Recultivation of abandoned agricultural lands in Ukraine: patterns and drivers

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Abstract

The recent rise in agricultural commodity prices and the expectation that high price will persist have triggered a wave of farmland expansion in regions where land resources are still available. One such region is the former Soviet Union, where the collapse of socialism caused massive agricultural abandonment and where some of these lands are now being brought back into production. Yet, the extent and spatial patterns of recultivation, and what determines these patterns, remains unclear. We examined the extent of recultivation of abandoned agricultural land in Ukraine since 2007 using a new, satellite-based recultivation map and assessed the effect of biophysical and socioeconomic determinants on recultivation patterns using boosted regression trees. We found key predictors of recultivation to be related to the suitability of land for agriculture (i.e., soil quality, temperature). Accessibility to major cities was also important, with most recultivation happening closer to settlements, but this influence varied across Ukraine. Variables related to agricultural management (fertilizer input, mechanization) and demography were negligible in explaining recultivation in our analyses. These factors suggest that recultivation patterns were primarily driven by factors related to land productivity, with recultivation focusing on the most promising areas. Given the remaining large amount of unused agricultural land in Eastern Europe and the former Soviet Union, and considering that much abandonment occurred in areas only marginally suited to agriculture, our findings provide important insights into where recultivation can be expected to happen and thus for assessing the potential socioeconomic and environmental impacts of recultivation.

Key words: land-use change, agricultural expansion, post-Soviet agricultural abandonment, boosted regression trees, spatial statistics, MODIS.

1. Introduction

Agriculture provides humans with essential food, fiber, and biofuel, but it is also a key driver behind the loss of ecosystem services and biodiversity (Foley et al., 2005). Although agriculture is still expanding in many tropical regions (Laurance et al., 2014), agricultural abandonment has become a common land-use change process, both in temperate regions such as Western Europe (Hatna and Bakker, 2011; MacDonald et al., 2000) and the United States (Ramankutty et al., 2010), as well as in some tropical areas, including Latin America (Izquierdo and Grau, 2009) and Asia (Zhang et al., 2014). Agricultural abandonment often occurs in more marginal areas, whereas agricultural production concentrates in fertile, accessible regions where profits from farming are larger. Moreover, agricultural abandonment can result not only from the outmigration of people from rural to urban areas but also from the displacement of agricultural production abroad (Kastner et al., 2014; Meyfroidt and Lambin, 2011). Where abandonment occurs, opportunities for restoring ecosystem services, such as carbon sequestration, soil stability and native biodiversity, arise (Cramer et al., 2008; Kurganova et al., 2014), and it is therefore important to understand the spatial patterns and fate of abandoned agricultural land.

Abandonment of agricultural land has been particularly pronounced and rapid in Eastern Europe and the former Soviet Union following the demise of socialism (Alcantara et al., 2013; Griffiths et al., 2013; Prishchepov et al., 2012). The transition from planned to marked-oriented economies led to a strong withdrawal of government support for agriculture, price liberalization of inputs and outputs, the disappearance of formerly guaranteed markets, tenure insecurity, and increasing competition on globalizing agricultural markets (Hartvigsen, 2014; Rozelle and Swinnen, 2004). Additionally, rural areas experienced aging populations and high rates of outmigration to cities (Philipov and Dorbritz, 2003). Together, this has led to widespread agricultural abandonment, with 31 million hectares (Mha) of abandoned cropland in European Russia, Ukraine, and Belarus (Schierhorn et al., 2013) and more than 50 Mha of abandoned farmland in Central and Eastern Europe (Alcantara et al., 2013). Whether these lands are permanently abandoned or only set aside for future use remains unclear.

A number of studies have assessed the spatial patterns of post-socialist land abandonment throughout Eastern Europe and the former Soviet Union, revealing substantial variation regarding the relationship between abandonment and its spatial determinants. For instance, in temperate European Russia, higher abandonment rates between 1990 and 2000 were associated with the lower grain yields of the late 1980s, larger distances from settlements, and lower population density (Prishchepov et al., 2013). Similarly, in post-communist Albania and Romania, abandonment rates increased further away from settlements, although more fragmented fields were prone to abandonment in Albania but not in Romania (Müller et al., 2009; Müller and Munroe, 2008). In Western Ukraine, higher abandonment rates between 1989 and 2008 were found in flatter areas, in close proximity to cities, and where population declined (Baumann et al., 2011). Overall, post-Soviet abandonment was often more widespread on more marginal lands (Prishchepov et al., 2013). However, institutional factors (e.g., land reforms, EU accession) affected abandonment patterns strongly in some regions.

In light of growing global demand for agricultural products (OECD/FAO, 2013), an emerging land scarcity (Lambin and Meyfroidt, 2011), and the drastic environmental costs of expanding agriculture further into natural ecosystems, interest in currently unused agricultural land is rising (Lambin et al., 2013; Schierhorn et al., 2014). For example, policies to increase biofuel production and rising commodity prices have resulted in widespread grassland to cropland conversions in both the United States and Europe (OECD, 2008), including the conversion of approximately 1.2 Mha of grassland in the US between 2008 and 2012 (Lark et al., 2015; Wright and Wimberly, 2013). The unused agricultural lands of Eastern Europe and the former Soviet Union have also been shifting into focus, particularly since 2000 when the region recovered economically and global prices of agricultural commodities began to rise

(Schierhorn et al., 2014; Visser and Spoor, 2011). As a result, recultivation of idle former farmland is increasing across the region (Griffiths et al., 2013; Kraemer et al., 2015; Schierhorn et al., 2013; Stefanski et al., 2014). Unfortunately, the spatial patterns and determinants of recultivation remain insufficiently known.

We are aware of only one study that assesses the extent and the spatial patterns of recultivation in the former Soviet Union. In Northern Kazakhstan approximately 45% of croplands were abandoned from 1990 to 2000, of which only 25% were recultivated by 2010, primarily on better soils (Kraemer et al., 2015). The scarcity of recultivation studies is problematic because knowledge of the spatial patterns and determinants of recultivation is required to understand how much land is potentially suitable for recultivation, where hotspots of recultivation are likely to be located and what both the production potential and environmental trade-offs of recultivation may be (Henebry, 2009; Schierhorn et al., 2013). Likewise, understanding the determinants of recultivation is important in mitigating socio-economic constraints to placing idle agricultural land back into production (Lambin et al., 2013). Further studies on both patterns and determinants of recultivation across Eastern Europe and the former Soviet Union are necessary to pinpoint potential areas for recultivation and to target policies that steer land use toward socially beneficial outcomes in terms of production and conservation.

Ukraine is a particularly interesting case because it harbors approximately 22 Mha of highly fertile black soil (*Chernozem*) (Fileccia et al., 2014). The country has approximately 4 Mha of abandoned former agricultural lands (Ukrstat, 1992, 2013), including those of high agronomic value that could play an important role in producing food and bioenergy for domestic and international markets. Additionally, abandoned lands may provide opportunities to restore steppe ecosystems, which have become rare in Europe (Korotchenko and Peregrym, 2012), and the carbon sequestration potential on Ukraine’s former croplands and pastures is substantial (Kuemmerle et al., 2011). The recultivation of agricultural lands that were abandoned after 1991 have been ongoing since the early 2000s (Estel et al., 2015) and will likely increase when Ukrainian land reform is completed and the existing moratorium on agricultural land sales is lifted. However, to our knowledge, no study has explored recultivation patterns in Ukraine.

The overarching goal of our research was to explore the extent, spatial patterns, and determinants of agricultural recultivation in Ukraine between 2007 and 2012. We relied on a new dataset of agricultural abandonment and recultivation for the period between 2001 and 2012 derived from a high-temporal Moderate-Resolution Imaging Spectroradiometer (MODIS) time series at a spatial resolution of 232 m (Estel et al., 2015). These data allow for analyzing recultivation patterns across all of Ukraine, stretching across five environmental zones and encompassing a wide range of agro-ecological conditions. We applied boosted regression trees to investigate the relative importance of a range of biophysical and socioeconomic determinants of recultivation for all of Ukraine, as well as separately for distinct environmental zones. Our specific research questions were:

- How much agricultural land that was recultivated in Ukraine between 2007 and 2012, and what are its spatial patterns?
- Which factors determine the spatial patterns of recultivation in Ukraine, and how do these factors differ across environmental zones?

2. Study area

Ukraine is Europe’s largest country (except for Russia) encompassing 603,550 km^2 and a population of approximately 45.4 million in 2013 (Ukrstat, 2014). Climatic and soil conditions change gradually across Ukraine, which is reflected by five distinct environmental zones (Fig. 1 C): (1) Mixed Forest, (2) Forest Steppe, (3) Steppe, (4) the Carpathian Mountains, and (5) the Crimean Mountains (Zastavnyi, 1994). In our research, we focused on the three non-mountainous zones, namely Steppe, Forest Steppe, and Mixed Forest, which occupy more than 90% of Ukraine's territory and include the vast majority of agricultural land and agricultural producers (Keyzer et al., 2013). We excluded larger urban areas, such as Kiev and Sevastopol, resulting in a final study area of approximately 575,600 km^2 (Fig. 1).

<<< Figure 1 here >>>

The Mixed Forest zone lies in northwestern and northern Ukraine in the Polissya lowland and covers approximately 20% of the area of Ukraine. Peatlands and forests occupy a substantial portion of this zone, and the cropland share is about 30%. Natural vegetation in the Mixed Forest zone includes mixed oak-pine and pine forest stands and swamp plant communities in the surface bottoms. The dominant soil is sod-podzolic (Greyic Arenosol) with low fertility, high acidity, and low water holding capacity. Agriculture thus depends on fertilizer and lime in this zone, and the main crops cultivated there are cereals (wheat, rye, buckwheat), flax, potatoes, and forage crops (Keyzer et al., 2013; Zastavnyi, 1994).

The Forest Steppe zone stretches across the central part of Ukraine and covers more than 200,000 km^2. Historically, much of this region was forested, mainly with oak and hornbeam (Bohn et al., 2003), but most former forests have been converted to agriculture. The climate of this zone is relatively warm with an average mean temperature of 18°C to 20°C in July and –5°C to –7°C in January. Average annual precipitation is 500 mm-600 mm. Fertile grey forest soils (Haplic Albeluvisol) and highly fertile podzolised Chernozems (Albic Phaeozem) are widespread in the Forest Steppe. The favorable climatic and soil conditions have resulted in an agricultural land share of approximately 70%, and the main agricultural crops include cereals (wheat, maize, barley), oil crops (sunflower, rape seed), sugar beet, and vegetables. However, harsh winters may cause harvest loss ("winterkill"), which, along with the water erosion of soils, is the main constraint on agriculture across this zone (Keyzer et al., 2013; Zastavnyi, 1994).

The Steppe zone in the south and the east occupies approximately 40% of Ukraine. The main soil types in the Steppe zone are Chernozems and Kastanozems and salinized soils near the coastlines of the Black Sea and Azov Sea. Annual precipitation ranges from 350 mm to 500 mm, and mean July temperature ranges between 21°C and 23°C, leading to substantial soil moisture deficits. Severe droughts (e.g., in 2003, 2007, 2010) are a key challenge for agriculture in this zone, in particular in regions that lack supplementary irrigation, such as around the Dnieper river mouth. Mainly winter wheat, sunflower, maize, and barley are cultivated in the Steppe zone (Keyzer et al., 2013; Zastavnyi, 1994).

Agriculture is one of the most important sectors of the Ukrainian economy contributing roughly 17% to GDP in 2013 and an average annual growth of the agricultural sector of 7% from 2008 to 2013 (Ukrstat, 2014). Approximately 20% of agricultural land still remains in state or communal property, and the rest was distributed among nearly 7 million rural residents during the 1990s (Plank, 2013). Although the sale or purchase of agricultural land in Ukraine was prohibited by the Land Code in 2001 (VRU, 2001), Ukraine is still an attractive country for foreign investment in agriculture, particularly in the Black Earth Region via the symbiosis of international companies with partner businesses in Ukraine (Visser and Spoor, 2011). At present, Ukraine is characterized by a dual agricultural structure with large and super-large corporate farms (*agroholdings*), that have a land bank of 10,000 ha to 500,000 ha per unit, which coexist alongside tiny subsistence farms (Keyzer et al., 2013). Agroholdings have developed rapidly since 2005 and demonstrate the integration of much of the agricultural value chain with land consolidation, production specialization, reduction in crop rotation, and arable land expansion (Demyanenko, 2008). Agroholdings are focused mainly on cultivation of profitable crops (e.g., wheat, sunflower, rape seed) at the expense of other crops (Frayer, 2012). Subsistence family farms often use household plots for agricultural production and have average size of approximately 3 ha. They contribute roughly 40% to gross agricultural production of the country. These farms mainly produce livestock, vegetables and fruits, and they have been fairly stable in terms of land area utilized. A new form of farm type in Ukraine are market-oriented private family farms, 77% of which operates more than 5 ha and specialize mostly on crop production (Ukrstat, 2013).

3. Materials and methods

3.1. Maps of recultivation

We used a new satellite-based dataset by Estel et al. (2015), which was derived from MODIS images and covers all of Ukraine at a spatial resolution of 232 m. MODIS Normalized Difference Vegetation Index (NDVI) time series were classified into active (i.e., managed) and fallow (i.e., unmanaged) agricultural land for each year between 2001 and 2012, with an average overall accuracy of >90%, assessed based on independent validation data. The annual information on fallow and active agricultural land was then used for calculating fallow/active frequency on a per pixel level (Fig. 1 A), as well as for translating fallow/active series into abandonment and recultivation trajectories (Estel et al., 2015).

The visual examination of this dataset revealed that places without any sign of management over the 12-year period (permanently fallow (Estel et al., 2015)) often represented unmanaged grasslands along river flood plains, mountain meadows, or peat bogs in northern Ukraine. Some of these lands were used during Soviet times, e.g., for livestock grazing. However, conversion of meadows alongside rivers into cropland is highly unlikely, and we therefore excluded these areas from our analyses. Our final dataset consisted of 462,420 km^2 (i.e., 46 Mha) agricultural land.

Although the land-use/cover dataset covers a period of 12 years, we focused on the period between 2007 and 2012 because recultivation became a dominant land-change process in Ukraine only thereafter and because the reliable detection of recultivation requires images from several years prior to the recultivation event (Estel et al., 2015). Given that any of crop rotation systems in Ukraine implies fallow period longer than 5 years we defined these parcels during 2001-2006 as “abandoned”. Following Estel et al. (2015), we used three differently restrictive definitions of recultivation for our analysis based on number of years a field was in use after recultivation (Table 1). We created three binary datasets, one for each recultivation definition that we subsequently used as dependent variables in our models.

<<< Table 1 here >>>

3.2. Explanatory variables

The most detailed level for which consistent statistical information exists in Ukraine is the district (i.e., *rayon*) level. Ukraine consists of 490 districts, 478 of which we used after excluding mountainous and urban areas. To link district-level statistical data with the other datasets, we used district boundaries from Eurogeographics (www.eurogeographics.org) that were examined, and, if necessary, manually improved using official Ukrainian boundaries available via the public cadastral map of Ukraine (http://map.land.gov.ua/kadastrova-karta).

We compiled a set of spatially explicit variables that we hypothesized to influence spatial patterns of recultivation. These variables comprised both biophysical (e.g., slope, temperature) and socioeconomic (accessibility, demographic, and agricultural management) predictors (Table 2). Explanatory variables available in raster format were resampled to the resolution of the recultivation maps (i.e., 232 m). In terms of biophysical variables, elevation and terrain slope were derived from the Shuttle Radar Topography Mission (SRTM) digital elevation model version 4 (Jarvis et al., 2008). We tested two variables capturing climatic patterns: the annual sum of mean daily temperatures above 5° C, calculated on the basis of 1 km resolution global climate data (Hijmans et al., 2005), and a global aridity index that represents the ratio of mean annual precipitation to average potential evapotranspiration during the year (Zomer et al., 2008). Soil data were obtained from a raster dataset at 1 km resolution that represent topsoil pH within the upper 30 cm layer (Hengl et al., 2014).

<<< Table 2 here >>>

We used a number of accessibility variables to proxy access to local and regional markets and transport costs, as well as to facilities for the storage and export of agricultural products. In the absence of official spatial information on road networks and settlement boundaries, these data were extracted from Eurogeographics and OpenStreetMap (www.openstreetmap.org) web resources. We then calculated the Euclidian distance of every location to (1) the nearest settlement, (2) the nearest major city with a population of >50,000 inhabitants, and (3) the nearest paved road. We also calculated the distance from the nearest forest edge based on a forest mask derived from the GlobCORINE land-cover map (Bontemps et al., 2009). We used this variable as a combined proxy of environmental marginality of a location for agriculture and accessibility. Moreover, this variable also captured aspects of land-use history, as the conversion of forest to agricultural land closer to contemporary forests happened more recently compared to agricultural areas today far away from forest land.

To capture demographic conditions, we used average rural population density (excluding major cities with populations of more than 50,000 inhabitants) and changes in population numbers between 2001 and 2006. To proxy labor availability, we included the dependency ratio (the share of people older than 65 and younger than 15 years in the total population) and the share of officially registered unemployed persons calculated as average value for the period 2001–2006 (Ukrstat, 2007).

To evaluate the influence of agricultural management on recultivation, we collected district-level statistics from 2001 to 2006 on average grain yields, the application of mineral and organic fertilizers, and the mechanization level (i.e., the number of grain combines and tractors) using official data (Ukrstat, 2007). Agricultural statistics in Ukraine lack information about subsistence farms because data are only reported for officially registered agricultural units (i.e., for joint stock companies, cooperatives, partnerships, and collective farms). However, both the number of subsistence farms and the area cultivated by them remained constant and occupied only approximately 15% of our study area (Ukrstat, 2013).

We made a pre-selection of covariates to reduce model complexity and to increase model interpretability. To define the final suite of variables for our statistical analysis, we assessed multi-collinearity between each variable pair, and, for each pair with a Pearson's correlation coefficient greater than 0.5, we retained only the variable that showed a higher correlation with the dependent variable. Descriptive statistics, our a-priori assumptions regarding the influence of variables, and additional information on the explanatory variables used in our analyses, can be found in Table 2.

3.4. Sampling design and regression setup

We estimated separate models for each of the three recultivation definitions (Table 1). We also estimated models for all of Ukraine as well as individual models for each of the three environmental zones (Mixed Forest, Forest Steppe, and Steppe). Thus, we estimated 12 regression models, nine for individual environmental zones (hereafter *regional models*) and three for all of Ukraine (hereafter *global models*). We only considered observations of unused agricultural land between 2001 and 2006, according to Estel et al. (2015), and therefore potentially available for recultivation between 2007 and 2012. We labeled observations that were recultivated as presence (and coded as "1") and unused agricultural land that remained unused between 2007 and 2012 as absence (or "0"). To reduce possible effects of spatial autocorrelation, we selected only observations with a minimum distance of 500 m between them, resulting in 16% decrease of Moran's I in comparison to the full dataset. These sampling steps reduced the number of observations to 169,387. Finally, from the resulting data, we randomly sampled 10,000 observations within each of the three environmental zones.

For the global models, we randomly chose 30,000 observations proportionally to the share of recultivation in the three environmental zones that we analyzed.

3.5. Boosted regression trees

As a regression framework, we used boosted regression trees (BRTs), which are a powerful non-parametric regression approach (Friedman et al., 2000). BRTs can capture complex, non-linear relationships between response and predictor variables, which are common in land systems (Levers et al., 2014; Müller et al., 2013). The central idea behind boosting is that the combination of many individual, potentially weak models into an ensemble will boost performance (Hastie et al., 2009). BRTs consist of individual decision trees, which explain the variance of a target variable by splitting up the variable space in a binary fashion. Boosting minimizes the loss function in decision trees by adding trees (i.e., existing trees remain unchanged when more trees are added, and only the fitted value is re-estimated). The first tree reduces the loss function the most, whereas all of the following trees focus on the residuals of the previously fitted model, which typically leads to a considerable increase in predictive accuracy (Friedman et al., 2000; Hastie et al., 2009). BRTs do not tend to overfit, are robust against missing data and collinearity in predictors, and can handle non-linear relationships and interaction effects well (Dormann et al., 2013; Elith et al., 2008).

The calibration of BRTs requires specifying four main parameters: bag fraction, tree complexity, learning rate, and number of trees. The bag fraction defines the share of the sample withheld from training while fitting each single decision tree (Hastie et al., 2009). We used a bag fraction of 0.5 (De'ath, 2007; Friedman, 2001), which implies an equal split of the total observations (i.e., 10,000 for the regional models, 30,000 for the global models) into training and testing samples. For the remaining parameters, we tested a range of combinations (complexity from 1 to 6, learning rates from 0.005 to 0.025), and used 10-fold crossvalidation to identify optimal parameter settings (using the area under the receiver operating characteristics curve (AUC) as a goodness of fit measure). As a result, we chose an interaction level of 4 and a learning rate of 0.01. These parameters were then used to automatically determine the number of trees required for optimal prediction by minimizing a loss function (Elith et al., 2008) using the *gbm.step* function within the *dismo* package (Hijmans et al., 2013) in R.

We derived partial dependency plots (PDPs) to visualize the results. PDPs show the relationship between the response variable and one predictor variable while keeping the remaining predictors at their mean (Friedman, 2001; Friedman and Meulman, 2003). We only interpreted variables with a relative contribution above that expected by chance (100% / number of variables; in our case: 100% / 12 = 8.33%) following Müller et al. (2013). To evaluate the goodness-of-fit of our models, we used the cross-validated AUC, explained deviance, and the percentage of correctly classified observations. Finally, we mapped the likelihood for recultivation using the results of three global models and then calculated an average value. To estimate recultivation likelihood within actually fallow agricultural land, we masked the maps applying the same rule (5 out of 6 fallow years; see Table 1) for the period between 2007 and 2012.

4. Results

The total area of recultivation in our study area varied, depending on the recultivation definition (Table 1), from 170,800 ha when using our exclusive definition (cultivation in at least 5 out of 6 years), to 445,100 ha for the intermediate definition (cultivation in at least 4 out of 6 years), and 978,800 ha for the most inclusive definition (cultivation in at least 3 out of 6 years). The area of recultivated land was nearly equal in the Steppe and Forest Steppe in our exclusive definition, yet twice as large in the Forest Steppe compared to the Steppe in the inclusive definition (Fig. 2). The area of abandoned agricultural land also differed substantially between environmental zones. For instance, over half of the fallow agricultural land between 2001 and 2006 was found in the Forest Steppe zone, one-third in the Mixed Forest, and the rest in the Steppe. In terms of *recultivation rates* (recultivated agricultural land relative to all unused agricultural land between 2001 and 2006), we found the highest rates in the Steppe zone (~52%) and the lowest rates in the Mixed Forest (~11%).

<<< Fig. 2 here >>>

Summarizing the rate of recultivation at the district level showed that districts with the highest recultivation rates (>50%) were all situated in the Steppe zone (Fig. 3). Particular clusters of recultivation occurred in Zaporizhya province in southern Ukraine, as well as in Odessa and Kharkiv provinces. These clusters were found across all recultivation definitions, consistently highlighting the highest recultivation rates in the Steppe zone. When assessing recultivated area, we found more uniform spatial patterns across the country, again irrespective of the recultivation definition. The largest extent of recultivated land was observed in eastern and central Ukraine, particularly in Dnipropetrovsk, Kharkiv, and Lugansk provinces, with smaller hotspots in the southwest within Odessa province (Fig. S.1, Supplementary material).

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Analyzing the collinearity among explanatory variables revealed strong correlation (>0.5 Pearson's coefficient) for some pairs. To account for this, we excluded aridity index, elevation, grain yields, population density, and population change variables from the final suite of predictors used in our study. Modeling the drivers of recultivation patterns showed, that accessibility variables and the annual sum of mean daily temperatures above 5° C contributed the most to model performance, followed by agricultural management and demographic explanatory variables. Distance to the nearest forest edge was the most important variable in 8 out of 12 of our models (Table 3). Temperature and accessibility had high explanatory power in all 12 models, and slope, unemployment rate, and mechanization level had a statistically meaningful influence in the Steppe only. Topsoil pH, dependency ratio, and mineral and organic fertilizer input did not contribute substantially to explaining total variance, with all these variables explaining less variance than what can be expected by chance (8.33%). In general, both the global and regional models showed better performance with the exclusive definition of recultivation (Table 4).

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In the global models and the Steppe models, the contribution of distance to forest edge gradually decreased from the exclusive to the inclusive recultivation definitions (from 23% to 16%), but the influence of temperature increased only marginally (from 9.7% to 10.3%). The contribution of other influential variables (distance to the nearest city, slope, and unemployment rate) remained stable across the definitions of recultivation. For the global models, AUC and prediction accuracy increased from 0.76 to 0.83 and from 0.86 to 0.96, respectively, for the exclusive recultivation definition. The increasing of performance parameters of the Steppe models was less pronounced than for global ones. However these models showed the highest true positive rate of prediction (Table 4).

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In the Forest Steppe models, the importance for the three accessibility variables decreased from the exclusive to the inclusive recultivation definition, and the influence of the distance to the city variable did not show clear patterns across definitions. Models for the Mixed Forest zone only showed a higher influence of distance to forest edge and temperature for the inclusive compared to the exclusive definition of recultivation.

The partial dependency plots provided further insight into the relationship of recultivation and the influential predictor variables (Fig. 4). For the entire suite of models, we found a very similar influence of distance to forest edge on the recultivation likelihood. Further away from the forest edge the likelihood of recultivation increased sharply, but leveled off at approximately 5 km (around 10 km in the Steppe model). The effect of distance to the forest edge was the strongest in the Steppe, followed by the global model, the Forest Steppe and the Mixed Forest.

Other accessibility variables, such as distance to settlements, had lower explanatory power. For instance, distance to nearest major cities had a near-uniform and small influence on the likelihood of recultivation in all models. The effect of distance to major cities was again larger in the Steppe model than it was for all other models (Fig. 4). Distance to the nearest paved road and to the nearest settlement were statistically important only in the Forest Steppe and Mixed Forest models, albeit with a small effect that was slightly more important in the Forest Steppe models. The increasing annual sum of mean daily temperatures above 5° C had a strong bearing on recultivation, in particular in the Steppe models and, to a lesser extent, in the global models.

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Mapping the likelihood of recultivation using the average value of the three global model predictions (Fig. 5) showed that the highest recultivation likelihoods were observed in the Steppe zone in the southeast, with hotspots in, for example, Donetsk, Dnipropetrovsk, and Lugansk provinces. However, this zone has experienced much recultivation during our study period, and remaining abandoned agricultural land there is scarce. When we masked out all active agricultural lands, the southern part of the Mixed Forest (e.g., Kiev province) and some areas in the central and northern Forest Steppe zones (e.g., Sumy and Cherkasy provinces) emerged as areas of high likelihood for further recultivation of abandoned agricultural land in Ukraine.

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5. Discussion

Recultivating recently abandoned agricultural land may be an attractive alternative to expanding agricultural areas into remaining natural ecosystems. Eastern Europe and the former Soviet Union experienced widespread agricultural abandonment after the demise of socialism. Ukraine, a former breadbasket country, is particularly interesting in this regard. However, the extent, spatial patterns, and determinants of recultivation are poorly understood. Our analyses suggest that recultivation has become a major land-use trend in Ukraine due to high agricultural commodity prices that have been seen since 2007 and expectations of continued high prices, which have attracted large-scale agriculture investments. Recultivation was particularly widespread in the Steppe zone (up to 50% of all abandoned agricultural land), where vast areas of fertile Chernozems are found. Across our models, recultivation patterns appear to be mainly driven by factors related to profit-oriented agriculture because we found the highest recultivation rates in areas with good agro-environmental conditions for agriculture. Our predictions of recultivation likelihood show that much potential for further agricultural expansion remains in Ukraine but also that hotspots of future recultivation may not coincide with recent hotpots because idle agricultural land with good agro-environmental conditions is becoming scarce. Recultivation of abandoned agricultural lands in Ukraine, as well as in Eastern Europe and the former Soviet Union, may make a substantial contribution to increasing agricultural production, and our results provide starting points for quantifying these potentials and the environmental trade-offs.

The extent of recultivated land ranged between 170,800 and 980,800 ha during 2007-2012, which comprises 0.4%-2.3% of the total agricultural land area in Ukraine. Large tracts of unused agricultural land on fertile Chernozems have attracted both domestic and foreign investment in agriculture, often in the form of agroholdings with vertically integrated structures (Demyanenko, 2008; Sarna, 2014). We found that approximately half of the recultivated fields were located on Chernozem soils, and only 20% of abandoned agricultural land on Chernozem soils remained unused after 2007. An emergence of agroholdings in the 2000s was a phenomenon of post-Soviet reform of the Ukrainian agrarian sector, which was possible thanks to (1) distributing land tittles, allowing to lease land from owners, (2) increasing the profitability of agricultural production due to low input costs and raising commodities prices, (3) access to cheaper credits compared to small farms, and (4) tax advantages and government subsidies to stimulate the establishment of agroholdings (Demyanenko, 2008). As a result, land managed by agroholdings increased from 4 to 6 Mha between 2010 and 2012 (AgriSurvey, 2014), which corresponds well with the trends found in our satellite-based recultivation maps. At the same time, our analyses showed that the southern and eastern provinces of Ukraine may not hold much more potential to recultivate abandoned agricultural lands, and future hotspots of recultivation may likely be found elsewhere.

The spatial pattern and hotspots of recultivation differed when assessing recultivated area and recultivation rates (Fig. 3). We found five provinces that both have substantial amount of recultivated land and high recultivation rates: Donetsk, Lugansk, Dnipropetrovsk, and Kharkiv in the east and Odessa in the south. However, the southern provinces (Kherson, Mykolaiv, and Zaporizhya), having relatively small areas of abandoned land, showed high recultivation rates (up to 69%) and therefore also constitute recultivation hotspots. In general, our analyses revealed that recultivation hotspots were found near larger urban centers within the Steppe zone (e.g., Dnipropetrovsk, Donetsk, Lugansk). Four factors explain these hotspots: (1) high demand of urban population in agricultural products, (2) better transportation and storage facilities (FAO, 2010; Smyrnov and Shmatok, 2012), (3) availability of qualified personnel in cities necessary for operating agroholdings (Deininger et al., 2013), and (4) a less fragmented land ownership, making it easier for agroholdings to lease large land areas (Shavaliuk, 2015).

Our boosted regression models suggested that the spatial patterns of recultivation were mainly determined by accessibility and agro-environmental conditions, but with varying effects across environmental zones. Temperature and distance to nearest forest had an important bearing on the likelihood of recultivation, with more recultivation in areas with higher temperatures and further away from forests. This highlights the importance of the suitability of a given plot for agriculture, given that distance to forests proxies marginality in terms of remoteness and environmental conditions (as forests in Ukraine typically occur in less accessible areas and on poor soils). The same was true for the distance to nearest city, which was associated with a higher likelihood for recultivation, particularly in areas close to cities. However, higher temperatures within the Steppe were associated with an increase in climate aridity, which in turn causes a ground moisture deficit and, thus, necessity of more water to ensure crop yields (Kovalenko, 2015). We speculate that due to climate aridity, the water balance in the Steppe is more important for recultivation than is the temperature regime. In general, our findings suggest that recultivation tends to happen in more suitable and less remote places where better opportunities for input purchases and output sales, as well as access to decision makers, arguably results in higher farm profits. This suggest spatially targeted policies, with agricultural policies aiming at regions with favorable environmental conditions for agriculture, and policies fostering afforestation and thus carbon sequestration and other non-provisioning services aiming at marginal agricultural land close to existent forests, would be beneficial. This would also have the co-benefit of improving structural connectivity between forest patches in Ukraine, which is low in the Steppe.

Our results match findings assessing the drivers of agricultural abandonment patterns across Eastern Europe and the former Soviet Union. Marginal agro-environmental conditions and adverse accessibility were the key factors determining spatial patterns of abandonment (Milanova et al., 1999; Müller et al., 2009; Müller and Sikor, 2006; Prishchepov et al., 2012), and our findings showed that among these lands, the most suitable lands were recultivated first. However, the pattern of land abandonment differed across post-socialist countries and regions, and the importance of agro-environmental factors were often superposed by macro-scale economic and institutional factors (e.g., reorganization of agricultural sectors, land reforms, economic state support for agriculture), as well as by local differences in farm structure, demography, and farmers' skills (Baumann et al., 2011; Grinfelde and Mathijs, 2004; Müller et al., 2009). One results show that factors related to the land productivity appear more important for determining recultivation patterns than for determining abandonment patterns.

Using our three global models to predict where future recultivation may occur showed that further cropland expansion is most likely in the Steppe zone, where better soils prevail but where little abandoned land remains. Moreover, due to recurrent droughts every 3-5 years, doing agribusiness in the Steppe is more risky (Rozwadowski, 2014). Recultivation in the Mixed Forest and Forest Steppe zones may be more extensive, as predicted by our models when considering only land available for recultivation (Fig 5). Furthermore, our models suggest that improving infrastructure and accessibility in the Mixed Forest and Forest Steppe zones may relax the currently strong constraints for recultivating unused agricultural lands in these regions, thus increasing the attractiveness of investing there.

We note that a substantial portion of the unused agricultural lands that we identified are located around the Chernobyl nuclear disaster zone and may still be contaminated (IAEA, 2006). Additionally, within the Polissya lowland in northern Ukraine and where excessive precipitation and wet soils are common, a huge network of drainage channels was constructed during the Soviet era. Much of this water regulation system became abandoned after 1991, and its restoration would require substantial investment (FAO, 2012). Widespread reforestation has already occurred on former agricultural areas in northern Ukraine, and recultivation in these areas will therefore be costly (Larsson and Nilsson, 2005). Recultivation in the form of hay making and extensive livestock grazing, which were traditional land-use practices in this region until World War II, may be viable options and have the co-benefit of restoring the traditional agricultural landscape (Elbakidze and Angelstam, 2007) with high farmland biodiversity (Fischer et al., 2012). Finally, the ongoing military conflict in Eastern Ukraine, which began after our study period, will affect where recultivation occurs (Baumann et al., 2014) and will likely lower foreign investment in eastern Ukrainian agriculture substantially.

Our study of patterns and drivers of agricultural recultivation was based on spatial and temporal factors, reliable detailed land-use maps (Estel et al., 2015), and a non-parametric regression framework that is powerful in explaining the most influential factors and predicting recultivation patterns (Hastie et al., 2009). Nevertheless, a few sources of uncertainty need mentioning. First, uncertainty in our results may originate from remaining error in the remote sensing data. For example, climate fluctuations may cause misclassifications of pixels in droughts years (e.g., 2003, 2007, and 2010) when cropland was not harvested and may lead to an underestimation of the amount of unmanaged land. Conversely, it may have been hard to distinguish grassland managed at low intensity from fallow land. To account for the latter, we excluded permanently fallow land from our study area as these areas mainly represented permanent grasslands (e.g. along rivers), but we cannot exclude that some land available for recultivation was omitted, meaning that our recultivation rates were overestimated. Second, to account for agricultural systems in Ukraine that may include a fallow period (e.g. once every three years) and to account for possible misclassification in the satellite-based dataset, we tested several definitions of recultivation, ranging from more exclusive ones (minimum 5 active years out of 6) to more inclusive ones (minimum 3 active years out of 6). All these definitions highlight the same regions as hotspots of recultivation of abandoned fields, attesting to the robustness of our analyses. Third, mixed pixels due to fields smaller than the minimum mapping unit of ~5.4 ha may lead to underestimating the amount of cultivated land, particularly in western and northern Ukraine, where small fields are common around settlements. Consequently, our results on recultivation patterns and its drivers concern mainly land managed by agroholdings and larger private farms, but not subsistence farming (which remained fairly constant during our study period). Fourth, while all our models demonstrated high explanatory accuracy (up to 0.99) sometimes they failed to predict true positive observations (i.e., predicting recultivation), except for the Steppe models. Fifth, the set of recultivation determinants we analysed was limited by data availability. Specifically, agricultural statistics at fine spatial resolution (i.e., farm level) would have been desirable, and would likely improve model performances, but to the best of our knowledge, there is no such data available for all of Ukraine.

In sum, we document for the first time, to our knowledge, the amount of recultivated agricultural land in Ukraine, its spatial patterns and determinants of recultivation. The former Soviet Union is repeatedly highlighted as a target region for expanding agricultural land at low environmental cost. Although our study did not assess the environmental costs of recultivation, we showed that recultivation has become a dominant land-use trend in the region since 2007 and that recultivation was mainly driven by profit-oriented agricultural actors focused on unused lands with the highest agricultural suitability and thus potential profitability. These findings provide starting points for assessing where recultivation may happen and thus what the production potential and the socioeconomic and environmental outcomes of recultivation may be. Predicting where future recultivation could occur suggests that the Forest Steppe zone and parts of the Mixed Forest zone will come more into focus, as unused agricultural lands there are still more widespread than in the most fertile Steppe zone. Our models also provide leverage points for releasing the currently unused production potential by highlighting the major constraints to recultivation, mainly accessibility, which can be remedied by investment in infrastructure. Given the remaining large extent of currently unused agricultural land in Eastern Europe and the former Soviet Union, our findings provide important insights into a neglected land-change process and assessing the socioeconomic and environmental impacts of recultivation.

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Figure captions

Figure 1: Study area of Ukraine. (A) Study area boundaries (red) and frequency of cultivation from Estel et al. (2015). (B) Location of Ukraine on the European continent. (C) Environmental zones of Ukraine (Zastavnyi, 1994).

Figure 2: Extent of recultivation by environmental zones of Ukraine.

Figure 3: Recultivation patterns at the level of districts (rayons). Top row represents total recultivated area, bottom row depicts recultivation rate of farmland classified as being abandoned in the period 2001-2006, and columns correspond to the three definitions of recultivation (see Table 1).

Figure 4: Partial dependency plots for influential variables for the intermediate recultivation definition. The y-axis shows the probability of recultivation and the x-axis the variable range of the respective variable. Rug plots on the bottom horizontal axis depict the data distribution for the Forest Steppe and Steppe models, and the top axis for the Global and Mixed Forest models of the respective plots.

Figure 5: Likelihood of recultivation based on an average prediction of the three global models. The top map represents recultivation likelihood for the entire extent of agricultural land, and the bottom row depicts likelihoods only for currently idle agricultural land.

Supplementary information captions

Fig. S1. Administrative division of Ukraine on regional (province) level

Tables

Table 1: The three definitions of recultivation employed in our analyses

Recultivation definitions	*2001–2006*	*2007–2012*
Exclusive	No sign of management in at least 5 out of 6 years	Cultivation in at least 5 out of 6 years
Intermediate		Cultivation in at least 4 out of 6 years
Inclusive		Cultivation in at least 3 out of 6 years

Table 2: Suite of variables selected for explaining recultivation patterns. Symbols for ‘Expected sign’ indicate *a-priori* assumption concerning the influence of a variable on recultivation, where (+) indicates an increasing relationship, (-) a decreasing relationship, (+/-) no a-priori assumption.

Predictors	*Unit*	*Spatial resolution*	*Source*	*Min*	*Max*	*Mean*	*SD*	*Expected sign*
Slope	degrees	90 m	SRTM / CGIAR (Jarvis et al., 2008)	0	29.4	1.98	1.89	-
Topsoil pH	units	1 km	ISRIC (Hengl et al., 2014)	4.0	8.0	6.25	0.54	+/-
Average annual sum of mean daily temperatures above 5° C	°C/100	1 km	Own calculation, WorldClim (Hijmans et al., 2005)	19.03	34.08	24.57	1.95	+
Distance to nearest settlement	km	232 m	Own calculation, OpenStreetMap	0.1	18.2	1.61	1.11	-
Distance to nearest major city	km	232 m	Own calculation, Eurogeographics	0.2	135.39	36.06	23.78	-
Distance to nearest paved road	km	232 m	Own calculation, Eurogeographics	0.1	20.3	1.15	1.25	-
Distance to nearest forest edge	km	232 m	Own calculation, GLOBCORINE (Bontemps et al., 2009)	0.2	48.7	1.31	2.06	+
Dependency ratio	%	district	(Ukrstat, 2007)	27.0	43.0	36.66	2.74	-
Unemployment rate	%	district	(Ukrstat, 2007)	0.3	13.5	4.84	2.27	+/-
Mineral fertilizer input	kg nutrients/ha	district	(Ukrstat, 2007)	0.0	118.0	32.18	21.49	-
Organic fertilizer input	tons/ha	district	(Ukrstat, 2007)	0.0	59.0	14.74	10.44	-
Mechanization level	#/10^3 ha	district	(Ukrstat, 2007)	6.0	94.0	21.05	10.42	-

Table 3: Relative importance of single predictors of the global and regional models. Statistically important variables (> 8.33%) are highlighted in **bold**. (Abbreviations for model names: Exc – exclusive, Int – intermediate, Inc – inclusive definition of recultivation)

Predictors	*Global*			*Steppe*			*Forest Steppe*			*Mixed Forest*		
	Exc	*Int*	*Inc*	*Exc*	*Int*	*Inc*	*Exc*	*Int*	*Inc*	*Exc*	*Int*	*Inc*
Distance to forest edge	**23.4**	**19.7**	**16.2**	**23.2**	**20.6**	**18.6**	**21.3**	**17.4**	**13.7**	**24.0**	**25.9**	**27.9**
Distance to city	**10.3**	**10.7**	**10.4**	**11.8**	**11.1**	**11.6**	**16.5**	**22.2**	**19.4**	**15.9**	**12.7**	**10.5**
Temperature	**16.5**	**21.4**	**24.6**	**9.7**	**9.8**	**10.3**	3.1	4.2	6.5	3.4	8.3	**13.4**
Distance to settlement	7.1	5.4	5.5	6.5	7.4	7.8	**14.4**	**11.7**	**10.7**	**10.5**	**8.9**	7.9
Distance to paved road	6.1	4.8	3.3	6.5	5.7	6.5	**10.8**	**8.6**	7.3	**15.0**	**9.9**	4.8
Slope	4.8	5.7	5.4	**9.1**	**10.2**	**10.8**	8.1	7.2	7.0	3.5	5.4	4.7
Unemployment rate	5.7	4.9	4.8	**8.9**	**9.0**	**8.6**	4.5	4.9	6.7	5.0	3.9	4.0
Mechanization level	6.7	7.4	6.3	6.3	6.5	6.1	2.7	4.4	5.9	6.3	8.0	**9.4**
Organic fertilizer input	5.4	6.2	6.7	4.7	5.4	5.1	4.3	8.0	7.8	7.0	4.9	5.1
Mineral fertilizer input	5.1	4.0	4.6	7.1	5.8	4.9	6.0	4.1	6.0	5.1	4.4	6.4
Topsoil pH	6.1	6.7	8.3	2.8	3.3	4.7	4.4	3.2	3.9	2.6	4.9	2.9
Dependency ratio	2.9	3.1	3.9	3.1	5.0	4.6	3.0	3.5	4.5	1.6	2.5	2.9

Table 4: Performance of BRT models in predicting recultivation. cv AUC = cross-validated area under the curve of the receiver operating characteristics; Accuracy = share of correctly predicted observations; True positive rate = proportion of correctly predicted observations with recultivation; True negative rate = proportion of correctly predicted observations without recultivation. (Abbreviations for model names: Exc – exclusive, Int – intermediate, Inc – inclusive definition of recultivation)

Model parameters	*Global*			*Steppe*			*Forest Steppe*			*Mixed Forest*		
	Exc	*Int*	*Inc*	*Exc*	*Int*	*Inc*	*Exc*	*Int*	*Inc*	*Exc*	*Int*	*Inc*
cv AUC	0.825	0.784	0.763	0.728	0.726	0.718	0.721	0.696	0.693	0.747	0.737	0.727
Accuracy	0.963	0.908	0.812	0.864	0.770	0.720	0.967	0.902	0.793	0.993	0.970	0.904
True positive rate	0.085	0.146	0.267	0.137	0.394	0.730	0.038	0.055	0.174	0.028	0.026	0.042
True negative rate	1.000	0.996	0.971	0.994	0.942	0.710	1.000	0.999	0.985	1.000	1.000	0.998
% deviance explained	17.3	15.7	15.4	10.1	11.1	10.7	6.9	6.6	8.2	6.7	7.9	9.5

Figure

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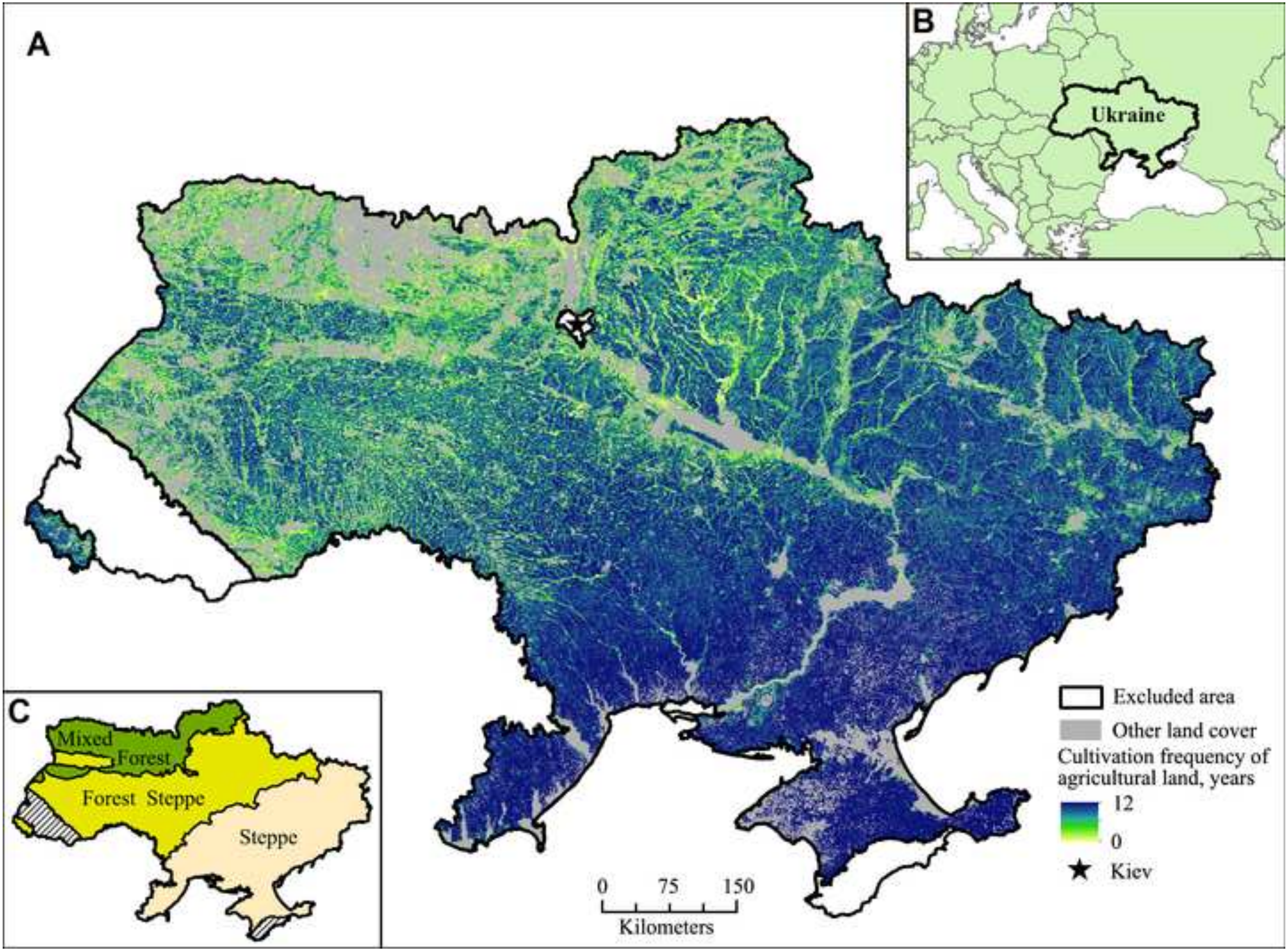

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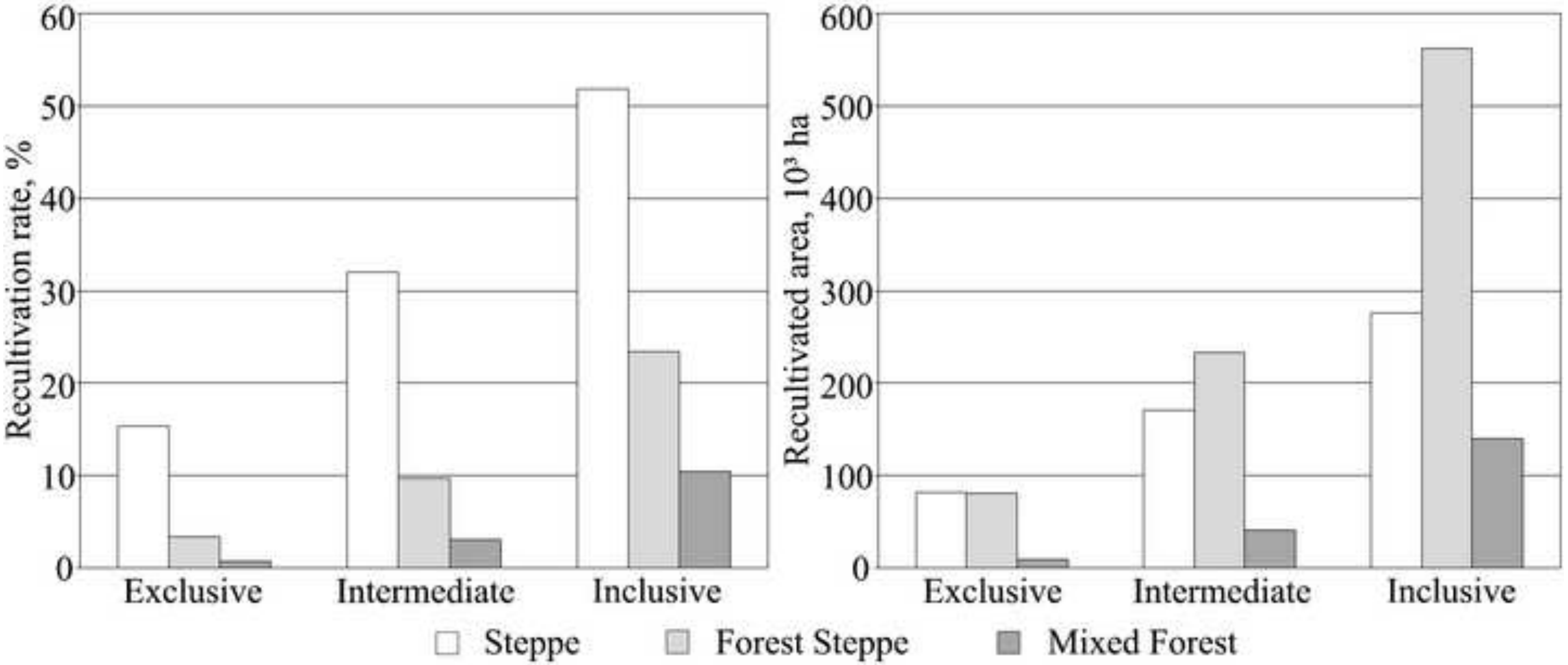

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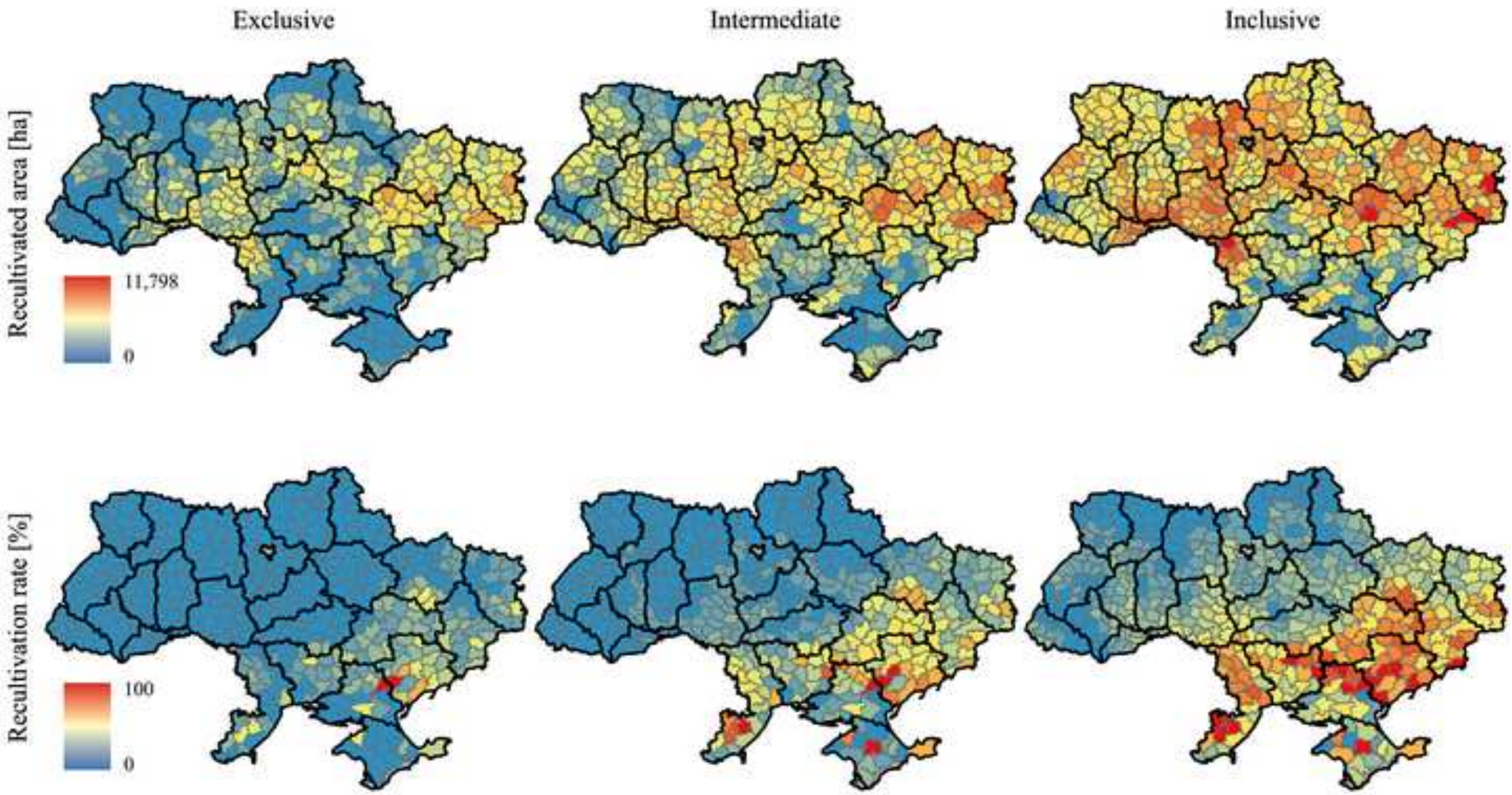

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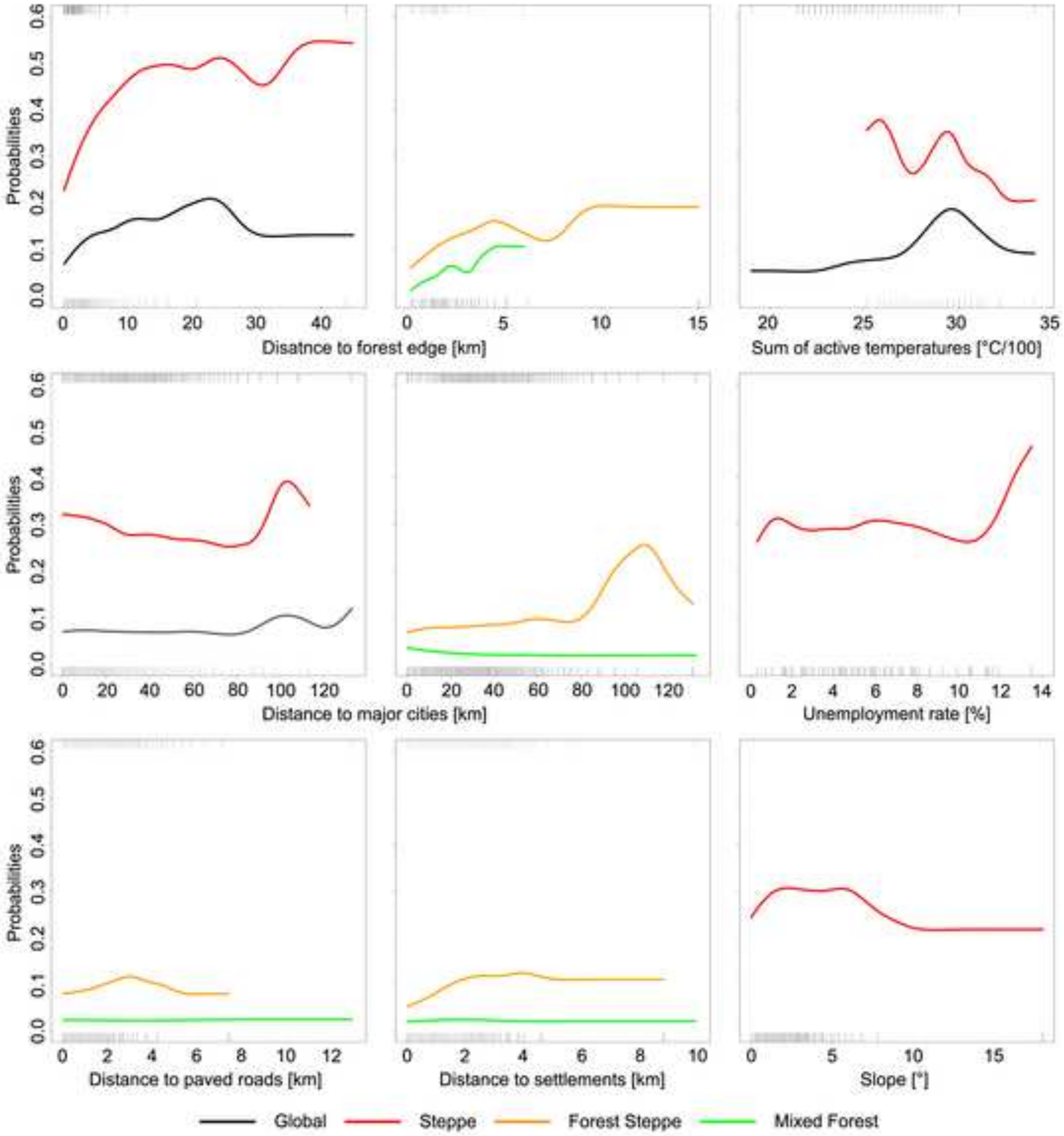

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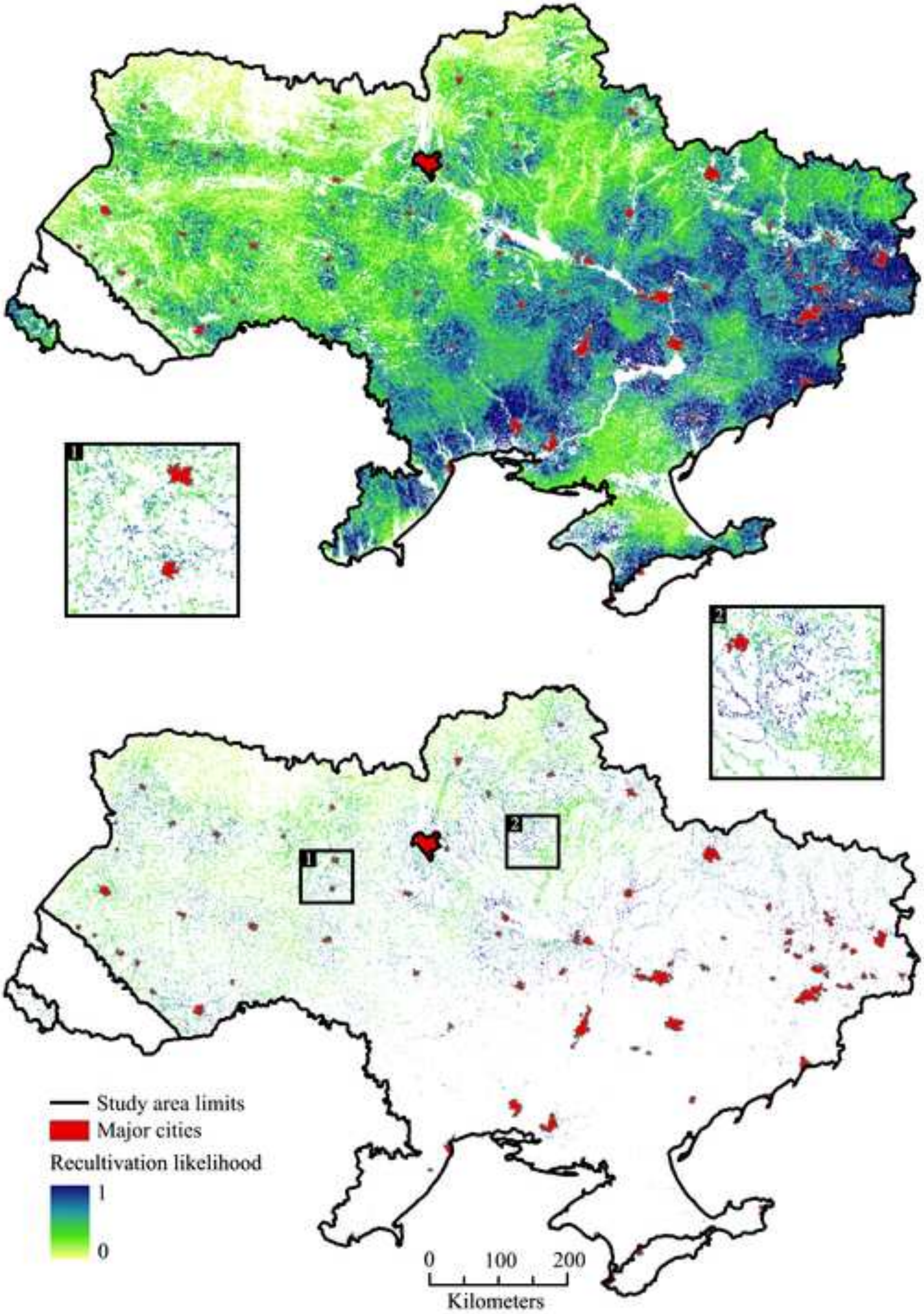

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