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Mapping the extent of abandoned farmland in Central and Eastern Europe using MODIS time series satellite data

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Abstract

The demand for agricultural products continues to grow rapidly, but further agricultural expansion entails substantial environmental costs, making recultivating currently unused farmland an interesting alternative. The collapse of the Soviet Union in 1991 led to widespread abandonment of agricultural lands, but the extent and spatial patterns of abandonment are unclear. We quantified the extent of abandoned farmland, both croplands and pastures, across the region using MODIS NDVI satellite image time series from 2004 to 2006 and support vector machine classifications. Abandoned farmland was widespread, totaling 52.5 Mha, particularly in temperate European Russia (32 Mha), northern and western Ukraine, and Belarus. Differences in abandonment rates among countries were striking, suggesting that institutional and socio-economic factors were more important in determining the amount of abandonment than biophysical conditions. Indeed, much abandoned farmland occurred in areas without major constraints for agriculture. Our map provides a basis for assessing the potential of Central and Eastern Europe's abandoned agricultural lands to contribute to food or bioenergy production, or carbon storage, as well as the environmental trade-offs and social constraints of recultivation.

Keywords: land use change, agricultural abandonment, fallow land, recultivation, Eastern Europe and the former Soviet Union, remote sensing



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1. Introduction

Population growth, surging consumption, and an increasing reliance on bioenergy will likely lead to rapid increases in the global demand for agricultural products (Erb *et al* 2009, Beringer *et al* 2011, Foley *et al* 2011). Most fertile land is already in use and agricultural expansion entails substantial environmental costs, such as greenhouse gas emissions and biodiversity loss, especially in the tropics (Lotze-Campen *et al* 2008, Lambin and Meyfroidt 2011). In order to minimize these environmental trade-offs, recultivating abandoned agricultural lands is an attractive alternative, especially where biophysical conditions are favorable. Abandoned farmland is widespread in parts of North America and Europe (MacDonald *et al* 2000, Brown *et al* 2005, Meyfroidt and Lambin 2011), and recultivating at least some of these lands may help to reduce pressure on pristine ecosystems elsewhere.

The collapse of the Soviet Union triggered widespread farmland abandonment (Ioffe *et al* 2004, Henebry 2009). Reforms of the agricultural sectors across Central and Eastern Europe involved price liberalization of inputs and outputs, and the privatization of agriculture in most countries (Brooks and Gardner 2004, Lerman *et al* 2004). Former markets vanished, international competition grew, capital investments declined, and outmigration from rural areas resulted in labor shortages (Seeth *et al* 1998, Ioffe *et al* 2004, Rozelle and Swinnen 2004). Together, this resulted in the contraction of the region's farming sectors and widespread farmland abandonment, including in former breadbaskets of European Russia (Prishchepov *et al* 2012), Ukraine (Baumann *et al* 2011, Hostert *et al* 2011), and Romania (Kuemmerle *et al* 2009), suggesting that there may be substantial untapped agricultural production potentials there (EBRD and FAO 2008, Liefert *et al* 2010). Unfortunately, the extent of agricultural abandonment in Central and Eastern Europe remains unclear, and estimates vary greatly (e.g., 20 Mha (Ioffe *et al* 2004), 26 Mha (Lambin and Meyfroidt 2011), 40 Mha (ROSSTAT 2010), 58 Mha (Baur *et al* 2006, Kalinina *et al* 2010)).

Several factors contribute to the differences in abandonment estimates, including differences in time periods assessed, varying abandonment definitions, and limitations of official statistics on abandonment. In addition, a major reason for uncertainty in regional estimates is that abandonment patterns were heterogeneous, making it difficult to extrapolate the results from case studies (Peterson and Aunap 1998, Bicik *et al* 2001, de Beurs and Henebry 2004, Baur *et al* 2006, Kuemmerle *et al* 2008, Müller and Munroe 2008, Kuemmerle *et al* 2011, Prishchepov *et al* 2012). This heterogeneity partly reflects variation in biophysical conditions (e.g., soil quality, climate), and farmland abandonment rates are generally appear to be higher in marginal areas than in more productive ones (MacDonald *et al* 2000, Gellrich and Zimmermann 2007, Prishchepov *et al* 2012). Another important set of factors affecting abandonment rates are institutional and socio-economic though, such as national-scale difference in land reforms (Lerman *et al* 2004), government support for

agriculture (Rozelle and Swinnen 2004, Hostert *et al* 2011), and the accession to the European Union. Understanding the spatial patterns of abandoned farmland in Central and Eastern Europe, and the factors that matter most in driving these patterns, are necessary in order to realize the region's currently idle production potentials.

A better understanding of the spatial patterns of abandoned agriculture is also important to assess the trade-offs between recultivating currently abandoned farmlands or letting them revert to forests. Post-socialist agricultural abandonment had, for example, positive effects on soil stability (Van Rompaey *et al* 2007), led to marked carbon sequestration (Vuichard *et al* 2008, Kuemmerle *et al* 2011), improved water quality (Pekarova and Pekar 1996), and benefited wildlife populations (Enserink and Vogel 2006). Likewise, economic costs of recultivating abandoned farmland vary strongly dependent on the time since abandonment and the level of vegetation succession. Thus, just as the patterns of abandonment vary, so do the trade-offs between recultivation and continued abandonment, further supporting the need for a detailed, wall-to-wall map of abandoned farmland across Eastern Europe.

Agricultural statistics in Russia and other Eastern European countries differ widely in their spatial and temporal coverage and reliability, limiting their relevance for broad-scale comparisons (Filer and Hanousek 2002, Klein Goldewijk and Ramankutty 2004). Satellite data is a potential alternative since it can map abandonment consistently across relatively large areas (Peterson and Aunap 1998, Baumann *et al* 2011, Alcantara *et al* 2012).

Here, our goal was to map abandoned farmland across Central and Eastern Europe. Specifically, our research questions were:

- (1) What are the spatial patterns of currently abandoned farmland in Central and Eastern Europe?
- (2) Are abandoned farmlands more strongly associated with institutional and socio-economic factors or with biophysical factors?

2. Materials and methods

2.1. Study area

Our study area encompassed six MODIS tiles (h19/v3, h19/v4, h20/v3, h20/v4, h21/v3, and h21/v4) covering 6.4 Mkm² across Central and Eastern Europe and the Balkan Peninsula, including 30 countries fully or partly (figure 1). The study area exhibits strong climate gradients, and is ecologically diverse, containing more than 40 ecoregions (Olson *et al* 2001) and four major mountain ranges (Ural Mountains, Carpathians, Dinaric Alps, and Caucasus). Potential natural vegetation in the north is boreal forest (mainly spruce, fir, pine, and larch), followed by a mixed forest zone (dominated by birch, aspen, gray alder, and pine), and a temperate forest zone (oak, beech, lime, maple, and ash). The southeast of the study area is arid, and the Caspian depression represents mainly grasslands and xeric scrublands.

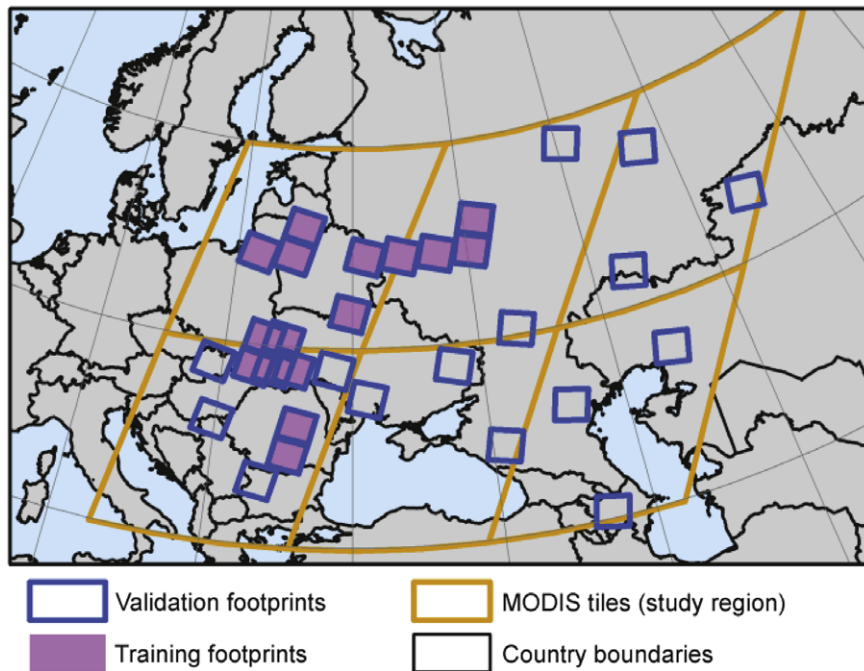


Figure 1. Study area delineated by six MODIS tiles in Central and Eastern Europe. Pink polygons represent high-resolution land use/cover change maps based on Landsat TM/ETM+ images used for training. Blue outlines denote Landsat footprints used for gathering validation data.

Agriculture is widespread in the western and southwestern portions of the study area, with agriculture dominating in the south, especially in the black-earth regions of Russia and Ukraine, and mixed farming in the central and northern part of our study region.

2.2. Mapping agricultural abandonment

We obtained MODIS normalized difference vegetation indices (NDVI) time series data (eight-day composites, 250-m resolution) from Terra (MOD13Q1 version 5) and Aqua (MYD13Q1 version 5) platforms for the time period from 1 January 2003 to 31 December 2009 (Alcantara *et al* 2012). We classified these satellite data into four classes: active agriculture (i.e., cropland and pastures), forest (i.e., coniferous, mixed and deciduous forest), abandoned agriculture, and other (i.e., water, urban areas, rocks, and wetlands). Abandoned agriculture included cropland and pastures that were likely actively farmed in the socialist period, but covered by successional vegetation (e.g., grasslands, shrubs) during the time when our satellite images were recorded, showing no signs of management such as plowing, mowing, intensive grazing.

To map farmland abandonment, we adopted the approach developed by Alcantara *et al* (2012) for a test area in the northeast of the study region. Training data for the MODIS classification was gathered from 30-m resolution Landsat TM/ETM+ footprints for which we obtained land use classifications that included agricultural abandonment (figure 1). We classified two summer and two fall images per footprint, centered on 1990 and 2005. These Landsat footprints covered parts of Poland, Latvia, Lithuania, Belarus,

and Russia (Prishchepov *et al* 2012), Romania (Kuemmerle *et al* 2009), Ukraine (Baumann *et al* 2011), Belarus and Ukraine (Hostert *et al* 2011), and Poland, Slovakia and Ukraine (Kuemmerle *et al* 2007, 2008). We recoded map legends to the four target classes. To gather training points for our classification, we selected a stratified random sample of 1000 MODIS pixels per target class within the Landsat maps, using a minimum distance of 2500 m between points to minimize spatial autocorrelation. We used only used training pixels with a single dominant land cover class of at least 90% abundance in the Landsat maps (see Alcantara *et al* 2012).

To map abandoned farmland across our study region from the MODIS imagery, we used support vector machines (SVMs), which fit an optimal separating hyperplane between two classes in the multidimensional feature space (Huang *et al* 2002). SVM are well-suited to handle spectrally complex classes, and have been used successfully to map abandoned farmland (Kuemmerle *et al* 2008, Baumann *et al* 2011, Hostert *et al* 2011). Our SVM was based on Gaussian kernel functions that required estimating the kernel width γ and the regularization parameter C , and cross-validation to determine the optimal parameter combination (Janz *et al* 2007). The SVM was applied to growing-cycle NDVI data from three years centered around 2005 plus six phenology metrics derived for the entire 2003–2009 time series. This set of features yielded the highest classification accuracy in previous tests (Alcantara *et al* 2012). We applied a Savitsky–Golay filter to the time series (2003–2009) and used TIMESAT 2.3 (Jönsson and Eklundh 2004) to calculate the (1) start of the growing cycle, (2) end of the growing cycle, (3) base NDVI, (4) maximum NDVI, (5) length of the growing cycle, and (6) center of the growing cycle for each year. Our final dataset

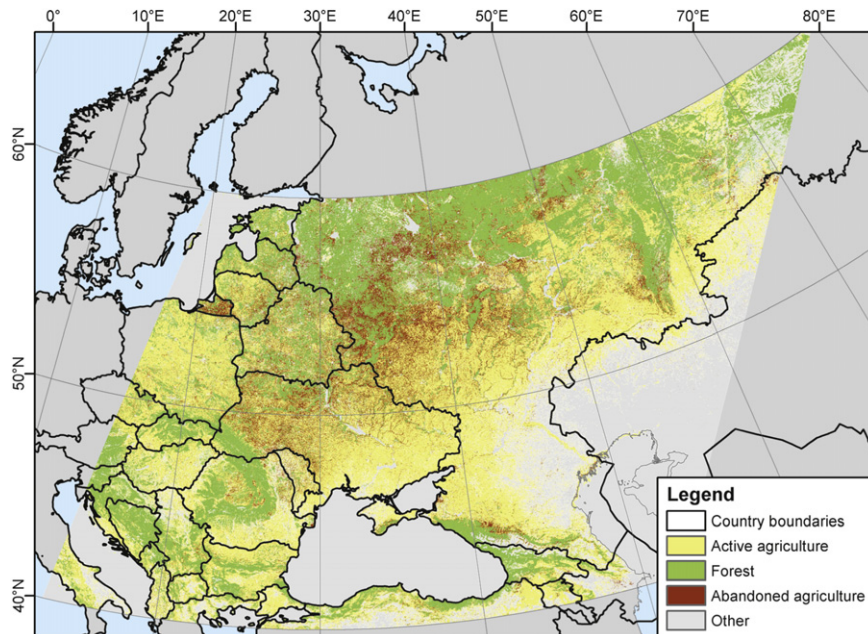


Figure 2. Land cover classification for 2005 for Central and Eastern Europe based on MODIS NDVI time series at a resolution of 250 m.

thus had 108 bands (i.e., 22 of NDVI data for 2004–2006, plus six phenology metrics per year for 2003–2009).

To validate our classification, we gathered independent data from the footprints used for training (using a minimum distance of 2500 m between points) as well as from 15 additional Landsat TM/ETM+ footprints that we selected randomly (figure 1). We used only cloud-free imagery including five ETM+ SLC-off images where cloud-free TM-5 images were unavailable. We selected 120 MODIS pixels for each of the four classes using a stratified random sample and a 2500 m minimum distance between points. We selected at least 20 points per class and MODIS tile. The resulting MODIS pixels were interpreted visually using the Landsat images, and, where available, high-resolution QuickBird images in GoogleEarth, to determine the dominant land cover class in 2005, and to calculate contingency tables and overall, user’s, and producer’s accuracies (Foody 2002). We corrected for potential bias in the accuracy measures based on land cover class abundance (Card 1982, Olofsson *et al* 2013). The 1990 and 2005 Landsat data also allowed us to quantify the proportion of abandoned farmland that had been in use during the last years of the Soviet era. Finally, we compared our abandonment map to cropland abandonment estimates at the province level for European Russia, Ukraine, and Belarus (Schierhorn *et al* 2013), which used district-level sowing area statistics from 1990 to 2009 to estimate the decline in cropland use after the breakdown of the Soviet Union.

2.3. Analyzing patterns of abandoned farmland

To summarize patterns of abandoned farmland across Central and Eastern Europe, we calculated (1) the percentage of abandoned farmland compared to the total land area within a country in our study region, and (2) the abandonment

rate, i.e., the percentage of abandoned farmland relative to the sum of abandoned plus active farmland. Country-level summaries can obscure regional variability for large countries, and we therefore also summarized abandonment rates by administrative units (provinces) for countries which had province-level administrative units (‘oblasts’) during Soviet times. Administrative boundaries were taken from Natural Earth layers (www.naturalearthdata.com) and the ESRI Data and Maps Kit 2008 (www.esri.com). We also summarized abandonment rates by biophysical suitability for agriculture, using the crop suitability index from the Global Agro-Ecological Zones (GAEZ) dataset, version 3.0. GAEZ 3.0, which is based on the Harmonized World Soil Database (HWSD) and climate data for 1961–1990. We selected the crop suitability index for low input levels of rain-fed cereal production, the prevailing cultivation system in the region (Fischer *et al* 2002, IIASA and FAO 2012). We summarized abandonment rates for seven discrete classes of the crop suitability index, and for unique combinations of province/country-level administrative units.

3. Results

Abandoned farmland was widespread across our study region, totaling 52.5 Mha in 2005 (figure 2), which is equal to a share of 8.18% of the study region. Active agriculture and pastures covered 38.09% (244.3 Mha) of the study region, whereas forest covered 27.36% (175.5 Mha) and other land covered 26.36% (169.1 Mha). Large areas of abandoned agriculture occurred in temperate European Russia, often along the borders of forest and active agriculture. Abandoned farmland was also widespread in northern and western Ukraine, southwest of the Urals, in central Romania, and the northern foothills of the Caucasus. Abandoned farmland was generally

Table 1. Error matrix, user’s accuracy (UAC) and producer’s accuracy (PAC) for the land cover change map derived from the MODIS time series.

		Classification				Total	PAC (%)
		AG	F	AB	O		
Reference	Agriculture (AG)	65	5	6	25	101	57.16
	Forest (F)	24	105	12	6	147	72.93
	Abandoned agriculture (AB)	58	10	34	21	123	17.27
	Other Classes (O)	48	13	15	33	109	42.44
	Total	195	133	67	85	480	
UAC (%)		33.33	78.95	50.75	38.82		

less widespread in Central Europe (e.g., Poland, Slovakia, and Hungary) and the Balkan states. Active agriculture was widespread in the plains (with the exception of northwestern Ukraine) and in the South of European Russia.

The rates of abandoned relative to active agriculture differed markedly among countries. Ten countries (Russia, Ukraine, Belarus, Poland, Romania, Lithuania, Latvia, Turkey, Moldova, and Kazakhstan; note that some countries are only partly in our study region), together comprising 86% of the study area, contained 95.7% of the abandoned farmland. The largest area of abandoned farmland occurred in Russia (32.2 Mha, 61% of all abandoned farmland in the study region). Large areas of abandoned farmland also occurred in Ukraine (9.2 Mha), Belarus (3.4 Mha), Poland (1.5 Mha), Romania (1.0 Mha), Lithuania (0.9 Mha), and Latvia (0.6 Mha). At the country-level, Belarus had the highest abandonment rate (34%), followed by Latvia (27.6%), Lithuania (23.7%) and Russia (22.5%) (table 1). Ukraine, Moldova, and Estonia also had high abandonment rates (20.5%, 18.9%, and 16.8%, respectively; table 1).

The comparison of the share of total agricultural land (active and abandoned) within a country versus the rate of abandoned farmland highlighted distinct groups of countries (figure 3). First, Belarus, Latvia, Russia and Lithuania had large areas of agricultural land and high abandonment rates (between 17% and 35%). Second, Estonia had relatively moderate agricultural area, yet high abandonment rates. Third, Ukraine and Moldova had high abandonment rates (~20%) and very high proportion of agricultural land (59% and 55%, respectively). Fourth, a large group of countries had high shares of agriculture (29%–60%), yet relatively low rates of abandonment (e.g., Czech Republic, Poland, Hungary, Bulgaria, Albania, and Kosovo). A final group of countries (e.g., Georgia, Montenegro, Croatia, Bosnia and Herzegovina, and Slovenia) had moderate agricultural area, and low abandonment rates (<6%).

Summarizing abandonment rates by administrative regions highlighted substantial heterogeneity within the larger countries (figure 4). For example, in Russia, abandoned farmland was especially prevalent in the provinces of Smolensk (85% abandonment rate), Tversk (85%), Yaroslav (80%), Ivanov (66%), and Kalush (78%) located along the border with Belarus and north and northwest of Moscow (abandoned + active agriculture in 2005) per country. All data are based on map estimates (figure 2).

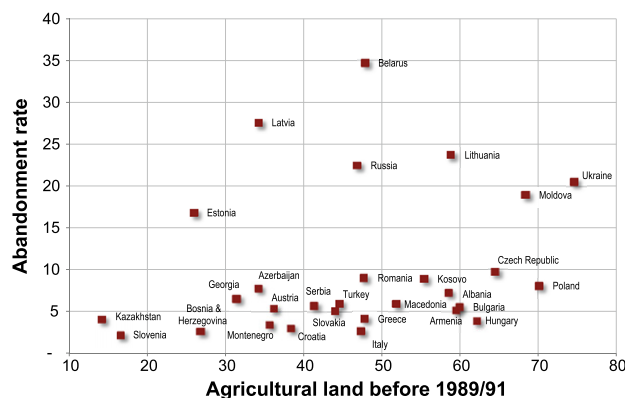


Figure 3. Scatterplot of abandonment rates (abandoned agriculture/(abandoned + active agriculture in 2005)) versus the share of agricultural land before the collapse of socialism (abandoned + active agriculture in 2005) per country. All data are based on map estimates (figure 2).

Summarizing abandonment rates for each suitability class within each country revealed three interesting patterns (figure 5). First, most countries had higher abandonment rates in areas less well-suited for agriculture. Second, few countries (Russia, Latvia, Estonia, Croatia) showed a surprising trend of higher abandonment rates in areas of medium and high suitability for agriculture. In total, 27.7 Mha of abandoned farmland occurred in regions with very high and high suitability for agriculture, especially in Russia (19 Mha), Ukraine (6 Mha), and Belarus (1 Mha).

The accuracy assessment of our MODIS-based land use/cover change map suggested an overall area-adjusted accuracy of 48.7%. Forest had the highest user’s (78.9%) and producer’s accuracies (72.9%), followed by active (33.3%/57.2%) and abandoned farmland (50.7%/17%). Visual assessments of the 1990s Landsat images used for collecting validation points revealed that 62% of the locations labeled as agricultural abandonment in the MODIS analyses were areas that had indeed been cultivated until 1989/1991 and were abandoned afterwards. The remaining 38% of our points had successional vegetation already in the early 1990s, suggesting earlier abandonment or permanent grasslands or shrublands.

Comparing our abandonment estimates with those derived from official sown area statistics (ROSSTAT 2010) shows overall high agreement between these two independent data sources (figure 6, Pearson $R^2 = 0.35$). For most provinces, our map shows higher abandonment rates, which is

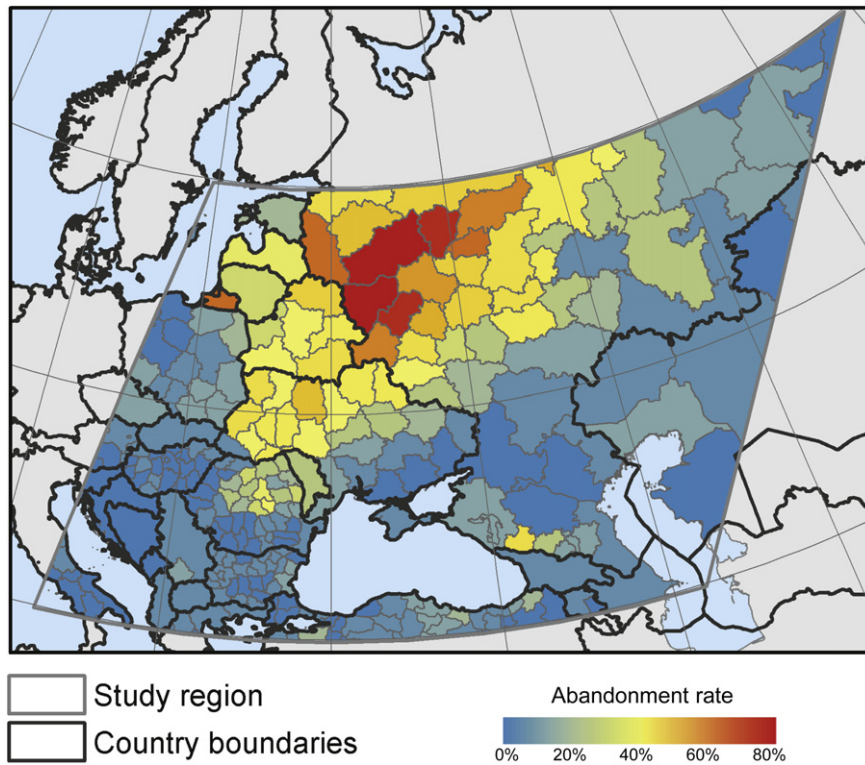


Figure 4. Abandonment rates by administrative units (country-scale for small countries, state/province scale for large countries). All data are based on map estimates (figure 2).

Agro-ecological constraints	Countries																													
	Belarus	Estonia	Latvia	Russia	Ukraine	Lithuania	Moldova	Romania	Czech Republic	Azerbaijan	Kosovo	Poland	Georgia	Albania	Kazakhstan	Slovakia	Turkey	Bulgaria	Armenia	Austria	Macedonia	Serbia	Greece	Hungary	Croatia	Montenegro	BiH	Italy	Slovenia	
No constraints				8	7				7	13					9					5		0					0	0		
Very few constraints				31	22		21	8	6	8		10	12	5		7	9	5	5	11	6	4	2	5	4	7	5	3	1	1
Few constraints	35	21	29	26	18	31	21	6	10	10		10	6	9	7	6	6	6	5	4	3	4	4	4	4	3	2	2	2	
Partly with constraints	30	20	27	32	27	38	15	11	9	10	10	8	6	8	10	4	6	6	3	6	6	6	6	4	3	4	3	3	3	2
Frequently severe constr.	38	30	30	26	26	15	20	10	11	10	7	7	6	6	3	7	5	6	6	7	5	9	4	4	2	3	3	3	2	
Very frequent severe constr.	37	42	6	19	42	20	15	5	8	4	8	8	7	7	8	4	9	5	8	4	8	5	4	5	3	5	2	3	4	
Unsuitable for agriculture	35	14	26	8	6	17	17	19		14		9	6		2	3	2	3	3	4		3		4	5		1	2		
Severe climate constraints				5									16		4															

Figure 5. Abandonment rates per crop suitability class for low input level rain-fed cereals and country. All abandonment data are based on map estimates (figure 2) and suitability indices (SI) based on GAEZ 3.0 (<http://gaez.fao.org>).

reasonable because the sown area statistics refer to cropland abandonment only, whereas our map captures abandoned cropland and pasture alike. Agricultural abandonment appears to be underestimated by our analyses for a few provinces in the steppes zone of Russia (e.g., Saratov, Orenburg, Volgograd). Omitting these three regions improved the correlation between the two data sources substantially (Pearson $R^2 = 0.56$).

4. Discussion

Understanding the spatial patterns of abandoned farmland is important for assessing the potential of these lands to contribute to food production, carbon sequestration, or bioenergy production, and thus to relieve land use pressure on

natural ecosystems elsewhere. Here, we show that abandoned farmland in Central and Eastern Europe covered about 52.5 Mha in our study area in 2005. While our map depicted plausible spatial patterns of abandoned farmland and compared favorably with fine-scale assessments of farmland abandonment, our accuracy assessment suggested that our map represents a conservative estimate of abandonment.

We found strong differences in abandonment rates among countries, but not as strong relationships between the natural suitability for agriculture and the share of abandoned farmland. One potential reason for this was that GAEZ 3.0 may have underestimated crop suitability for the highly fertile black soil regions in Southern Russia and Eastern Ukraine (where abandonment rates are low) where average cereal yields are high (Ioffe *et al* 2004). Conversely, GAEZ

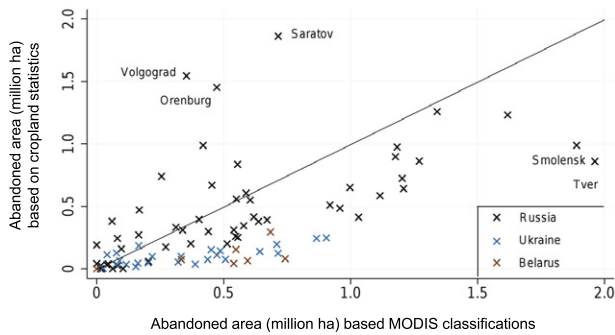


Figure 6. Abandoned area (including both cropland and pastures) derived from MODIS (this study) versus abandoned cropland area based on official statistics (Schierhorn *et al* 2013). The line is a 1:1 line for comparison purposes and not a line that was fitted to the data.

reported the highest crop suitability in the region north of the black soil areas where abandonment rates are notably higher, but average cereal yields are lower (Ioffe *et al* 2004). Nevertheless, our results suggested that the variation in agricultural abandonment rates across the region was to a large extent driven by differences in institutional and socio-economic factors among countries (e.g., differences in agricultural subsidies, land reforms, and EU accession) rather than biophysical settings.

Our map of abandoned farmland in Central and Eastern Europe, to our knowledge the first of its kind, yielded plausible spatial patterns. Our best estimate of abandoned farmland was 52.5 Mha, out of which 32.2 Mha were in Russia. This is in the range of previously reported estimates based on statistical data (e.g., 26 Mha in Russia (Lambin and Meyfroidt 2011), 31 Mha in Russia, Belarus, and Ukraine (Schierhorn *et al* 2013), 58 Mha in Russia (Baur *et al* 2006, Kalinina *et al* 2010)). It is important to note though that prior estimates refer to abandoned cropland only, whereas our satellite-based mapping considered former croplands and pastures.

Our MODIS-based estimates of abandonment were in general conservative when compared to case studies that were based on 30-m resolution Landsat images. For instance, our map suggested that 16.8% of the agricultural land was abandoned in Estonia whereas previous work reported 32% (Peterson and Aunap 1998). In southern Romania, prior studies reported an abandonment rate of 21% (Kuemmerle *et al* 2009), while our map depicted only 9% abandoned farmland. Similarly, we found 13% of Albania’s agricultural land to be abandoned, whereas a Landsat-based study reported an abandonment rate of 27% (Müller and Sikor 2006). Finally, we found an abandonment rate of 22.5% in European Russia, while a Landsat-based study reported a rate of 37% (Prishchepov *et al* 2012). We caution, though, that direct comparisons are challenging, because the time periods and abandonment definitions used vary among these studies.

Adjusting our map estimates according to our accuracy assessment (table 1) yielded a substantially higher area estimate of abandoned farmland (154.27 Mha) than depicted in our map (52.49 Mha). This suggests our abandoned

farmland map is a conservative estimate, but we caution that the higher estimate is far out of the range of the area of abandoned farmland that other studies had suggested. It is also important to note that the general abandonment trends found in fine-scale studies across the region were captured well by our maps and that remaining differences between our MODIS and Landsat-based studies can at least partly be attributed to different mapping periods and uncertainty in the Landsat change maps. Our MODIS-based map of abandoned farmland showed plausible spatial patterns, had a high user’s accuracy for our target class, and an overall accuracy comparable to similar broad-scale mapping efforts (Alcantara *et al* 2012), suggesting our map provides a reasonable, while somewhat conservative estimate of post-Soviet farmland abandonment.

A few factors contributed to uncertainty in our map. First, moderate map accuracies were expected, given the complexity of this land cover (i.e., a wide range of successional vegetation stages) and the environmental heterogeneity of the study region. This particularly applies for the dry steppes regions where agricultural abandonment was underrepresented by our MODIS-based map (figure 6), and where the detection of abandonment via remote sensing is hampered by low spectral contrast between active agriculture and successional vegetation. Moreover, our map did not provide information on the timing of abandonment (e.g., early or late 1990s). Second, we used training data from multi-temporal Landsat analyses between the late 1980s and the 2000s, but MODIS images are only available since 2000. Because most post-Soviet abandonment occurred in the early 1990s (Ioffe *et al* 2004, Kuemmerle *et al* 2009, Baumann *et al* 2011), we could only indirectly map abandoned farmland, and our class may include some permanent grasslands or shrublands (e.g., in floodplains in southern Russia or in mountain regions, figure 2). Third, the relatively coarse spatial resolution of the MODIS NDVI time series (250 m) may be limiting in areas where fields are much smaller than the pixel size (Latifovic and Olthof 2004, Ozdogan and Woodcock 2006), especially in countries with highly fragmented land use patterns (e.g., Poland, Romania, Bulgaria, or Lithuania). Indeed, visual inspection of misclassified reference pixels suggested that many of them consisted of mixed pixels (active and abandoned farmland within one MODIS pixel). Finally, although we used an extensive set of training data from 16 Landsat footprints, we could not fully rule out geographic bias in our training set, plus the individual studies covered varying time periods and used slightly different abandonment definitions, all of which may lowered classification accuracy.

Irrespective of the accuracy of our classification, it is clear that abandoned agricultural land was widespread. Market disruption, price liberalization of inputs and outputs, limited access to capital, increasing competition, tenure insecurity, and a lack of new technology, equipment and technical support were all important drivers of post-Soviet abandonment across Central and Eastern Europe (Liefert and Swinnen 2002, Lerman *et al* 2004, Rozelle and Swinnen 2004). Our results highlighted substantial heterogeneity in abandonment rates across the region. We found the highest abandonment rates north and west of Moscow

(figure 4). Differences in abandonment rates among countries were very pronounced and more pronounced than among different suitability classes for agriculture (figure 5). This suggested that institutional and socio-economic factors were important drivers of this heterogeneity. Several factors may explain this finding. First, countries took very different approaches as they reformed their agricultural sectors, ranging from drastic market liberalization (e.g., Albania, Poland, Romania) to gradual reforms (e.g., Belarus, Ukraine) (Lerman *et al* 2004, Prishchepov *et al* 2012, Müller *et al* 2013). Governmental support for agriculture after 1989/1991 also varied substantially across the region, ranging from a 90% drop in state support in Russia, to continuing high support in Belarus (Ioffe 2004, Prishchepov *et al* 2013). Second, countries chose different land reform pathways, including restitution of agricultural land (e.g., in the Baltics and Slovakia), distribution of land shares (e.g., Russia, Ukraine), or continuation of state-ownership (e.g., Belarus) (Lerman *et al* 2004). Varying tenure insecurity across the region and poorly functioning land markets were also causes of the heterogeneity in abandonment patterns. Third, several countries joined the European Union in 2004 (e.g., Poland, Lithuania, Latvia, and Estonia) and 2007 (e.g., Bulgaria and Romania), enabling farmers to access agricultural subsidies and new markets (DLG 2005). This likely dampened abandonment rates even before EU accession took official place.

Understanding patterns of agricultural abandonment is important because abandonment affects a range of ecosystem services as well as biodiversity. Food production ceases on abandoned land, and abandonment can increase fire risk and lead to the loss of farmland biodiversity and traditional landscapes (Hochtl *et al* 2005, Dubinin *et al* 2010, Fischer *et al* 2012). Conversely, abandonment increases carbon sequestration (Kuemmerle *et al* 2011, Schierhorn *et al* 2013), reduces soil erosion and increase water quality (Van Rompaey *et al* 2007, Cramer *et al* 2008), and benefits the wildlife of natural ecosystems (Enserink and Vogel 2006, Sirami *et al* 2007). Our results showed that much farmland abandonment occurred in regions that are suitable for agriculture, highlighting the potential of Central and Eastern Europe to contribute to increasing agricultural production by recultivating suitable but currently idle farmlands. However, assessing the potential environmental trade-offs and social constraints of recultivation is important, and our map of abandoned farmland can aid to this end. Broad-scale satellite analyses like the one presented here can thus provide the necessary baseline information to guide land use and conservation planning.

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