing based on a kernel-weighted, local polynomial regression to predict to forest area for each year without data. The local polynomial regression fits the dependent variable (i.e., forest area) to a polynomial form of the independent variable (i.e., year) with locally-weighted least squares and without making assumptions about the functional form. We used a Gaussian kernel with a third-degree polynomial smoothing function. The kernel bandwidth that controls the degree of smoothing was determined automatically by minimizing the conditional weighted mean squared error across a range of possible band-widths (StataCorp, 2013). We also calculate 95% confidence intervals for the local polynomial fit.

Using the interpolated time series, we then derived forest transitions as the low point in forest area if a time series had a minimum. To avoid false detections, we only considered the minima as forest transitions if (i) a low-point occurred more than three years after the start or before the end of the time series, (ii) the ratio between minimum and maximum forest cover was smaller 0.1, and (iii) the difference between minimum and maximum forest cover was larger than 3%. We also derived forest area change rates for every 20-year interval since 1900. Finally, we compared our forest-area estimates with satellite-based estimates from the Globcover land cover map for the year 2009 (http://due.esrin.esa.int/globcover).

Estimation of contemporary carbon stocks

To assess the current state of carbon stocks in the European part of the Former Soviet Union, we ran the LPJ Dynamic Global Vegetation Model (LMfire version; Kaplan et al., 2012, Pfeiffer et al., 2013). LPJ simulates vegetation composition in terms of nine plant functional types (PFTs). In the Eastern Europe region considered in this study, five PFTs are present: temperate evergreen needleleaf trees (e.g., *Pinus* spp.), temperate broadleaf

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deciduous trees (e.g., *Quercus* spp, *Acer* spp.), cold needleleaf evergreen trees (e.g., *Picea* spp.), cold deciduous trees (e.g., *Larix* spp, *Betula* spp.), and temperate herbaceous plants (grasses and forbs).

LPJ simulates carbon storage in several compartments (Sitch et al., 2003, Kaplan et al., 2012, Pfeiffer et al., 2013): living vegetation, fast-turnover litter (e.g., leaves), slow-turnover litter (e.g., coarse woody material), below-ground litter (e.g., dead fine roots), surface soil organic matter (O-horizon), fast-turnover soil organic matter, and slow-turnover soil organic matter. When reporting changes in carbon storage in this paper, we report the total of all pools. Following conversion of forest land to agriculture, the soil organic matter pools typically continue to lose carbon for decades to centuries, as a result of the diminished inputs of carbon to soils (for more details of the carbon accounting in LPJ, see Kaplan et al., 2012).

The LPJ model was driven by standard gridded climate and soils datasets, a time series of atmospheric CO_2 concentrations (Pfeiffer et al., 2013), and an anthropogenic land-cover change scenario. To quantify the effect of land-cover change on carbon stocks, we ran four experiments: Scenario 0: no land use, Scenario 1: our reconstruction, Scenario 2: KK11 (Kaplan et al., 2012), and Scenario 3: HYDE 3.1 (Klein Goldewijk et al., 2010). For each scenario run, the model was calibrated for 1,020 years with the de-trended climatology and the land-change scenario estimate for 1700 (the start of our land-cover reconstruction). Following the spin-up period, the model was run in a transient simulation for the period 1700-2010. Because no paleoclimate reconstruction containing all climate variables needed for our LPJ model is currently available, we used the same low-frequency, de-trended, interannually variable climate used in the model spin-up over this period. The model protocol for simulating the effect of land cover change on carbon stocks was the same as that used in Kaplan et al. (2012). We excluded the northern and southern Caucasus (i.e., the southernmost

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Russian provinces and Armenia, Azerbaijan, and Georgia) from our analyses because forest area estimates from before 1927 were unavailable for these regions.

RESULTS

Homogenizing forest area statistics at the state/country level revealed marked changes in forest area in the European part of the former Soviet Union during the last 300 years (Fig. 1). Forest area declined in large areas of contemporary Belarus, Ukraine, the Baltic States and central European Russia during much of the 18th, 19th, and early 20th century. After 1914, and especially after World War II, slow forest recovery was the dominant trend in these regions, albeit with large regional variability. However, deforestation continued in many more northern regions throughout much of the 20th century (Fig. 1).

Reconstructing forest area changes at the state- and country-level based on our database of homogenized statistics (see Tables S1 and S2) resulted in plausible forest area trajectories (Fig. 2). The interpolation resulted in a smoothing of forest trajectories, thereby lowering the influence of outliers that were mostly due to different data sources. Confidence intervals were generally larger in the 20th century, when we relied on a variety of data sources, compared to the pre-1914 period, when we relied on the homogenize time series of Tsvetkov. The shape of forest trajectories differed markedly across our study region, with regions depicting one or more waves of deforestation and recovery, continued deforestation, or relatively stable forest trends (Fig. S2).

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Summarizing forest area change rates for every 20-year period in the 20th and 21st century confirmed the overall pattern of decrease in most regions before WW-II, and increasing forest area thereafter (Fig. 3). However, there was a substantial geographic variability in the rates of forest area change. Clusters of relatively extensive deforestation occurred particularly in Belarus and north-eastern European Russia at the beginning of the 20th century, where deforestation trends also continued well into the 20th century. Conversely, many areas in central and southern European Russia, as well as in Ukraine experienced increasing forest cover already before WW-II and throughout most of the 20th century, albeit at smaller rates. Some areas, for example Komi or Karelia in Russia's north, were characterized by net forest loss even in the late 20th and early 21st century (Fig. 3).

Forest transitions occurred in most regions of the European part of the former Soviet Union (74 out of 92 regions), albeit with substantial geographic variation in their timing (Fig. 4). The earliest forest transitions occurred in central European Russia (e.g., 1892 in Marij Ehl, 1897 in Vladimir, 1899 in Bryansk,1904 in Moscow) and eastern Ukraine (e.g., 1863 in Dnipropetrovsk, 1898 Chernivitsi). In more northern and western regions, many forest transitions occurred around 1920, for example in the Baltic States (1920 in Estonia, 1922 in Lithuania and Latvia), north of Moscow (e.g., 1921 in Tver, 1926 in Pskov), and in western Ukraine (e.g., 1920 in Rivne). Forest transitions occurred in the 1930s for most of Belarus and many regions in the southern Russian taiga (e.g., Leningrad, Novgorod). Twenty-two out of 92 regions experienced forest transitions after 1940, mainly in southern and western Ukraine (e.g., Mykolayiv, Kherson, Lviv) and northern Russia (e.g., Vologoda). Some boreal and steppe regions experienced forest transitions only after 1970 (e.g., Tatarstan). Many regions in Russia's southern forest steppe regions and some central Russian regions did not experience forest transitions (18 in total, Fig. 4). Aggregating the state-level forest trajectories to the country level revealed that forest transitions took place in 1927, 1936, and

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1937 in Ukraine, European Russia, and Belarus, respectively (Fig. S3).

Forest dynamics in the European part of the former Soviet Union translated into substantial changes in the region’s carbon budget over the last 300 years (Fig. 5). Substantial agricultural expansion had already occurred before 1700 in our study region, resulting in a reduction of the carbon (C) stored in vegetation and soils by 41% (from 147 to 87 Pg C) as compared to a control simulation without land use. Agricultural expansion led to a slow, gradual decrease in C storage until 1875, accompanied by a slight increase in C on agricultural land. Between 1875 and 1950, C stored in vegetation and soils decreased more strongly (by about 18%). The lowpoint in C storage occurred around 1950 at 58 Pg C, thus suggesting that net carbon emissions were larger before 1700 (60 Pg C) than thereafter (29 Pg C). Overall, agricultural abandonment was negligible before the early 20th century, but increased substantially after WW II and led to ~5.45 Pg C stored in reforesting former agricultural land in 2010 (Fig. 5). Overall though, the amount of C in reforesting areas was small, and no clear rebound pattern emerged for the study region as a whole.

Comparing late 19th century C stocks to those from 1930, 1970, and 2010 revealed that most regions in our study area had not recovered from C-losses during the 20th century until 2010 (Fig. 6). Most regions, especially those with relatively high shares of forest, continued to lose C until 1970, after which some regions in central Russia, Belarus, and the Baltics recovered, albeit not to 1890 levels. Carbon emissions remained substantial even after 1970 in the north and east of our study region (e.g., Karelia, Arkhangelsk). Only some northern regions surpassed 1890 carbon stocks during the 20th century, including the surrounding of St. Petersburg, whereas most forest steppe regions in Russia’s and Ukraine’s south showed slightly higher levels of total C storage in 2010 compared to 1890 (Fig. 6).

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Carbon budgets estimated based on our forest area change dataset differed substantially from those based on the HYDE 3.1 (Fig. 5), which assumes very little agricultural extent in 1800, and thus large amounts of C stored in vegetation and soils, with rapid agricultural expansion thereafter. Our carbon budget estimations were closer to KK11, with similar trends in C stored in both used and unmanaged lands. However, our land-use reconstruction suggested larger emissions before 1700 and thus lower amounts of C in vegetation and soils and lower emissions from deforestation throughout our study period. Nevertheless, our dataset suggested even greater deforestation in the 18th and 19th centuries than both the KK11 and HYDE 3.1 scenarios (Fig S4). Our datasets also revealed substantially lower amounts of C stored in recovering vegetation and soils on former agricultural land compared to KK11 (5.45 vs. 12.02 Pg C, respectively). Finally, our dataset also showed a geographically varied pattern of differences in source and sink regions when compared to the KK11 and HYDE 3.1 scenarios, with strongest differences in Central European Russia (Fig S5).

DISCUSSION

Long-term forest changes in Eastern Europe, and how they affected the region's carbon budget, remain poorly understood. We used a range of forest statistics to provide the most spatially detailed reconstruction of forest trajectories since 1700 to date for the European part of the Soviet Union. We found substantial geographic variation in the timing of forest transition, with earlier transitions in European Russia's heartland and later transition towards the periphery. Deforestation was widespread already before 1700, with related emissions twice as large as thereafter, likely due to extensive slash and burn agriculture. Soviet land-management has retarded abandonment, and therefore forest regrowth, on marginal sites - a situation that reversed after the breakdown of the Soviet Union. Compared to the KK11 and HYDE land-use scenarios, our reconstruction suggests substantial emissions before 1700,

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stronger deforestation after 1700, and a lower rebound effect, together underlining the regions substantial sequestration potential in regrowing forests. Our results also suggest a very heterogeneous pattern of source and sink dynamics, emphasizing the need for regionalized, context specific strategies to foster carbon sequestration in order to mitigate climate change.

Forest transitions in the European part of the former Soviet Union remain weakly understood (Meyfroidt and Lambin, 2011, Kaplan et al., 2012). Our forest area reconstructions revealed clear east-west and north-south trends in the timing of forest transitions (Fig. 4). An explanation of this pattern lies in the history of the Russian Empire, which had its heartland in central European Russia (i.e., around Moscow), where settlement, population growth, and agricultural expansion occurred earlier than in the Empire's periphery (e.g., southeast European Russia, Belarus, Ukraine). Similarly, parts of contemporary Belarus and western Ukraine formed the periphery of other Empires (i.e., the Polish Kingdom and the Austro Hungarian Empire), resulting in later and less settlement and agricultural expansion (Riasanovsky, 2000). Overall, forest transitions in Eastern Europe appear to have occurred substantially later than in western European countries (i..e, mainly in the 18th and 19th century, Mather, 1992, Mather et al., 1999, Kozak et al., 2007, Meyfroidt and Lambin, 2011, Niedertscheider et al., 2014) and North America (Ramankutty et al., 2010). Two reasons explain these patters. First, industrialization and agricultural intensification happened substantially later in Europe's east compared to its west (Chirot, 1991), with shifting cultivation being practiced in some Russian regions until the mid-20th century. Second, Soviet land management paradigms emphasized production increases via both, area expansion and intensification until at least the 1970s (Shaffer, 1977), leading to the slower reforestation we found in our study area compared to Europe's west (Fig. S3).

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Forest transition studies have so far mainly been carried out at national scale, largely as a result of data scarcity at sub-national scale (Rudel et al., 2005, Kauppi et al., 2006, Meyfroidt and Lambin, 2011). Our study shows, similar to prior work on forests in the United States (Ramankutty et al., 2010), that this can be problematic for large countries. National-scale gross forests trends can mask important sub-national dynamics, including co-occurring regions of forest decline, stability, and recovery within a country. This suggests that the theories explaining forest transitions, which have to date operated at the national scale, may need refinement. Better understanding forest transitions and their drivers requires exploring spatial heterogeneity in forest trends and defining the appropriate geographic extent to examine transitions (Meyfroidt and Lambin, 2011, Redo et al., 2012). Moreover, our results caution against uncritically interpreting forest transitions as indicators of shifts towards more sustainable land systems, as national-scale forest transitions can mask the continued loss of old-growth forests (Echeverria et al., 2006, Ramankutty et al., 2010, Brandt et al., 2012), as in our case in Russia's north throughout much of the 20th century.

We found substantial carbon emissions from deforestation in Eastern Europe, with emissions before 1700 roughly twice as large as thereafter. Interestingly, our dataset suggests stronger pre-1700 emissions than even the KK11 dataset (Fig. S4), which is often viewed as an upper boundary of historic deforestation and related carbon emissions (Ellis et al., 2013). Thus, our results support views of a historically large land-use footprint due to more land-intensive agricultural practices, and underline the importance of considering agricultural intensification, and especially changes in land area utilized per person, when assessing past land-use change and associated emissions (Ellis et al., 2013). This point is further reinforced by carbon budgets from our land-use scenario being overall much more similar to those from KK11 (which accounts for changes in land productivity and intensification) than those from HYDE (which assumes constant land area per person, Fig. 5).

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Compared to the KK11 and HYDE land-use scenarios, our data also suggests net emissions throughout much of the 20th century and overall a slower and less pronounced rebound effect in terms of carbon stored on former agricultural lands. Later industrialization and urbanization (i.e., outmigration from rural areas) in Eastern Europe compared to Europe's west and slow technology diffusion (e.g., lower availability and delayed adoption of iron plows, drainage, tractors, and artificial fertilizer) and thus a delayed abandonment of marginal farmland explain these patterns. Moreover, a major goal of Soviet land management policies was to expand agriculture in order to attain self-sufficiency (McCauley, 1976, Brooks and Gardner, 2004, Ioffe and Nefedova, 2004). This led to marked agricultural expansion, mainly into steppes but also in other parts of European Russia at the expanse of forests (Tsvetkov, 1957, Lyuri et al., 2010). At the same time, agriculture was intensified via collectivizing land into large-scale, state-controlled farm enterprises, increasing reliance on heavy machinery, and rising use of pesticides and industrial fertilizer. Agricultural enterprises were also not only output oriented but also had an important social role, providing job opportunities and infrastructure structures in the countryside (Shaffer, 1977). Thus, while some Soviet regions experienced a concentration of agriculture on fertile areas with marginal land being taken out of production and reverting back to forests (Lyuri et al., 2010), by and large Soviet land management likely retarded such a polarization trend, contributing to the slow reforestation we observed.

Taken together, our results therefore suggest that the legacies from past land-use will continue to affect future carbon budgets substantially. One the one hand, as forest transitions in most regions in the former European part of the Soviet Union occurred relatively recent, substantial areas of young forests exists, which will continue to accumulate carbon in the

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coming decades. Indeed, many countries in Eastern Europe have currently age class distribution heavily skewed towards younger stands (Yaroshenko et al., 2001, Kuemmerle et al., 2011, Vilén et al., 2012). On the other hand, while Soviet land management retarded farmland abandonment, the collapse of the Soviet Union triggered a pulse of widespread agricultural abandonment (more than 30 Mha in European Russia, Belarus and Ukraine alone, Schierhorn et al., 2013). While some of these lands are progressively put back into production, much will eventually reforest. Abandoned lands have already sequestered substantial amounts of carbon (most of which belowground, Schierhorn et al., 2013, Kurganova et al., 2014), but the bulk of carbon storage is yet to happen as these areas transform to full-grown forests. Sequestration may also increase in the future due to warmer climates (i.e., leading to higher productivity in more northern regions) and CO_2 fertilization (Sitch et al., 2008, Hickler et al., 2012). Assessing how these trends superpose with the heterogeneous land-use legacies from deforestation and regrowth is important for understanding the region's future carbon budgets.

A number of reasons for uncertainty need mentioning. First, we assembled and homogenized a wide range of data sources to reconstruct the spatially most detailed picture of forest trends in Eastern Europe for the last 300 years. Yet, we partly relied on forest estimates from a time when forest inventorying was in its infancy and surveys took relatively long to implement, which may translate into higher levels of uncertainty for our forest estimates from the 18th century. However, this would only marginally affect carbon dynamics from the 20th century. Second, we used a simply disaggregation method based on area shares. We tested alternative aggregation schemes (e.g., using contemporary forest area as weights) which resulted in highly similar forest trajectories. Nevertheless, we cannot fully rule out that more complex disaggregation procedures (e.g., Fuchs et al., 2012) would result in different forest

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trends. Third, we used a well-established dynamic global vegetation model in order to reconstruct trends in carbon storage in vegetation and soils. However, this model neither includes forest management (i.e., logging) nor changes in the location of agriculture (i.e., shifting cultivation). Both of which would lead to further declines in primary forests, suggesting that our carbon emission estimates are conservative. Fourth, while our LPJ model did account for broad changes in vegetation composition across our study region (i.e., from boreal forests in the north to a mix of temperate forests and forest steppes in the south) we did not account for potential changes in forest composition brought about by changes in climate or forest management. Climate change over the last 300 years was not substantial enough to affect natural forest composition at the spatial scale of our simulations. However, the establishment of plantation forestry led to marked changes in tree species composition in parts of Europe in the 19th and 20th century, which may have affected carbon storage, yet planation forestry in our study region is much less widespread than in Europe's West, suggesting that our results are generally indicative of the changes in carbon storage that occurred over recent centuries. Finally, we relied on forest area statistics and did not consider satellite estimates that are only available for recent decades. Comparing our forest area statistics with satellite-based forest area assessments also suggest high agreement of these data sources (Fig. S6). Yet, while satellite-based forest maps would allow to better consider forests regrowing on agricultural abandoned after 1991, they have the disadvantage of mapping purely land cover, thus blending land-use conversions (i.e., deforestation or abandonment) with management (i.e., clearcutting). As our focus was on land-use change in the last 300 years, and as forest expansion on abandoned agriculture after 1991 has been slow, we chose to rely on forest area statistics for consistency reasons.

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Past land use can have strong and long-lasting legacies for carbon budgets in the future. Our study showed that Eastern Europe may be a region where land-use was more widespread and related emissions were higher than previously appreciated already 300 years ago. Moreover, strong legacy effects for future carbon trends may exist in the region because forests have rebounded only moderately from past deforestation. We found substantial variation in forest trends, including continued deforestation throughout much of the 20th century, which cautions against uncritically interpreting national-scale forest transitions as indicators of shifts to more sustainable land systems. The breakdown of the Soviet Union, along with climate change, may lead to accelerated forest expansion and growth in the future. Understanding the opportunities for climate-change mitigation arising from these trends, as well as the carbon trade-offs of intensifying agriculture in this region, will require taking into account legacy effects in a spatially detailed way.

ACKNOWLEDGEMENTS

We thank L. Baskin, K. Ostapowicz, and V.C. Radeloff for helping with the data collection and for constructive discussions, as well as M. Baumann, B. Bleyhl, R. Kramer, and F. Schierhorn for help with GIS analyses. We gratefully acknowledge support by the European Commission (VOLANTE, No. 265104; HERCULES, No. 603447; COEVOLVE, No. 313797), the Federal Ministry of Food and Agriculture (GERUKA), the Leibniz Association (EPIKUR), and the Einstein Foundation Berlin. We are grateful for the constructive and helpful comments provided by two anonymous reviewers.

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SUPPORTING INFORMATION LEGENDS

Fig. S1: Administrative boundaries of the study region

Table S1: Data sources for reconstructing forest area time series 1700-1914

Table S2: Data sources for reconstructing forest area time series 1914-2012

Fig. S2: Interpolated forest trajectories per administrative unit

Fig. S3: Forest trajectories at the country-level

Fig. S4: Total C stored in vegetation and soils on unmanaged land and abandoned lands (i.e., regrowing forests)

Fig. S5: Carbon stock patterns at key time periods across land-use scenarios

Fig. S6: Comparison of forest statistics and satellite-based forest estimates

FIGURE CAPTIONS

Fig. 1: Forest area at the state-level (Russia, Ukraine, Belarus) or national-level (Estonia, Latvia, Lithuania, Moldova, Armenia, Azerbaijan, Georgia) for the European part of the Soviet Union (see Tables S1 and S2 for sources).

Fig. 2: Forest area observations, interpolated forest area trajectories and 95% confidence interval around the polynomial estimator. Forest transitions (FT) were derived as the minimum of the interpolated forest area trajectories. Forest area curves and FT points for all states/countries are provided in Figure S2.

Fig. 3: Change rates for every 20-year interval since 1900, calculated from the interpolated forest area time series.

Fig. 4: Spatial variation in the timing of forest transitions (i.e., the shift from net deforestation

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to net forest increase) across the European part of the former Soviet Union. Forest transitions did not occur during the last 300 years in a major share of the regions investigated.

Fig. 5: Terrestrial carbon stored in vegetation and soils on unmanaged land (i.e., mainly forests), agricultural land, and in natural vegetation and soils recovering on abandoned agricultural lands for (a) the forest trajectories reconstructed in this paper, (b) the KK11 land-use reconstruction, and (c) the HYDE 3.1 land use reconstruction.

Fig. 6: Patterns of total carbon stored in vegetation and soils (unmanaged land, agricultural land, abandoned agricultural areas) in 1890 (a) and differences in total C storage compared to the 1890 baseline for the years 1930 (b), 1970 (c), and 2010 (d).

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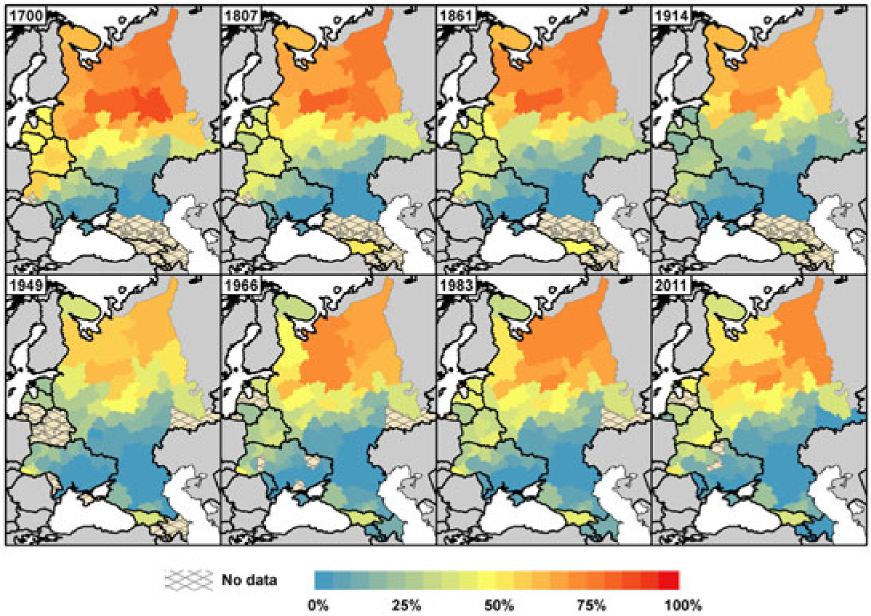

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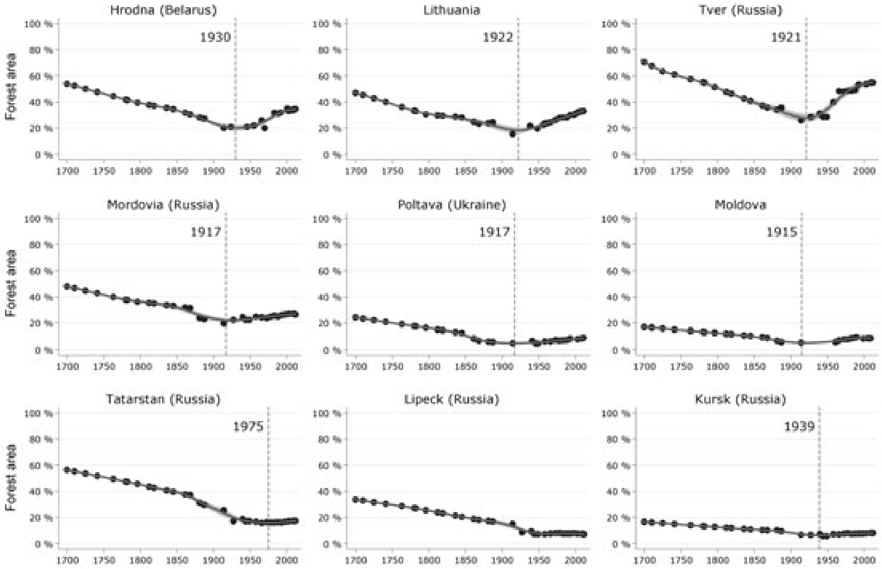

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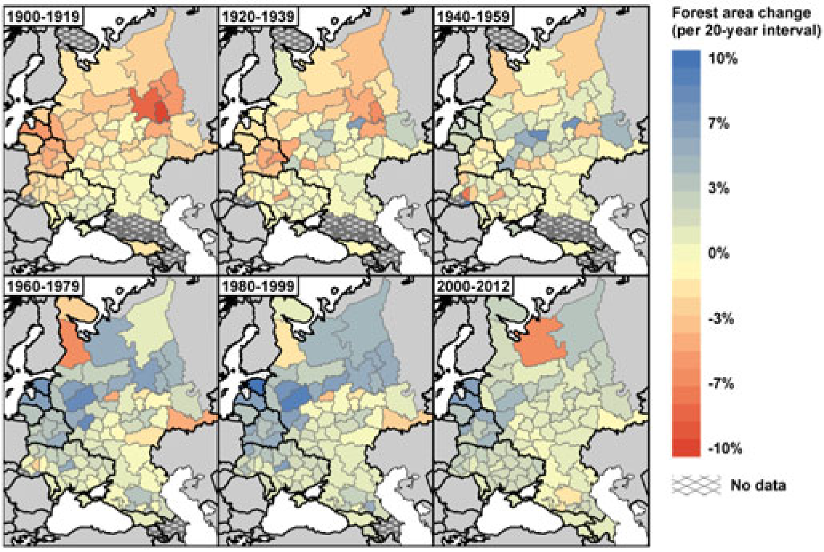

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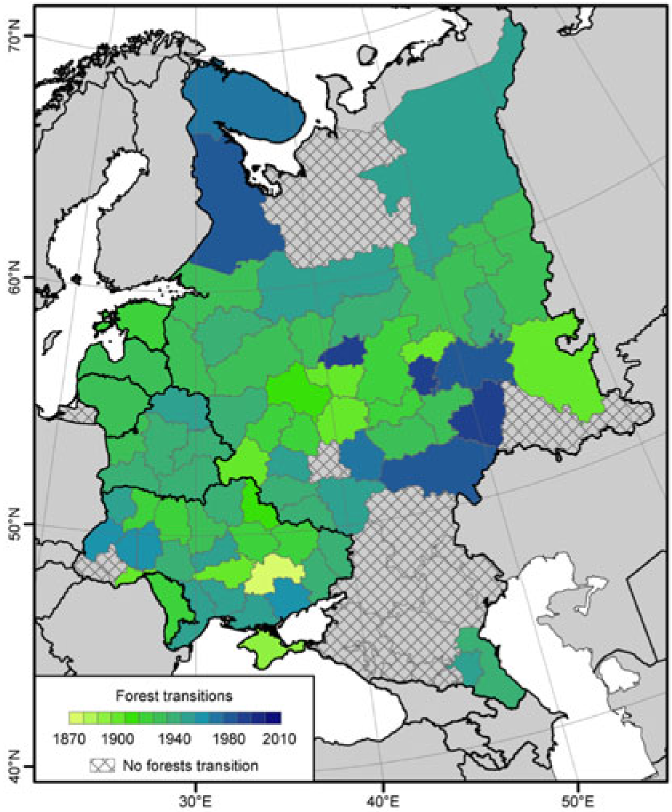

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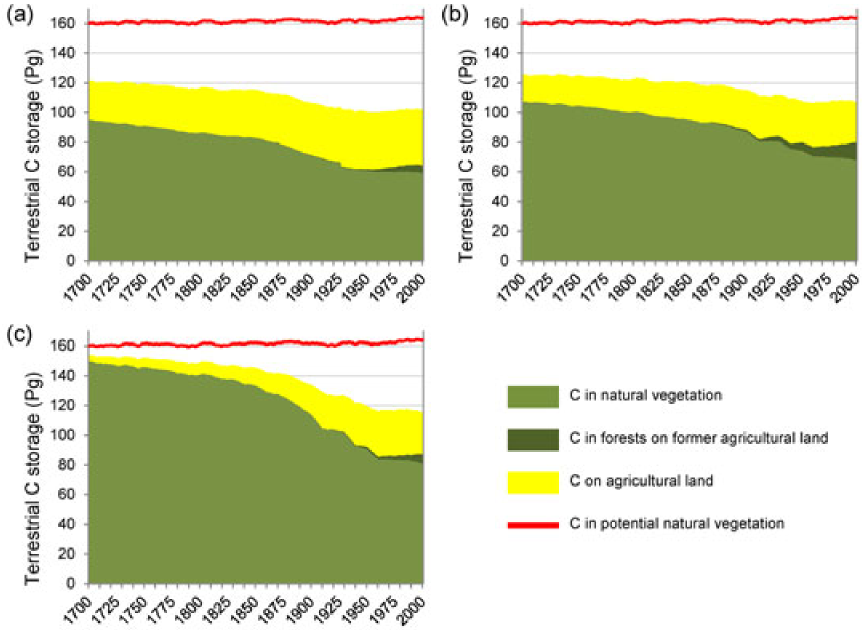

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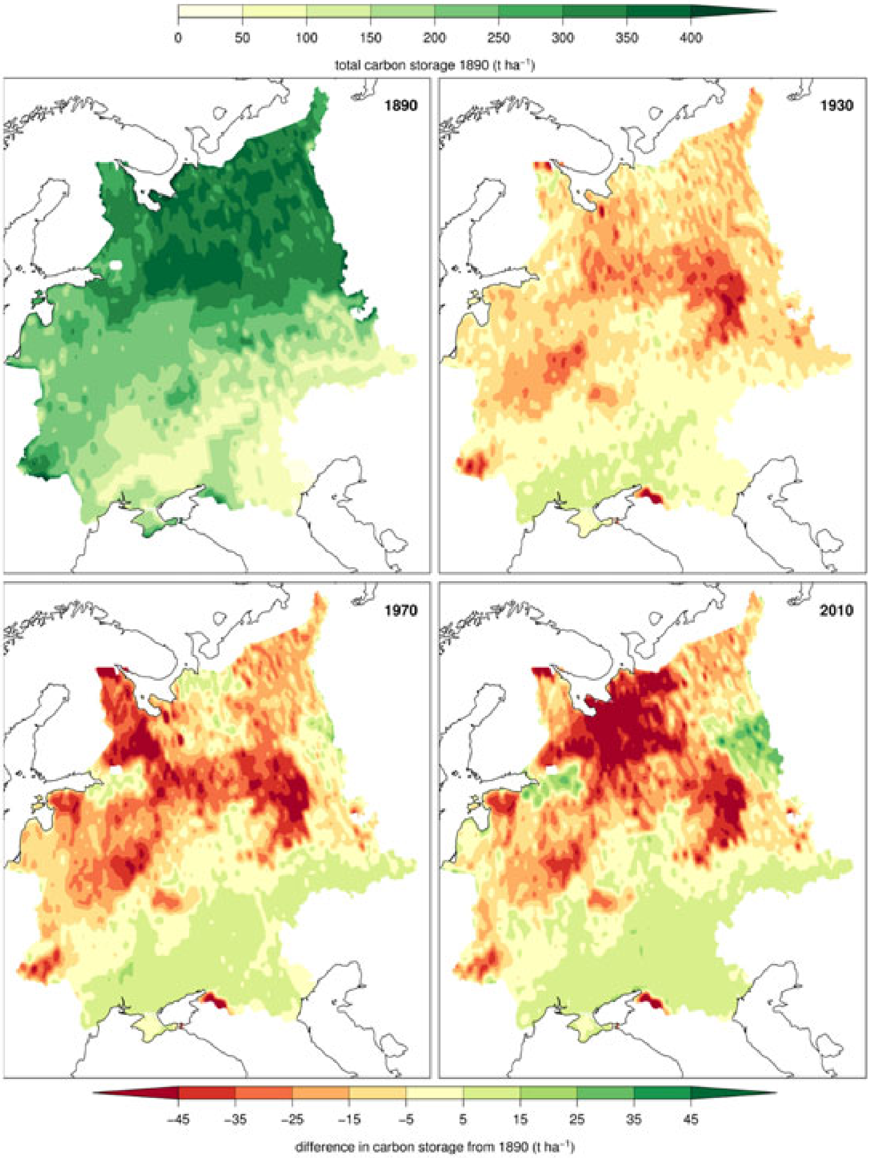

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