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Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus

Florian Schierhorn,[1] Daniel Müller,[1,2] Tim Beringer,[3] Alexander V. Prishchepov,[1]
Tobias Kuemmerle,[2,3] and Alfons Balmann[1]

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[1] Widespread cropland abandonment occurred after the collapse of socialism across the former Soviet Union, but the rates and spatial patterns of abandoned lands are not well known. As a result, the potential of this region to contribute to global food production and estimates of the carbon sink developing on currently idle lands are highly uncertain. We developed a spatial allocation model that distributes yearly and subnational sown area statistics to the most agriculturally suitable plots. This approach resulted in new, high-resolution (1 km^2) annual time series of cropland and abandoned lands in European Russia, Ukraine, and Belarus from 1990 to 2009. A quantitative validation of the cropland map confirms the reliability of this data set, especially for the most important agricultural areas of the study region. Overall, we found a total of 87 Mha of cropland and 31 Mha of abandoned cropland in European Russia, Ukraine, and Belarus combined, suggesting that abandonment has been severely underestimated in the past. The abandonment rates were highest in European Russia. Feeding our new map data set into the dynamic vegetation model LPJmL revealed that cropland abandonment resulted in a net carbon sink of 470 TgC for 1990 to 2009. Carbon sequestration was generally slow in the early years after abandonment, but carbon uptake increased significantly after approximately 10 years. Recultivation of older abandoned lands would be associated with high carbon emissions and lead to substantial amounts of carbon not being sequestered in vegetation formations currently developing on idle croplands. Our spatially and temporally explicit cropland abandonment data improve the estimation of trade-offs involved in reclaiming abandoned croplands and thus in increasing agricultural production in this globally important agricultural region.

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1. Introduction

[2] The surging demand for food and feed during the 20th century has been met by large production increases in agriculture [*Foley et al.*, 2007], but this has come at substantial environmental costs. For example, humans currently appropriate nearly a quarter of the Earth's terrestrial net primary productivity [*Haberl et al.*, 2007], and land use accounts for about a third of global greenhouse gas (GHG) emissions. Moreover, global population growth and changing consumption patterns are likely to double global food demand by 2050 [*Cirera and Masset*, 2010; *FAO*, 2010; *Godfray et al.*, 2010], and ambitious renewable energy targets are currently formulated [*Fargione et al.*, 2008]. The question of how to increase agricultural output while mitigating emissions from land use is therefore a key challenge for humanity [*Foley et al.*, 2011].

[3] One prominent strategy for increasing agricultural production is to expand cultivated areas into native ecosystems, such as in many parts of the tropics. However, most suitable arable land is already under cultivation [*Lambin and Meyfroidt*, 2011; *Ramankutty et al.*, 2008], and converting unused productive land, particularly in the tropics, will cause significant GHG emissions [*Foley et al.*, 2005; *Gibbs et al.*, 2010; *Tan et al.*, 2009; *West et al.*, 2010] and diminish carbon sequestration [*Post and Kwon*, 2000; *Stoate et al.*, 2009; *Tilman et al.*, 2002]. Land expansion into previously uncultivated areas is therefore unlikely to be a sustainable approach to increasing the supply of agricultural products.

[4] An alternative is to reclaim previously cultivated but currently abandoned agricultural land. The largest areas of

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[1]Leibniz Institute of Agricultural Development in Central and Eastern Europe (IAMO), Halle (Saale), Germany.

[2]Department of Geography, Humboldt-Universität zu Berlin, Berlin, Germany.

[3]Potsdam Institute for Climate Impact Research, Earth System Analysis, Potsdam, Germany.

Corresponding author: F. Schierhorn, Leibniz Institute of Agricultural Development in Central and Eastern Europe (IAMO), Theodor-Lieser-Str. 2, Halle (Saale), Sachsen-Anhalt, DE-06120, Germany. (schierhorn@iamo.de)

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abandoned agricultural land have been observed in the Eastern and Midwestern United States, Brazil, Argentina, Western Europe, India, China, and Australia [*Cai et al.*, 2010; *Campbell et al.*, 2008], as well as in the territory of the former Soviet Union (FSU) countries [*Henebry*, 2009]. However, recultivation often requires significant investments, depending on the type of successional vegetation, the time elapsed since abandonment, and economic and institutional constraints affecting the profitability of farming [*Larsson and Nilsson*, 2005; *USDA-FAS*, 2008]. Moreover, depending on the soil properties, climate conditions, and the time since abandonment, which are the main determinants of natural succession after abandonment, abandoned land may sequester significant amounts of carbon [*Kuemmerle et al.*, 2011; *Rhemtulla et al.*, 2009], and recultivation is likely to be associated with considerable GHG emissions [*Guo and Gifford*, 2002; *Vuichard et al.*, 2008]. Understanding the spatial patterns, biophysical characteristics and land use history of abandoned cropland are therefore important in identifying areas where recultivation is associated with modest carbon emissions.

[5] The collapse of the Soviet Union triggered the most drastic episode of land use change in the 20th century, most importantly the widespread abandonment of agricultural land [*Henebry*, 2009]. Available agricultural statistics on sown areas suggest that approximately 50 million ha (Mha) of cropland were abandoned after 1990 in Russia, Ukraine, and Belarus [*BELSTAT*, 2004; *ROSSTAT*, 2010; *UKRSTAT*, 2009]. These vast, currently unused land resources suggest large untapped agricultural production potential [*Lambin and Meyfroidt*, 2011; *Liefert et al.*, 2010], which could be of great importance for global food production and mitigation of land use pressure in other parts of the world, in the light of increasing global competition for land.

[6] The large extent of agricultural land abandonment in Russia, Ukraine, and Belarus, as well as the suitable biophysical conditions for natural succession, has triggered significant carbon sequestration to date. By integrating global land use data covering the time span from 1991 to 2000 into a process-driven ecosystem model, it was estimated that the abandonment of agricultural lands of the FSU resulted in a total carbon sequestration of up to 64 TgC [*Vuichard et al.*, 2008]. According to field measurements, total carbon sequestration due to agricultural land abandonment was between 585 and 870 TgC [*Kurganova et al.*, 2013]. One important question is why there are such large differences between the estimates. In short, the estimates of carbon sequestration due to cropland abandonment differ widely because of inconsistent methods and models, different time periods, and most importantly because of outdated and divergent statistics on agricultural land abandonment [*Dolman et al.*, 2012].

[7] Quantifying agricultural production potentials and the carbon trade-offs of recultivation is hampered by incomplete knowledge of the quantity and location of cropland changes since the collapse of the Soviet Union. While a variety of satellite-based global land cover maps exists [*Bartholomé and Belward*, 2005; *Bicheron et al.*, 2008; *Friedl et al.*, 2002; *Hansen et al.*, 2000; *Loveland et al.*, 2000], these maps differ substantially for the FSU and do not contain information on abandoned agricultural land. Combining satellite-derived land cover products with agricultural inventory data is an important alternative, but existing global maps also differ greatly for the FSU [*Erb et al.*, 2007; *Klein Goldewijk*, 2001; *Leff et al.*, 2004; *Pittman et al.*, 2010; *Portmann et al.*, 2010; *Ramankutty et al.*, 2008]. As a result, reliable spatiotemporal data on contemporary and abandoned croplands are not available for most parts of the FSU. This is unfortunate, given the importance of reliable land use and land cover data in capitalizing on the idle agricultural potential of FSU countries and assessing carbon sequestration due to cropland abandonment and carbon emissions associated with recultivating abandoned lands.

[8] Our main goal in this study was to map the cropland extent for each year since 1990, which would make it possible to estimate the extent and duration of abandonment and recultivation since the collapse of socialism and quantify carbon fluxes on cropland. To do this, we developed a spatially explicit cropland allocation model to produce yearly cropland maps for European Russia, Ukraine, and Belarus. We used the yearly cropland data to calibrate a dynamic global vegetation model (the Lund-Potsdam-Jena managed Lands or LPJmL model) to assess rates, spatial patterns, and the total quantity of carbon sequestration due to cropland abandonment.

2. Data and Methods

[9] The allocation routine combines global land cover data, agricultural inventory statistics as well as data sets on geophysical characteristics and accessibility to map annual cropland cover. The cropland maps are then fed into LPJmL to estimate carbon fluxes (Figure 1).

2.1. Cropland Mask from Global Land Cover Data

[10] We applied a statistical fusion procedure similar to that used by *Ramankutty et al.* [2008] to generate a binary cropland mask that separates potential locations of cropland from grasslands and other seminatural land cover/use classes. This procedure is a combination of satellite-based global land cover data sets, namely, Global Land Cover 2000 (GLC2000) [*Bartholomé and Belward*, 2005], MODIS Land Cover [*Friedl et al.*, 2002], and GlobCover [*Bicheron et al.*, 2008], and subnational statistics on sown area (details of this procedure are outlined in the Text S1). The cropland mask is a conservative cropland representation because we ensured that the amount of cropland covered by the mask exceeds the reported cultivated areas for all regions and all years by at least 20% (see Text S1). The spatial allocation model distributes yearly sown area statistics on observations identified as cropland in the cropland mask based on plot suitability.

2.2. Agricultural Inventory Statistics

[11] Most global cropland maps to date have been based on agricultural inventory statistics from the Food and Agriculture Organization of the United Nations (FAO). For the FSU, however, FAO data are problematic because they fail to capture large amounts of abandoned cropland (Figure 2) and thus overestimate currently cultivated lands. For example, for Russia, the country with the highest cropland abandonment rates of the FSU, global land use maps based on FAO indicate 125 Mha of cropland (Table 1). According to Russian statistics on sown areas, this is an overestimation of more than 45 Mha.

[12] We assessed the quality of the Russian sown area data by validating official agricultural inventory statistics on sown

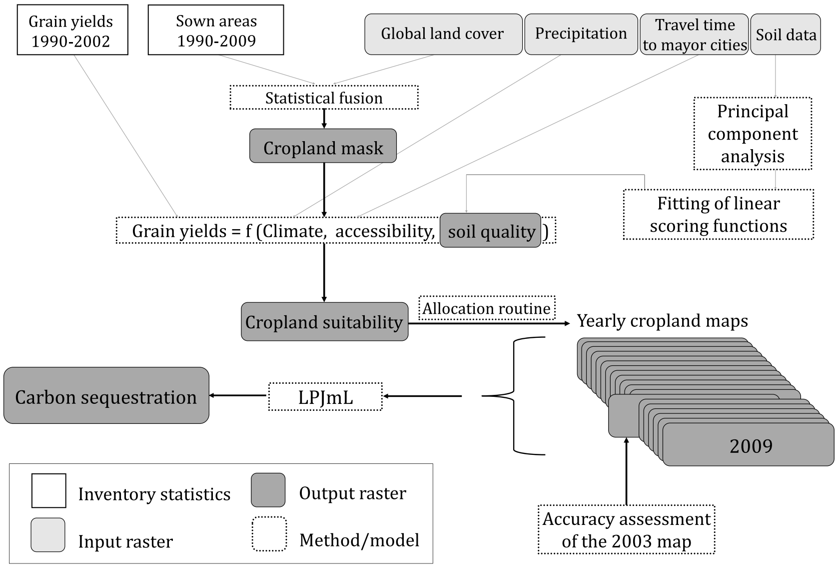

Figure 1. Method flowchart.

areas ([*ROSSTAT*, 2010], http://www.gks.ru) for all districts of two provinces (Kaluga and Rjazan) with Landsat-based abandonment and cropland maps [*Prishchepov et al.*, 2012]. The validation of these data showed very good agreement (Pearson $R^2 = 0.74–0.86$). Good agreement with other independent estimates for cropland abandonment further corroborates the reliability of sown area data from official agricultural inventory statistics (Figure 2), which was also reported by *Ioffe et al.* [2004]. We assume that the sown area data from national official agricultural inventory statistics in Ukraine [*UKRSTAT*, 2009] and Belarus [*BELSTAT*, 2004] are also the best data available. To the best of our knowledge, these data have previously not been used to produce global cropland maps or to derive cropland abandonment maps. Sown area statistics were available for all 80 provinces (oblasts) of European Russia and Ukraine, covering the time spans from 1940 to 2009 and from 1940 to 2008, respectively (Table S1). Missing years in the statistics between 1940 and 1990 were approximated using spline interpolation. For Belarus, we obtained sown area statistics for all six provinces for the period from 1990 to 2003 (Table S1).

[13] We also obtained grain yield data for 2173 districts (*rayons*) for multiple years between 1990 and 2009 (Table S1). We omitted grain yield data from drought years, computed the area-weighted mean of grain yields from nondrought years at the district level, and thus finally obtained an estimate of habitual grain yields. For identification of drought years, we used the hydrothermal coefficient (HTC) [*Dronin and Kirilenko*, 2008], which is an index of annual drought severity that integrates daily average temperature and precipitation data over the growing season (see the Text S2 for more details).

2.3. Geophysical Variables and Accessibility

[14] Using daily gridded precipitation data at a spatial resolution of 0.5° [*Schuol and Abbaspour*, 2007], we estimated annual precipitation sums over the growing period (reported by the U.S. Department of Agriculture (USDA), *USDA* [2013]), the time when precipitation most effectively triggers crop growth. We then computed the area-weighted mean annual precipitation for the nondrought years (indicated by the HTC; see above) at the provincial level for 1990 to 2009.

[15] Likewise, soil quality is a key biophysical determinant of agricultural suitability. We used soil maps from the Harmonized World Soil Database (HWSD) ([*Fischer et al.*, 2008], available at http://www.iiasa.ac.at/Research/LUC/External-World-soil-database) at a spatial resolution of approximately 1 km. The details of the generation of the soil quality map are outlined in the Text S3.

[16] The physical accessibility of a plot to nearby market centers is a strong indicator of the degree of marginality [*Schneider et al.*, 2011] and of agricultural land change before and after the collapse of the Soviet Union [*Ioffe et al.*, 2004; *Prishchepov et al.*, 2013]. If the distance to markets increases, the ratio of output to input prices deteriorates due to increasing transportation costs, which reduces the

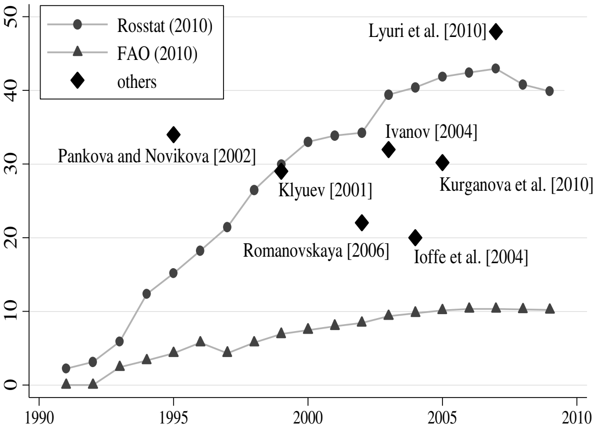

Figure 2. Cropland abandonment in Russia from various sources. Note: *ROSSTAT* [2010] shows cumulative cropland abandonment and *FAO* [2010] shows cumulative abandonment of arable land and permanent crops. The diamonds indicate independent point estimates of abandoned cropland. Additional information on source, period/year, and labels of abandonment estimates can be found in Table S1b.

Table 1. Previous Estimates of Cropland Extent for Russia, Ukraine, and Belarus (Mha)

Source	Year	Label	Asian Russia	European Russia	Sum Russia	Ukraine	Belarus
Ramankutty et al. [2008]	1993	Cropland	36.70	87.59	124.29	33.98	6.16
Portmann et al. [2010]	~2000	Cropland	21.76	57.38	79.13	27.68	6.11
Biradar et al. [2009]	~2000	Cropland			128.67	31.28	11.05
Klein Goldewijk et al. [2011]	2000	Cropland	45.80	77.78	123.58	33.24	5.60
Erb et al. [2007]	2000	Cropland	37.83	88.32	126.16	33.42	6.29
FAO [2010]	2009	Arable land and permanent crops			123.54	33.38	5.66
BELSTAT [2004]	2003	Sowing area					5.56
UKRSTAT [2009]	2008	Sowing area				30.89	
ROSSTAT [2010]	2009	Sowing area	26.85	50.96	77.81		
Bartholomé and Belward [2005]	2000	Cropland	21.98	64.58	86.56	27.78	3.77
		Forest - cropland complexes	5.79	20.63	26.42	6.68	3.65
		Cropland - grassland complexes	14.79	27.08	41.87	9.51	2.85
		SUM	42.56	112.30	154.85	43.97	10.27
Friedl et al. [2002]	2000	Cropland	29.02	101.66	130.68	43.59	7.40
		Cropland/natural vegetation mosaic	31.05	33.01	64.05	6.68	5.11
		SUM	60.07	134.67	194.74	50.27	12.51
Bicheron et al. [2008]	2005	Rainfed croplands	8.29	34.06	42.35	15.38	3.11
		Mosaic cropland (50–70%) / vegetation (grassland/shrubland/forest) (20–50%)	25.61	57.26	82.87	20.96	4.85
		Mosaic vegetation (grassland/shrubland/forest) (50–70%) / cropland (20–50%)	15.38	23.19	38.57	8.88	2.18
		SUM	49.27	114.51	163.79	45.22	10.14

profitability of agriculture. In addition, poor accessibility in post-Soviet landscapes typically correlates with low soil fertility and lower rural population densities [*Ioffe et al.*, 2004]. We measured market access as the travel time to the nearest major towns at a spatial resolution of 30 arc seconds using a map of travel times to major cities (*Nelson*, 2008, available at bioval.jrc.ec.europa.eu/products/gam/index.htm). Both the geophysical and the accessibility variables were assumed to be time invariant. We masked all data sets to the same spatial extent, resampled them to a spatial resolution of 1 km, and projected them to an Albers Equal Area coordinate system.

2.4. Mapping Cropland Suitability

[17] Spatial regression analysis is frequently used to derive the suitability of a plot of land for specific land use activities [*Overmars et al.*, 2007; *Verburg et al.*, 2006]. To map cropland suitability, we related grain yields to mean soil quality, travel time to major cities, and precipitation during the growing season for all 2173 districts in European Russia, Ukraine, and Belarus.

[18] Global regression models are not well suited for deriving land suitability because they are unable to capture the substantial spatial variability that characterizes the study area. For example, summer precipitation is decisive for grain yields in the southern parts of European Russia, where grain yields are restricted by shorter growing periods [*Dronin and Kirilenko*, 2008]. Likewise, soil quality is heterogeneous across the study region and has a crucial impact on the spatial variation of the grain yields. To account for this spatial variation, we partitioned the study area into the three prevalent major habitat types, i.e., biomes ([*Olson et al.*, 2001]; Pontic steppe, mixed forest and forest steppe, Taiga; see Figure S1, left). We assigned each province to the biome that has the largest area share in the province (Figure S1, right). For each biome, we estimated separate ordinary least square (OLS) regressions of grain yields at the district level. Because Lagrange multiplier tests confirmed spatial dependency, we also calculated spatial error and spatial lag models with the same set of dependent and independent variables [*Anselin*, 1988]. We therefore estimated nine regression models (i.e., standard OLS, spatial error, and spatial lag models for three biomes).

[19] Diagnostic tests showed that the spatial lag model best accounted for spatial dependencies and had the best fit (Table S2); hence, we used these models for mapping cropland suitability. Grain yields in these models were positively correlated ($p < 0.1$) with soil quality and negatively correlated with the travel time to major cities in all three biomes, as expected (Table S2). Precipitation exerted a significantly positive effect on grain yields in the mixed forest and forest steppe as well as in the Pontic steppe, but was negatively associated with grain yields in the Taiga biome. We used the regression results to predict grain yields at the district level and compared the predictions to observed yields for each biome (Figure S2). Finally, we multiplied the coefficients from the spatial lag models with the independent variables and the spatial lag term at the 1 km^2 grid level to obtain probability maps of grain yields, which we used as a proxy for cropland suitability (Figure S3, right).

2.5. Spatial Allocation Routine

[20] The biophysical characteristics of a location, natural suitability for agriculture, and physical access affect transportation costs. We assumed that cropland change during the Soviet period (mainly cropland expansion) and after the collapse of the Soviet Union (mainly cropland abandonment) are mainly determined by cropland suitability and that the least suitable plots are the first to be abandoned [*Ioffe et al.*, 2004; *Prishchepov et al.*, 2013]. Hence, our allocation algorithm distributed the sown areas for each year to the most suitable locations for the cultivation of crops in the study area, resulting in yearly maps of sown areas.

[21] Our allocation algorithm distributed sown areas for each year since 1750 to the most suitable location for the cultivation of crops, resulting in yearly cropland maps. For 1940 to 2009, we used official agricultural inventory statistics on sown

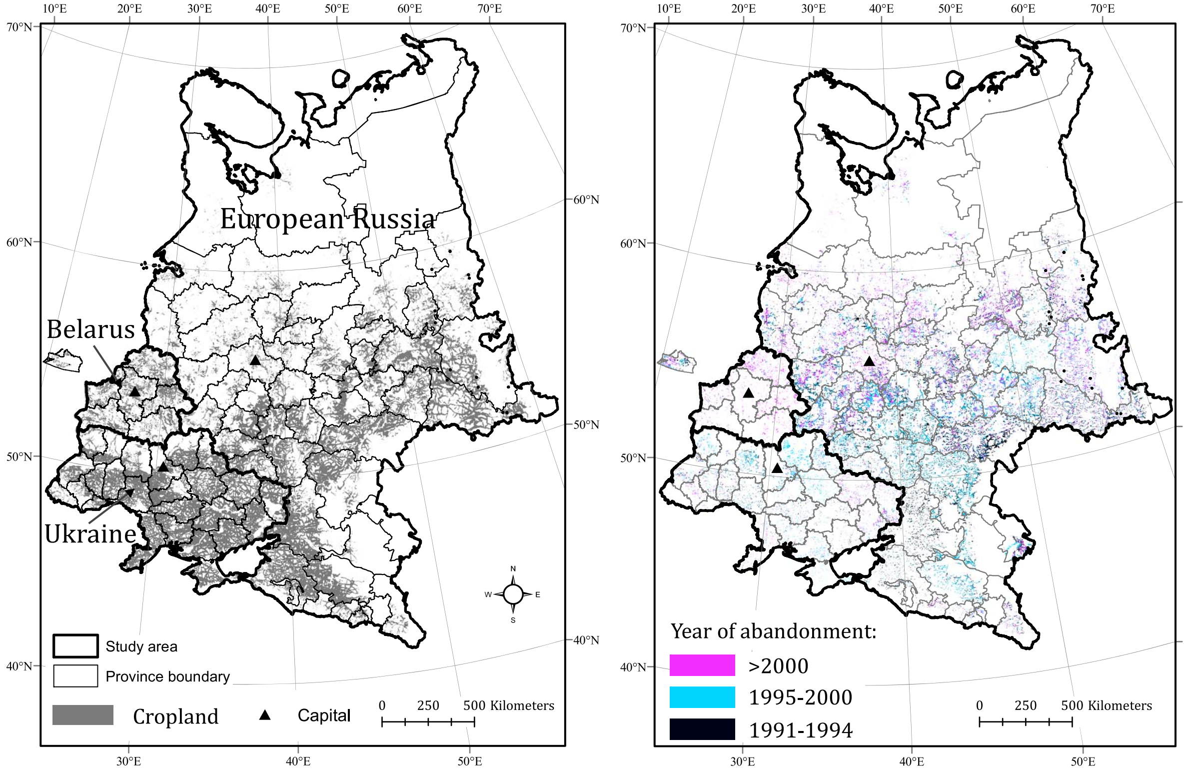

Figure 3. Distribution of (left) cropland and (right) abandoned cropland. Note: The map at left represents cropland in 2009 for European Russia, 2008 for Ukraine, and 2003 for Belarus. The (right) colors indicate the duration of abandonment from 1990 to 2009 (European Russia), 1990 to 2008 (Ukraine), and 1990 to 2003 (Belarus). Yearly cropland and cropland abandonment maps are available from the authors upon request.

areas (see 2.2). Sown area statistics were not available from 1750 to 1939 and we used the HYDE 3.1 database [*Klein Goldewijk et al*., 2011] to approximate yearly sown areas for this period. We considered locations as abandoned if the land use changed from cultivation to any other land use from one year to the next. We ignored intermediate fallow operations and transitions from cropland to managed grassland because the proportion of fallow land is relatively constant over time and the extent of transitions from cropland to managed grassland is negligible [*Ioffe et al*., 2004]. The dramatic contraction of the livestock sector in Russia after 1990 [*FAO*, 2010] suggests only minor conversions from managed cropland to managed grasslands and, if so, as an intermediate stage preceding abandonment.

2.6. Accuracy Assessment

[22] Very high-resolution (VHR) imagery available in Google Earth (http://earth.google.com) is a valuable data source for validating land cover maps, especially for large areas for which ground-based data collection is not feasible [*Biradar et al*., 2009; *Clark et al*., 2010; *Fritz et al*., 2011; *Pittman et al*., 2010]. To assess the reliability of our cropland map, we focused on the year 2003, because the latest statistics on sown area available for the entire study were from this year. We randomly selected 1546 pixels proportional to the share of cropland and noncropland in 2003 in each ecoregion. Ecoregions are nested within biomes and characterized by distinct natural communities, geographical properties, and ecological processes [*Olson et al*., 2001]. To avoid spatial autocorrelation, we used a minimum distance of 10 km between points (Figure S4). Two interpreters independently labeled each point as cropland or noncropland. Each interpreter estimated the percent of cropland within the sampled pixels in 10% intervals. Estimates of cropland shares of 50% or larger were labeled as “cropland” and all others as “noncropland.” When the two interpreters differed in their assessment (i.e., what was labeled as cropland by one interpreter was not by the other), a third independent interpreter was asked to label the point to reach a majority decision. Using this validation data set, we calculated the overall accuracy and the users’ and producers’ accuracy for the 2003 cropland map [*Foody*, 2002]. We did not validate the cropland abandonment class because identifying abandoned fields based on single-date imagery is challenging due to the complex and place-dependent spectral signature of abandoned cropland.

2.7. Simulating Carbon Dynamics

[23] Dynamic vegetation models are excellently suited to quantifying the gross and net ecosystem responses to environmental changes [*Cramer et al*., 2001]. The LPJmL model, a well-established dynamic vegetation model, simulates key ecosystem processes, including photosynthesis [*Collatz et al*., 1992; *Farquhar et al*., 1980], plant and soil respiration, carbon allocation, evapotranspiration, and phenology in natural ecosystems, croplands, and pastures [*Bondeau et al*., 2007; *Gerten et al*., 2004]. Nine plant functional types (PFTs) represent natural vegetation at the level of biomes [*Sitch et al*., 2003]. LPJmL is well suited for our purposes because it also includes 12 crop functional types representing

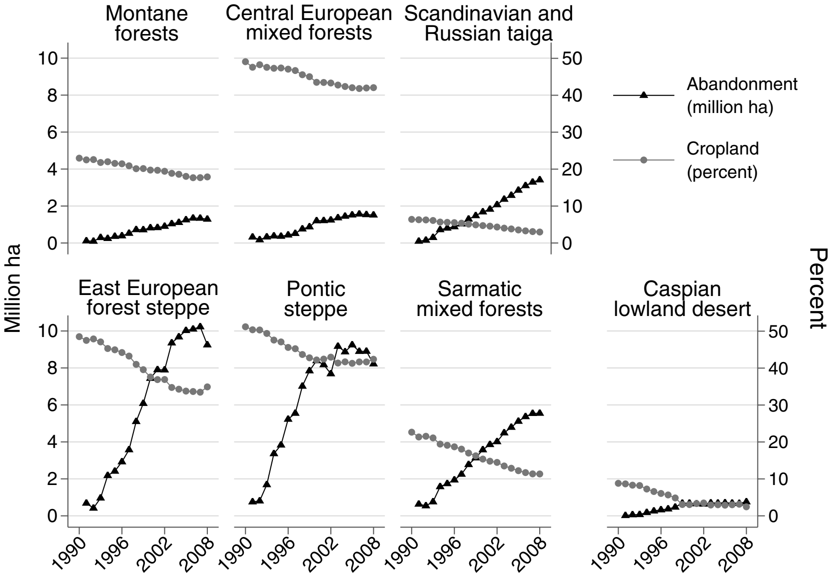

Figure 4. Cropland abandonment (Mha) and cropland (percent of total land) by ecoregion. Note: Belarus is excluded because of missing data for cultivated area statistics.

the most important economic crops [*Bondeau et al.*, 2007]. LPJmL is able to reproduce key features of the global carbon cycle [*Jung et al.*, 2008], water cycle [*Gerten et al.*, 2004; *Wagner et al.*, 2003], vegetation patterns [*Cramer et al.*, 2001; *Hickler et al.*, 2008], plant phenology [*Lucht et al.*, 2002], and fire patterns [*Thonicke et al.*, 2001]. LPJmL also includes CO_2 sensitivity within the range of free-air CO_2 enrichment (FACE) experiments [*Gerten et al.*, 2004; *Hickler et al.*, 2008].

[24] For this study, we calibrated LPJmL with the Climate Research Unit's (CRU) time series (TS) 3.1 data for temperature and cloud cover [*Mitchell and Jones*, 2005] and the Global Precipitation Climatology Centre's (GPCC) gridded precipitation data (version 5) [*Rudolf et al.*, 2010]. Land uses and land use changes were prescribed using the cropland maps for European Russia and Ukraine developed in this study (we excluded Belarus because statistical data after 2003 were not available). Because the legacy of past land use can have strong effects on carbon budgets [*Kuemmerle et al.*, 2011; *Rhemtulla et al.*, 2009], we initiated our LPJmL model runs in 1750. We calculated carbon sequestration on former agricultural land as the difference between the simulated land carbon stocks with and without land abandonment. In the presentation and interpretation of results, we focus on cropland abandonment and carbon sequestration since 1990 because most cropland abandonment occurred after the collapse of the Soviet Union.

3. Results

3.1. Cropland Maps

[25] Cropland covered 50.96 Mha in European Russia in 2009, 30.89 Mha in Ukraine in 2008, and 5.56 Mha in Belarus in 2003 [*BELSTAT*, 2004; *ROSSTAT*, 2010; *UKRSTAT*, 2009]. These numbers are considerably lower than most previous estimates of cropland for the study region (Table 1).

[26] Our allocation model produced cropland maps with a spatial resolution of 1 km and a yearly temporal resolution from 1990 to 2009 for European Russia, from 1990 to 2008 for Ukraine, and from 1990 to 2003 for Belarus. Based on the regression results, cropland was allocated in areas close to markets, with favorable soil conditions and higher precipitation. Figure 3 (left panel) reveals high densities of cropland in southern Russia and Ukraine where the East European forest steppe and the Pontic steppe are located (42% and 35% of total land area in 2008, respectively, see Figure 4 and Figure S1). Moreover, the 2008 cropland map (Figure 3, left) shows the lower cropland density toward northern Belarus and European Russia. For example, in 2008, cropland density in the Scandinavian and Russian taiga and the Sarmatic mixed forest ecoregions was only 3% and 11% of total land area, respectively.

3.2. Accuracy Assessment of the 2003 Cropland Map

[27] The validation of the 2003 cropland map revealed an overall accuracy of 65%, with a producer accuracy of 55% and a user accuracy of 56% (Table S3). The accuracy of the cropland maps differs significantly among ecoregions (Figure 5). Most importantly, the ability of the allocation

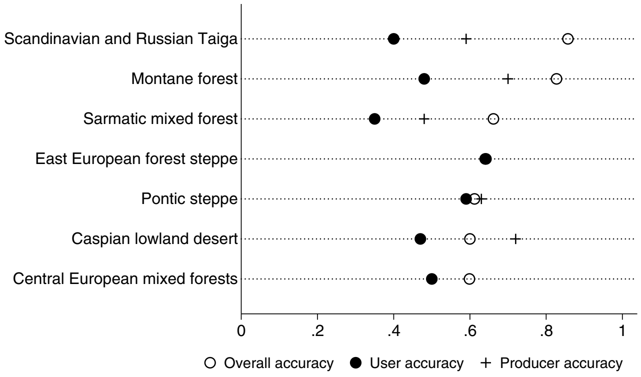

Figure 5. Variations in accuracies among ecoregions.

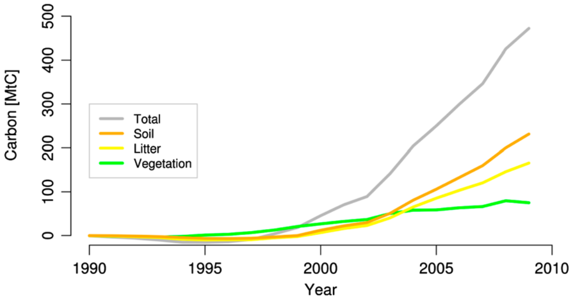

Figure 6. Total carbon sequestration in vegetation and soils due to cropland abandonment in European Russia and Ukraine between 1990 and 2009. Note: Belarus is excluded because of missing data for cultivated area statistics. Cropland abandonment area and associated carbon sequestration are negligible in Belarus.

model to differentiate between cropland and noncropland was higher for the ecoregions that cover the most important agricultural regions of Russia and Ukraine. For these breadbasket regions, the producers' and users' cropland accuracies were 64% (East European forest steppe), 63% (Pontic steppe), 64% (East European forest steppe), and 59% (Pontic steppe). In the northern and temperate ecoregions, the uncertainties were larger, arguably due to the low proportion of cropland in the total land area and the dominance of mixed land cover classes.

3.3. Cropland Abandonment

[28] Between 1990 and 2009, 27.2 Mha of cropland was abandoned in European Russia, a decrease of 39%. In Ukraine, 3.2 Mha (8%) was abandoned between 1990 and 2008, and in Belarus, 0.6 Mha (9%) was abandoned between 1990 and 2003. Cropland abandonment since 1990 followed distinct patterns in different ecoregions, and the highest declines were recorded in the Scandinavian and Russian Taiga (3.5 Mha or 53%), and in the Sarmatic mixed forest ecoregion (5.7 Mha or 47%). More than 8 Mha of cropland was abandoned in the Pontic steppe after 1990. The abandonment rates were considerably lower in the central European mixed forest ecoregion, at 15%, the Pontic steppe zone, at 18%, and the east European forest steppe, at 28% (Figure 4).

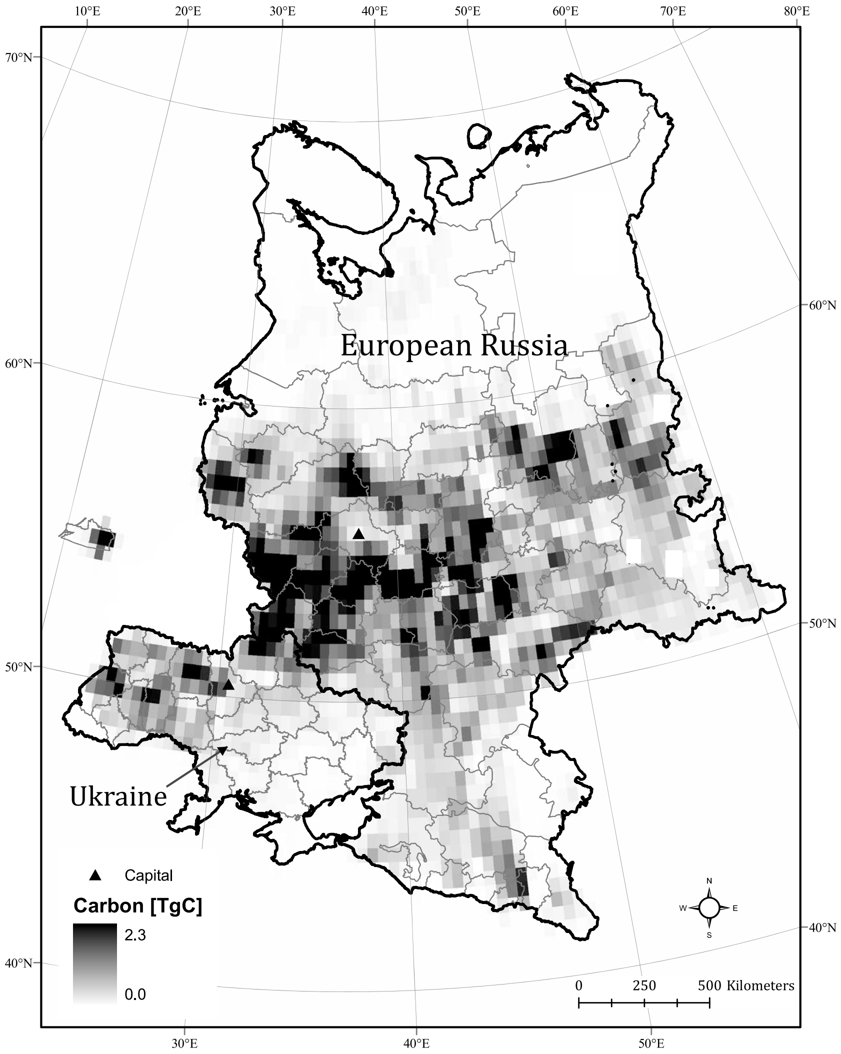

Figure 7. Spatial distribution of total carbon storage on abandoned cropland between 1990 and 2009. Note: Belarus is excluded because of missing data for cultivated area statistics. Cropland abandonment area and associated carbon sequestration are negligible in Belarus.

[29] Clusters of cropland abandonment were concentrated in the central northern part of European Russia, where the agricultural suitability is relatively low, while less abandonment occurred in Ukraine and Belarus (Figure 3, right). Massive cropland abandonment is also evident in the southern regions of European Russia, along a northwest-southeast precipitation gradient, with a spatial concentration in the dry Pontic steppe region at the border with Kazakhstan. Cropland coverage remained relatively stable in the central and southern regions of European Russia, which enjoy favorable soil and climatic properties.

[30] Our annual cropland maps permit calculation of the time since abandonment. Almost 70% of cropland abandonment occurred within the first 10 years of the transition from a state command to a market-driven economy. After approximately 2000, cropland abandonment slowed significantly in Ukraine. This pattern was mirrored at the ecoregion level, namely, in the Pontic steppe, the east European forest steppe, and the central European mixed forest ecoregions (Figure 4). Recultivation of abandoned cropland has been taking place in the Pontic steppe since approximately 2003, in the mixed forest ecoregion since 2006, and in the forest steppe since 2007. In contrast, cropland abandonment has continued unabated in the montane forest ecoregion.

3.4. Carbon Sequestration

[31] The LPJmL simulations showed that cropland abandonment in the study region led to a small carbon source over abandoned agricultural areas during the first years of the study period, as a consequence of low plant productivity and continuing carbon emissions from former cropland soils (Figure 6). The model results suggest that early successional vegetation was established after approximately seven to eight years, when growing productivity started to influence the regional carbon balance with increasing rates of carbon sequestration. A net carbon sink developed in subsequent years, predominantly driven by rising levels of soil carbon sequestration due to high belowground productivity and turnover of grasses (Figure 6).

[32] The total carbon sequestration due to cropland abandonment for the entire study region was estimated by LPJmL as 470 TgC for the 1991–2009 period, with an average sequestration rate of 70 gC/m^2/yr. The 2009 carbon sequestration rates varied between 50 and 80 TgC/yr across the study area, which is equivalent to 35% of the recent sink documented for the forests of European Russia [*Pan et al.*, 2011]. The largest amount of postabandonment carbon accumulation occurred in the western and central parts of the study area (Figure 7), similar to the results from *Vuichard et al.* [2008], where cropland abandonment occurred early and extensively in the 1990s and climatic conditions foster higher plant productivity than in the east of the study region. Natural ecosystems in these areas include mixed forests and forest steppes, whereas steppe vegetation is the natural vegetation in the southeastern parts of our study region.

4. Discussion

[33] Existing cropland maps for Russia, Ukraine, and Belarus are highly uncertain, mainly because they rely on unreliable and outdated agricultural statistics [*Ioffe et al.*, 2004; *Ramankutty et al.*, 2008]. This is a major obstacle to assessing cropland abandonment in the FSU, and thus to identifying the potential of idle cropland to improve global food production [*Lambin*, 2012]. Likewise, inaccurate cropland maps impair the assessment of carbon trade-offs of recultivating abandoned croplands.

[34] We developed a spatial allocation model to produce maps of cropland and cropland abandonment in European Russia, Ukraine, and Belarus. The products are available for download at http://www.iamo.de/lsc/downloads. Our model allocates time series of agricultural statistics based on geophysical features and accessibility. Our overall accuracy is 65%, which is relatively high if compared to the overall accuracies of recent land cover maps produced by remote sensing alone for the same region [*Alcantara et al.*, 2013; *Gong et al.*, 2012]. This is partly because other and more complex classes were mapped (for example, *Alcantara et al.* [2013] captured agricultural abandonment), but also due to the difficulty to accurately map land cover/use change using remote sensing.

[35] We utilized the best available agricultural statistics for sown areas, which are correlated with fine-scale remotely sensed land cover data [*Prishchepov et al.*, 2012]. These statistics suggest that European Russia contained 50.96 Mha of cropland in 2009. This is 36.63 Mha, or 42%, less than the estimates of cropland cover in the region suggested by *Ramankutty et al.* [2008], which were based on national statistics from 1993 (Table 1). Likewise, the sown area statistics utilized in this work are 3.09 Mha (9%) lower for Ukraine and 0.6 Mha (10%) lower for Belarus. The lower area differences for Ukraine and Belarus are due to the less substantial decline of cropland after the collapse of the Soviet Union in these countries. Similar overestimations of contemporary croplands in European Russia, Ukraine, and Belarus exist in other available cropland maps (Table 1). Because of these overestimations, cropland abandonment following the breakup of the Soviet Union has been grossly underestimated, particularly in European Russia. For example, *Campbell et al.* [2008] derived estimates of agricultural land abandonment up to 2000 from the History Database of the Global Environment 3.0 (HYDE 3.0) [*Klein Goldewijk*, 2001] and from the Center for Sustainability and the Global Environment (SAGE) cropland map [*Ramankutty and Foley*, 1999], both of which rely on FAO statistics that fail to capture the extent of post-Soviet cropland abandonment.

[36] Errors in our cropland maps can originate from our simplifying approach to allocate annual sown area statistics on the cropland mask solely based on a suitability map that relies on the land rent theories of Ricardo and von Thünen. Moreover, the cropland suitability map may contain inaccuracies due to imperfect input data and limitations of the spatial regression model. Maybe more importantly, the location of sown areas also depends on factors not considered here, such as institutional support for agriculture [*Wandel et al.*, 2011], farm productivity [*Bokusheva and Hockmann*, 2006], path dependency in agricultural production, and changes in rural demography [*Ioffe and Nefedova*, 2004]. Improvements in accuracy of cropland maps are possible with finer agricultural inventory statistics, particularly on yields and sown areas, and more precise geophysical data. In addition, a more detailed and spatially explicit understanding of the drivers of cropland change can help improving the allocation rules.

[37] Our simulation results highlight the nonlinear change in carbon sequestration rates on former croplands after the beginning of postsocialist agricultural land abandonment, which corresponds to field measurements from the region

[*Kurganova et al*., 2013]. Net carbon uptake in vegetation and soils accelerated particularly after 2000 (i.e., 10 years after the collapse of the Soviet Union) as a consequence of two concurrent processes. First, vegetation regrowth on former croplands passes through a transition from carbon source to sink during the first 5–10 years after abandonment, which is typical for boreal forest succession [*Goulden et al*., 2011]. Similarly, field investigations in temperate Russia have demonstrated that former croplands provide stable sinks four to five years after abandonment [*Kurganova et al*., 2013]. Second, cropland abandonment was not a singular event but evolved gradually, especially in the first 10 years after the collapse of the Soviet Union. During this period, carbon sources in newly abandoned areas partly counterbalanced the emerging carbon sinks in areas in later stages of succession. This effect diminished over time with decreasing cropland abandonment rates. A major conclusion from our work is thus that after the transitional period, during the early years of natural vegetation regrowth, carbon uptake and thus potential emissions from recultivating abandoned areas increase significantly each year.

[38] Carbon sequestration occurs predominantly in soil carbon stocks, typically in systems in which early succession is dominated by C3 grass species with high belowground productivity. Establishment and regrowth of tree species are relatively slow under the prevailing climatic conditions, under which evergreen trees will ultimately determine species composition in natural vegetation during later succession stages, beyond the temporal scope of this study [*Goulden et al*., 2011]. Overall, our simulations showed that the carbon sequestration rate on abandoned lands by 2009 was still approximately 50% less than for the mature natural vegetation that would ultimately develop on these lands. Carbon sequestration will therefore continue for many years until it decreases again in old-growth boreal forests [*Luyssaert et al*., 2008]. Recultivating all abandoned areas could release more than 400 TgC into the atmosphere and would result in foregone future carbon sinks in natural vegetation. Recultivation would thus not only threaten to release the carbon stored since abandonment but would also lead to substantially less carbon sequestration by preventing current systems from reaching climax vegetation. Both carbon stored at present and foregone future carbon sequestration should hence be accounted for, particularly if recultivation would focus on bioenergy production for climate mitigation purposes [*Vuichard et al*., 2009].

[39] We have developed the first high-resolution time series of cropland and cropland abandonment maps for this agriculturally important region. These maps show that cropland abandonment has been severely underestimated in the Soviet Union and that patterns of abandonment were heterogeneous across the region and during the period after 1990. Using these maps in a dynamic vegetation model reveals a nonlinear relationship between the time since cropland was abandoned and the amount of carbon sequestered. We also showed that abandonment led to substantial carbon sequestration and that recultivation of the currently abandoned lands would be associated with high carbon emissions. Our spatially and temporally explicit cropland abandonment data therefore improve the estimation of carbon costs involved in reclaiming abandoned croplands and will help to identify trade-offs involved in increasing agricultural production in this globally important agricultural region.

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