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Agricultural land change in the Carpathian ecoregion after the breakdown of socialism and expansion of the European Union

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Abstract

Widespread changes of agricultural land use occurred in Eastern Europe since the collapse of socialism and the European Union's eastward expansion, but the rates and patterns of recent land changes remain unclear. Here we assess agricultural land change for the entire Carpathian ecoregion in Eastern Europe at 30 m spatial resolution with Landsat data and for two change periods, between 1985–2000 and 2000–2010. The early period is characterized by post-socialist transition processes, the late period by an increasing influence of EU politics in the region. For mapping and change detection, we use a machine learning approach (random forests) on image composites and variance metrics which were derived from the full decadal archive of Landsat imagery. Our results suggest that cropland abandonment was the most prevalent change process, but we also detected considerable areas of grassland conversion and forest expansion on non-forest land. Cropland abandonment was most extensive during the transition period and predominantly occurred in marginal areas with low suitability for agriculture. Conversely, we observed substantial recultivation of formerly abandoned cropland in high-value agricultural areas since 2000. Hence, market forces increasingly adjust socialist legacies of land expansive production and agricultural land use clusters in favorable areas while marginal lands revert to forest.

Keywords: Europe, land use change, agricultural abandonment, fallow land, recultivation, grassland conversion, forest expansion, remote sensing, image compositing, Landsat

1. Introduction

Humanity derives essential goods and services from land use, but simultaneously land use changes have become a



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primary driver of global environmental change and caused significant biodiversity loss as well as the deterioration of ecosystem services (Tilman *et al* 2002, Foley *et al* 2005). Changes in agricultural land use were particularly widespread, with ample consequences for humans and nature. One major environmental concern is the rapid expansion of croplands and pastures at the expense of tropical and subtropical forests, and the various adverse consequences for biodiversity and carbon budgets (Sala *et al* 2000, van der Werf *et al* 2009). But while agricultural land use continues to expand in many tropical regions, areas used for agriculture tend to decrease in the temperate zone. A large body of research has been devoted to understanding agricultural expansion in tropical settings, but the patterns and processes of the decrease of agricultural land are less well understood (Kuemmerle *et al* 2009, Ramankutty *et al* 2010, Hostert *et al* 2011). This is unfortunate, because abandonment of agricultural land has strong implication for agricultural production and affects carbon pools (Vuichard *et al* 2008), biodiversity (MacDonald *et al* 2000) and food security (Schierhorn *et al* 2012). A better understanding of the rates and spatial patterns of agricultural land abandonment is therefore crucial.

One of the most drastic recent episodes of land change that resulted in massive rates of agricultural abandonment occurred after the collapse of socialism in the countries of the former Soviet Union and in Central and Eastern Europe (CEE) (Henebry 2009). The socialist agricultural system was strongly subsidized in these countries with guaranteed output and input prices and high land and labor inputs, often with the aim to increase self-sufficiency in agricultural production (Csaki 1990, Lerman *et al* 2002). State support largely disappeared following the collapse of socialism and agricultural production was economically no longer viable in many areas due to price liberalizations, dilapidated infrastructure and increasing competition with other economic opportunities, leading to production decreases and rural emigration (Rozelle and Swinnen 2004, Mueller and Munroe 2008, Mueller *et al* 2009). Consequently, vast areas of agricultural land were abandoned. Abandoned lands subsequently experienced natural succession and many areas have now reverted back to young forests, contributing to the forest transition in Eastern Europe (Taff *et al* 2010). However, most evidence regarding the extent of agricultural abandonment to date relies on case studies, while the spatial and temporal patterns for large, contiguous areas are not well understood.

Agricultural abandonment tends to cluster in areas with comparatively low suitability, such as mountain areas, while fertile lands often continue to be cultivated (MacDonald *et al* 2000, Ioffe *et al* 2012, Prishchepov *et al* 2013). However, today's agricultural production in Russia and CEE is often below the potential yields under the given environmental conditions and therefore these lands represent interesting options for increasing food production (Foley *et al* 2011, Schierhorn *et al* 2012). Given the recent rises in global agricultural commodity prices, abandoned agricultural land in post-socialist countries today represents an attractive source of income and increasingly becomes a target for investors

(Deininger 2011, Visser and Spoor 2011). In the face of the recent increase in agricultural commodity prices, quantifying recultivation of abandonment lands can shed light on the effects of growing profit opportunities in agriculture on agricultural land use.

The eastward expansion of the European Union may also have contributed to recultivation of abandoned lands. New member states in 2004 included, among others, the Czech Republic, Hungary, Poland and Slovakia and in 2007 Romania became part of the EU. New member states became subject to the influence of the European Union Common Agricultural Policy (EU CAP), which grants direct subsidy payments in support of agricultural production and rural development. However, little is known about how the EU accession has affected agricultural land change in CEE countries.

The focus of this study is to map and analyze agricultural land change across the Carpathian ecoregion in Eastern Europe since before the collapse of socialism until 2010 at 30 m (i.e. Landsat) spatial resolution. The Carpathians are Europe's largest mountain region and extend over seven countries (Austria, Czech Republic, Slovakia, Poland, Hungary, Ukraine and Romania). All countries except Austria were under socialist governance between 1945 and 1991 and all countries except Ukraine are now members of the EU. The Carpathians are a highly diverse ecoregion, which historically translated into a large variety of land use structures (Turnock 2002) that may have been affected differently by the contrasting post-socialist reform policies and economic development trajectories. However, no consistent and spatially explicit dataset on recent land change exists for the Carpathians as a whole.

We utilized Landsat satellite imagery to fill this gap. Landsat imagery is a great data source for retrospective land change assessments, as it provides a continuous record of synoptic observations since decades with 30 m spatial resolution and adequate spectral detail. Recent changes in data policy as well as advancements in data quality, preprocessing and analysis algorithms have greatly improved the potential of Landsat data to quantify agricultural land change for large areas (Wulder *et al* 2012). Taking advantage of these developments, our objectives were to (a) quantify the spatial and temporal patterns of agricultural land change in the Carpathians between 1985 and 2000 as well as between 2000 and 2010, and to (b) assess and compare environmental and agro-ecological characteristics of areas where agricultural land change occurred. The year 1985 was chosen as this is roughly the earliest year that Landsat Thematic Mapper data is available over Europe while land use was still fully controlled by socialist land management regimes. The year 2010 should capture the situation following the EU accession of most Carpathian countries. The year 2000 lies in the middle between socialism and EU accession and post-socialist transformation processes are potentially captured in satellite imagery while processes related to the EU accession are only beginning to trigger spatial changes.

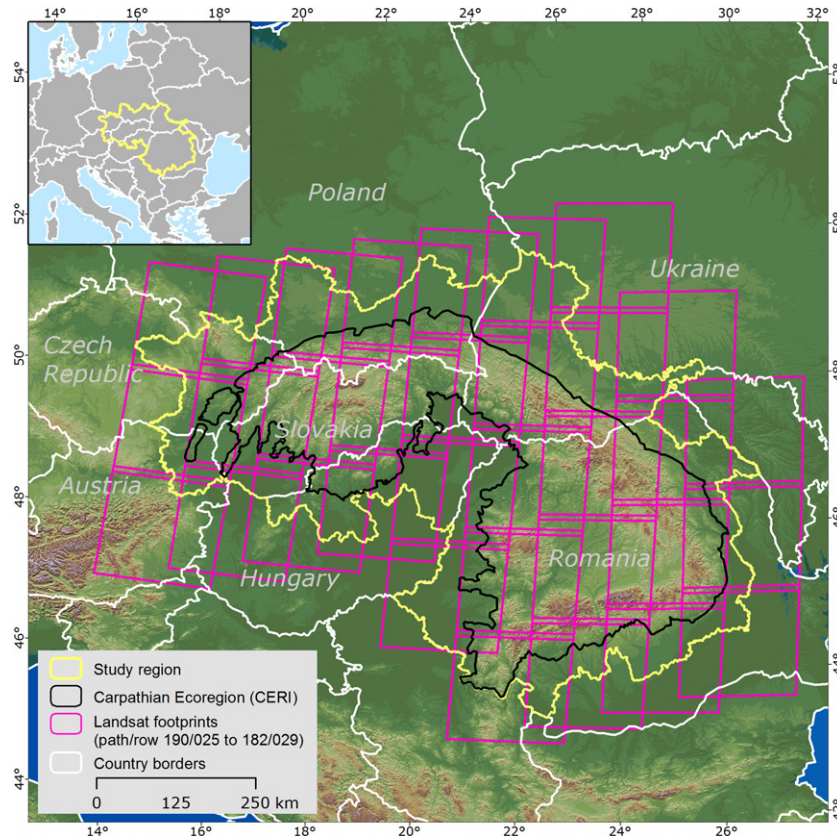


Figure 1. Overview of the Carpathian study region (yellow), the ecoregion boundaries (black) and country borders (white). Additionally, the coverage of Landsat footprints is shown (magenta), which were used to produce three seasonal image composites (spring, summer and fall) for three reference years (1985, 2000 and 2010).

2. Data and methods

Our study region is the Carpathian ecoregion (CERI 2001) including intersecting administrative units (Nomenclature of Territorial Units for Statistics, Level 3—NUTS3), resulting in an area of approximately 380 000 km² (figure 1). Elevation in the study region ranges from 400 m in the plains to 2500 m in the Southern and Western Carpathians. A wide range of agricultural land use types exists, ranging from large scale, intensively managed cropland to subsistence agriculture and kitchen gardens. Cropland in the region is predominantly used for cereals (wheat, corn, barley, rye, oat) and legumes (potatoes, sugar beets, peas), but also to grow energy crops (e.g., rapeseed/canola). Perennial crops exist in the form of fruit tree orchards, vineyards or hop fields. Grassland is utilized as pastures or hay fields and at higher elevations meadows are used for seasonal sheep grazing.

The majority of agricultural land in the Carpathian countries was under collective or state farm management during socialism, except in the Polish Carpathians where private farms persisted (Lerman 1999, Kozak 2010). After 1989, private property was reintroduced and collectivized lands were restituted, auctioned or distributed to farmers, historical owners or their heirs, which led to considerable structural change in agriculture including the emergence of many small fragmented farms alongside large private

cooperatives (Sarris *et al* 1999). The Carpathian ecoregion hence offers a diverse and, from a remote sensing point-of-view, challenging region to study due to the prevailing heterogeneous landscapes and mountainous terrain. This makes it an ideal test bed to improve the understanding of the complex land change trajectories that occurred during the recent turbulent decades of change and to elaborate how remote sensing can contribute to disentangling these complex spatio-temporal patterns.

Multi-temporal Landsat imagery has recently been used to map agricultural abandonment in CEE and it has been shown that including imagery acquired at key stages of crop development (i.e. leaf emergence, plowing) can considerably improve the differentiation of cropland, grassland and fallow land (Baumann *et al* 2011, Prishchepov *et al* 2012b). However, the 16-day repeat cycle of Landsat satellites coupled with frequent cloud coverage in mountainous regions constrains the availability of such imagery. Thus, while such sets of multi-temporal imagery might be available for individual footprints, acquiring such specific datasets over larger regions is hardly feasible. Consequently, most studies that mapped agricultural abandonment only compared two reference periods, and used only one or two observations from different seasons for each considered period. This increases the risk of false interpretations, e.g. assessing an area as being abandoned even though it was only imaged during a

fallow stage within a crop rotation cycle. To circumvent these limitations, our approach incorporates all available, useful observations, i.e., thousands of images from the Landsat archive and utilizes automated data preprocessing and image compositing algorithms. Such an approach enables generating regional, cloud free datasets that are radiometrically and seasonally consistent (Griffiths *et al* 2013a, 2013b).

To produce the image composites for the large area covered by 32 Landsat footprints (figure 1), all precision terrain corrected imagery (L1T) with no more than 70% cloud cover was downloaded from the USGS Landsat archive (ca. 5000 images). We produced three image composites that approximate specific seasonal states (spring, summer and fall) centered around three reference years that capture the situation (i) during socialism (ca. 1985), (ii) after 10 years of post-socialist transition (ca. 2000), and (iii) after the EU accession (ca. 2010), yielding a total of 9 image composites (18 bands for each reference period = 56 spectral bands). These temporally targeted image composites represent 'extended snapshots' that maximize spectral and temporal separability of agricultural land use classes and changes. The seasonal composites were supplemented with 27 bands of statistical metrics that capture the spectral–temporal variability of a given pixel for each season (e.g., variation and mean of the normalized difference vegetation index (NDVI) for spring observations). We further added layers containing specific metadata information per pixel, e.g. the image acquisition day-of-year (yielding a total number of 100 bands).

We focused our analysis on four main land change categories that relate directly or indirectly to changes in agricultural land use: abandonment (conversion of cropland to other uses), grassland conversion (conversion of grassland to other use), recultivation (conversion of grassland to cropland during the first period, conversion of abandoned cropland to cropland for the second period) and forest expansion (forests establishing on non-forest lands). We assessed the rates of these processes for two change periods: the transition period (1985–2000) and the EU accession period (2000–2010). In order to differentiate forest expansion occurring on non-forest land from forest areas that are regrowing after forest disturbance, we overlaid our change map with a recent forest disturbance map which was derived for the same area through multi-temporal classification of Landsat image composites that were optimized for forest change detection (Griffiths *et al* 2013a). We included the conversion of grassland to cropland as recultivation because we assume that the majority of these areas were once covered by forests but cleared for cropland use and were converted to grassland prior to 1985. Table 1 provides descriptions of classes targeted for change detection as well as class summaries that were used to quantify the rates and patterns of land change.

For mapping and change detection, the 100 features were combined into one stacked dataset and a random forests (RF) classifier was parameterized to map the 15 classes of interest (Waske *et al* 2012, Griffiths *et al* 2013a). Belonging to the field of machine learning algorithms, RFs utilize ensembles of trained decision trees and make a final decision through

majority votes. Training areas were digitized on-screen on the original Landsat imagery using the following reference data sources to aid interpretation: high resolution imagery available in GoogleEarth, high temporal frequency satellite time series, Street View data (Google 2013) and the full temporal record of the original Landsat imagery. One global RF model was trained for the analysis. Due to imbalanced training data sizes, we sampled the same number of pixels from all classes (~1300 each). We then trained a RF model consisting of 2000 individual trees which considered 15 bands at each decision tree node. For validation of the resulting change map we generated a stratified random sample of 50 points per class. Samples were carefully interpreted using all above mentioned reference data. The key feature for identifying croplands was the presence or absence of plowed signals interchanging with vegetation in the Landsat imagery. Validation results were finally adjusted for potential sampling bias and then used to derive error adjusted area estimates and the 95% confidence intervals around these estimates (Card 1982, Olofsson *et al* 2013). Our validation design allows providing error adjusted area estimates for all classes on the level of the entire study region while on the level of countries or administrative units we provide map estimates. We applied a minimum mapping unit of five pixels (4500 m²) which represents a good compromise between accounting for a variety of field sizes and removing erroneous classified pixels. Subsequently, we aggregated the final change map to relevant process categories (table 1) and summarized change classes per country and time period.

In order to better understand the environmental characteristics of areas where agricultural land change occurred, we acquired data from the Global Agro-Ecological Zones database (IIASA and FAO 2012). Specifically, we used the crop suitability index (CSI) for rain-fed wheat production at intermediate fertilizer input levels available at one arc second spatial resolution. The CSI combines information on climate, soils and topography into a single proxy of overall agro-ecological condition. We then aggregated the CSI data and change maps to the level of administrative units and produced maps showing change rates at district/county level as well as scatter plots comparing the CSI with change rates for the 1985–2000 and 2000–2010 periods.

3. Results

Our results showed that extensive land changes occurred in the Carpathians since the mid-1980s. On the pan-Carpathian level, croplands decreased considerably until 2000, while grasslands increased almost proportionally (table 2). Croplands additionally decreased by approximately 2% until 2010 while the increase in grassland area during this period was marginal. Forest area increased continuously from roughly 40% in 1985 to 43% in 2010.

Agricultural abandonment was the most prevalent change process (figure 2). About 24% of the 1985 cropland area was converted to other uses until 2000, while cropland abandonment only accounted for about 11% of the 1985 cropland area in 2010. On the contrary, about 4% of

Table 1. Overview of the study design: the top section shows the targeted classes during change detection and mapping, which are provided with acronyms that refer to the land use/land cover during the individual reference years (top left). Class acronyms: C = cropland, F = forest, G = grassland. Using black squares, sections two to four illustrate how the spatial extents of cropland, grassland and forest were derived for the three reference years. Definitions of the class constituents are provided on the far right. Finally, sections five to eight illustrate (using colored squares) how the targeted land change processes were derived. For example ‘Abandonment 2000’ was derived by summing up ‘C–F–F’, ‘C–G–C’, ‘C–G–F’ and ‘C–G–G’. The abandonment rate for the socialist period was then derived as the percentage of the total ‘Cropland 1985’ against ‘Abandonment 2000’ (accordingly, ‘Grassland conversion 2000’ and ‘Recultivation 2000’ rates were derived relative to the ‘Grassland 1985’, while the ‘Recultivation 2010’ rate was calculated relative to ‘Abandonment 2000’).

	Mapped classes ^a												Definitions	
Socialism	C	C	C	C	C	C	C	G	G	G	G	G	F	
Transition	C	C	C	F	G	G	G	G	C	F	G	G	F	
EU accession	C	F	G	F	C	F	G	G	C	F	C	F	F	
Cropland1985	■	■	■	■	■	■	■							All farmed agricultural and cropland for cereals, root and energy crops, vegetables and others
Cropland 2000	■	■	■					■						
Cropland 2010	■			■				■		■				
Grassland ^b 1985								■	■	■	■	■		Pastures, hayfields, meadows, natural grasslands, small scale subsistence agriculture, permanent fallow land, shrub land, orchards
Grassland 2000								■	■	■	■	■		
Grassland 2010			■					■	■					
Forest 1985													■	All deciduous, mixed and coniferous forests
Forest 2000												■	■	
Forest 2010		■										■	■	
Abandonment 2000				■	■	■	■							All 1985/2000 cropland areas that were converted to other uses in 2000/2010
Abandonment 2010		■	■											
Grassland conversion ^c 2000									■	■				All 1985/2000 grassland areas that were converted to other uses in 2000/2010
Grassland conversion 2010					■	■				■	■			
Recultivation ^d 2000									■					Grassland-cropland conversions and recultivation of formerly abandoned cropland
Recultivation 2010					■					■				
Forest expansion ^e 2000				■						■				Forest expansion on non-forest lands
Forest expansion 2010		■				■						■		

^aWe additionally mapped a permanent built-up (B-B-B) and water class (W-W-W), but as these were not within the focus of the change analysis we did not include them in this summary table.

^bAs the separation of different grass-dominated land-use classes such as hayfields, pastures or natural grasslands is challenging with Landsat data, we focus on one broad grassland class. Depending on the level of management, perennial crops (vineyards, orchards, etc.) are regarded as belonging to the grassland class under low management conditions, and belonging to the cropland class under more intense management. This class also includes grass-dominated wetland areas.

^cTo prevent an overestimation of grassland conversions through inclusion of logged or harvested forest areas that are regrowing, we used a disturbance map from an earlier study to extract only those grassland conversions that are not related to regrowing forests. However, this might include forest areas recovering from logging/disturbances that occurred prior to 1985.

^dThe assessment of recultivation for the transition period mostly comprised grassland to cropland conversions. Here we assumed that all grassland areas were historically forest areas that were converted to cropland and subsequently converted to grassland.

^eWe used results from an earlier study to extract only those forest expansion areas that were not related to logging or other forest disturbances. However, this forest expansion also entails areas that were logged prior to the mid-1980s.

grasslands were converted to cropland use until 2000. Between 2000 and 2010, roughly 18% of the cropland that was abandoned until 2000 was brought back into production. In comparison to the 1985 forest area, forest expansion on non-forest lands summed up to 3.4% during the transition period and 2.3% during the EU accession period.

Some of the mapped land cover trajectories (table 1) occurred almost exclusively in certain countries (figure 3). For example, more than 67% of all cropland–grassland–cropland conversion was mapped in Romania (figure 3, frame 6), almost 95% of cropland–forest conversions between 2000 and 2010 occurred in Hungary (figure 3, frame 5), and

Table 2. Error adjusted area estimates for the study region wide extent of croplands, grasslands and forests for the three time periods.

	1985		2000		2010	
	(km ²)	(%)	(km ²)	(%)	(km ²)	(%)
Cropland	122 269	31.4	97 083	25	88 947	22.9
Grassland	100 002	25.7	119 321	30.7	121 064	31.1
Forest	154 638	39.8	160 504	41.3	166 898	42.9

cropland–grassland conversions were common in the Czech part of the study region while grassland–cropland conversions were virtually absent (figure 3, frame 1).

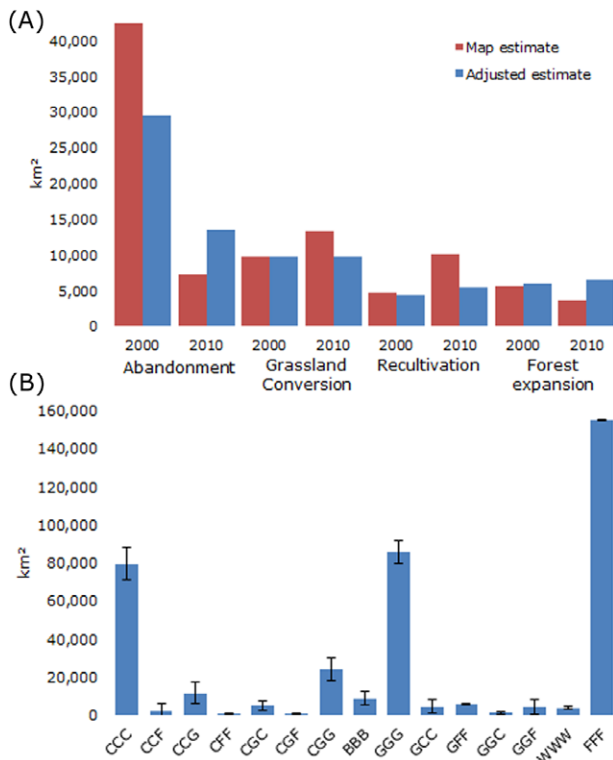


Figure 2. (A) Area estimates for cropland abandonment, grassland conversion, reclamation and forest expansion on non-forest land for the periods 1985–2000 and 2000–2010. Provided are the map estimates (i.e. aggregated classification results) and the error adjusted area estimate (derived using validation results). (B) Error adjusted area estimates for the change map results. Error bars indicate the 95% confidence interval around the adjusted area estimates.

Land changes showed strong differences on the national level. During the transition period, rates of cropland abandonment were highest in the Ukrainian Carpathians with 59%, followed by the Romanian (46%) and Polish (27%) Carpathians (table 3). Abandonment rates during the EU accession period dropped drastically in all countries but were highest in Ukraine (12%), followed by the Hungarian and Polish Carpathians. The highest rates of grassland conversion occurred between 2000 and 2010 in the Ukrainian, Romanian and Hungarian parts of the study region. The most extensive reclamation during the EU accession period occurred in Romania and Ukraine with 28% and 19% of formerly abandoned cropland being brought back into production, respectively (table 3). The highest rates of forest expansion on non-forest land occurred in the Hungarian Carpathians, while the greatest extent of forest expansion occurred in the Romanian Carpathians between 1985 and 2000.

Aggregating land change to the level of administrative units revealed distinct spatial patterns (figure 4). The highest rates of abandonment (~90%) were found in the mountain areas in Ukraine during the transition period. Comparably high abandonment rates were only found in parts of the Polish Carpathians. In several Romanian counties abandonment rates above 70% occurred during the transition period. During the

EU accession period abandonment rates were generally much lower, the highest rates occurred in the border region between Ukraine and Hungary as well as in northernmost part of the Ukrainian Carpathian foreland. Grassland conversion rates increased in several areas during the EU accession period, especially in the Ukrainian Carpathian foreland and Western Romania. High reclamation rates during the EU accession period concentrated on the Romanian Carpathian forelands, Western Hungary and in the forelands of the Polish and Ukrainian Carpathians. Finally, areas where forests expanded onto non-forest land were abundant throughout the study region during the transition period but the highest rates were found in North Eastern Hungary during the EU accession period (62% of the 1985 forest area).

The comparison of abandonment rates at administrative levels with agro-environmental suitability revealed predominantly negative correlations, i.e., higher suitability was associated with lower abandonment rates (figures 5(A) and (B)). This was most pronounced during the transition period, for example, in the Czech part of the study region (R^2 of -0.68 in 2000) but also in Romania, Slovakia and Ukraine (each around -0.5). Abandonment rates during the EU accession period were considerably lower than during the earlier period and in most cases less correlated. In Hungary, no pronounced correlations between abandonment and agro-ecological suitability were found. Between 2000 and 2010, abandonment rates in Ukraine tended to be higher in areas with greater crop suitability. As expected, reclamation predominantly occurred in more suitable areas (figures 5(C) and (D)). The overall highest correlations between reclamation rates and agro-environmental suitability were found in Ukraine and Romania during the EU accession period.

After adjusting our error estimates for class proportions, the validation suggested an overall high reliability with 90% overall accuracy despite the challenging class catalog (table 4). Most stable classes were mapped with user's and producer's accuracies of $>80\%$. The best performing change class was grassland–forest conversions (G–F–F). Cropland–grassland conversion classes achieved high accuracies and conversion detected during the transition period achieved 86% producer's accuracy but a lower user's accuracy (65%).

4. Discussion

We provide the first assessment of recent agricultural land change over the entire Carpathians at 30 m spatial detail. Our rates compare well to previous case studies in the region. For example, Kuemmerle *et al* (2009) detected 21% of abandoned cropland between 1990 and 2000. Our results suggest a somewhat higher abandonment rate of 29%. Likely reasons explaining these moderate differences are discrepancies in the abandonment definitions (the former study focused on cropland–grassland conversions while our study also considers cropland–forest conversions). Baumann *et al* (2011) assessed 46% of post-socialist farmland abandonment in the Ukrainian Carpathians (but for a smaller area) between 1986

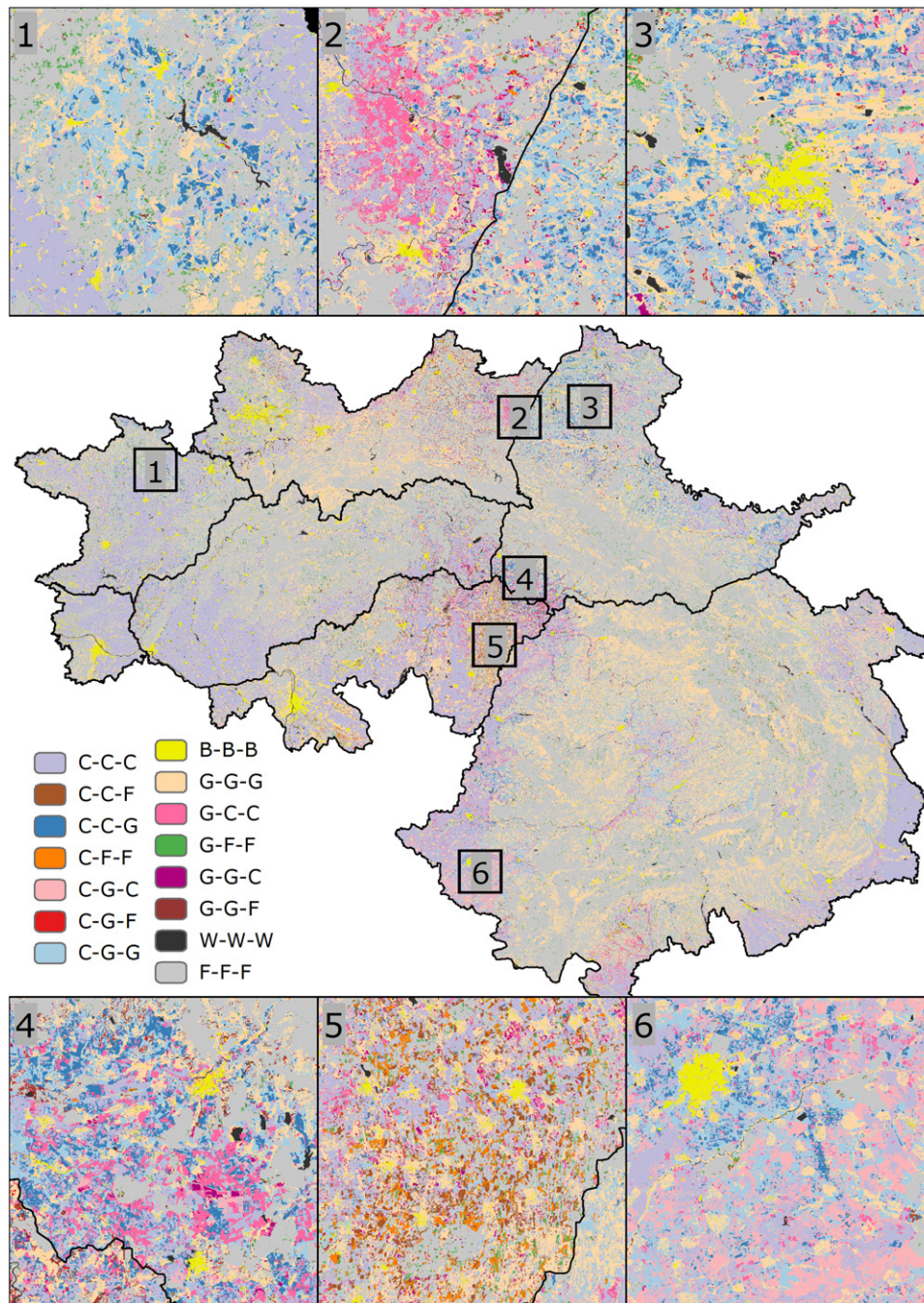


Figure 3. (Center) Change map derived from image composites and variance metrics. Classes relate to the land use/land cover during the respective reference year. Class acronyms: C = cropland, B = built-up, F = forest, G = grassland, W = water. Six representative close-up frames are provided for relevant process regimes (top and bottom): (1) cropland–grassland conversion in the Czech Republic; (2) contrasting land change on the Polish–Ukrainian border; (3) cropland changes in Ukraine; (4) change dynamics in the Ukrainian–Hungarian border region; (5) widespread forest expansion in Eastern Hungary; (6) cropland–grassland conversions and extensive recultivation in Romania. Map scale for all close-up frames is 1:750 000.

and 2008, which is about 12% below our estimate. Moreover, our abandonment rates are highest in the mountainous districts, while Baumann *et al* (2011) found the highest rates to occur in the plains. The differences in spatial patterns likely result from different methodological approaches for change detection. Moreover, we used three observations per time step and therefore are more likely to capture land management (e.g. plowing, harvesting) compared to Baumann

et al (2011) who used two images to characterize the 1980s. Regarding grassland conversion, a case study conducted in the Carpathians forelands in Hungary (Biró *et al* 2013) based on military survey maps assessed an annual conversion rate of 1.3% between 1988 and 1999 and a lower rate (0.35%) for the period from 1999 to 2010. While the first rate agrees very well with our current assessment of grassland conversion rates in the Hungarian part of the study region, our results do not

Table 3. Change processes summarized for the countries in the Carpathian study region as total area (km²) and as percentage. Country acronyms are: AU = Austria, CZ = Czech Republic, HU = Hungary, PL = Poland, RO = Romania, SK = Slovakia, UA = Ukraine. Percentages relate to the total country cropland area in 1985 for the abandonment rates and to the 1985 grassland area for the grassland conversion rates. Note that the rate for 'Recultivation 2010' is relative to the 'Abandonment 2000' areas, while the rate for 'Recultivation 2000' is calculated relative to the 1985 grassland areas. Forest expansion rates are calculated relative to the 1985 forest area in a given country (see the text for details).

	AU		CZ		HU		PL		RO		SK		UA		Total (km ²)
	(km ²)	(%)	(km ²)	(%)	(km ²)	(%)	(km ²)	(%)	(km ²)	(%)	(km ²)	(%)	(km ²)	(%)	
Abandonment 2000	243	5.7	1606	13.7	2170	13.3	3044	27.3	22605	45.8	2132	13.1	10599	58.9	42399
Abandonment 2010	60	1.4	662	5.6	1104	6.8	727	6.5	1603	3.2	894	5.5	2089	11.6	7138
Grassland conversion 2000	26	3.9	393	10.5	1365	13.8	845	6.1	4460	9.4	895	10.8	1256	9.7	9240
Grassland conversion 2010	49	7.3	158	4.2	1334	13.5	1375	9.9	6984	14.7	804	9.7	2433	18.8	13137
Recultivation 2000	2	0.3	87	2.3	977	9.9	475	3.4	2169	4.6	407	4.9	571	4.4	4688
Recultivation 2010	37	15.0	92	5.7	692	31.9	607	19.9	6209	27.5	412	19.3	1984	18.7	10032
Forest expansion 2000	29	1.6	318	3.3	804	11.5	461	2.5	2369	3.4	508	2.2	767	3.1	5257
Forest expansion 2010	13	0.7	71	0.7	1014	14.5	774	4.1	784	1.1	393	1.7	452	1.8	3501

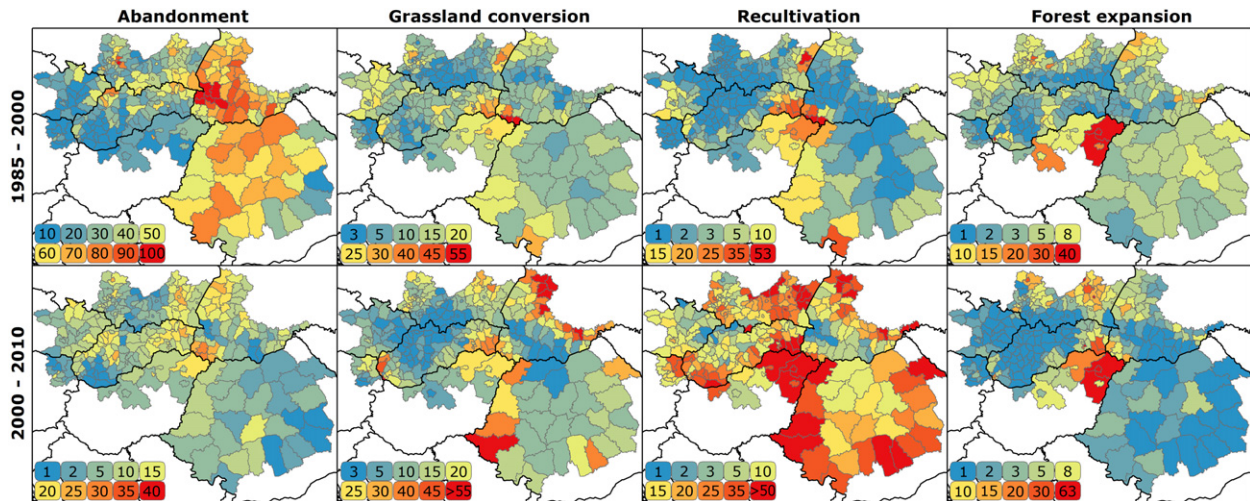


Figure 4. Process maps showing rates of cropland abandonment, grassland conversion, recultivation and forest expansion summarized to the level of administrative units (NUTS3 for Romania, Hungary and Austria; district level for Poland, Ukraine, Slovakia and the Czech Republic). The top row shows the rates for the transition period (1985–2000) the bottom row provides rates for the EU accession period (2000–2010). Note: different color table scaling for the two periods of cropland abandonment rates.

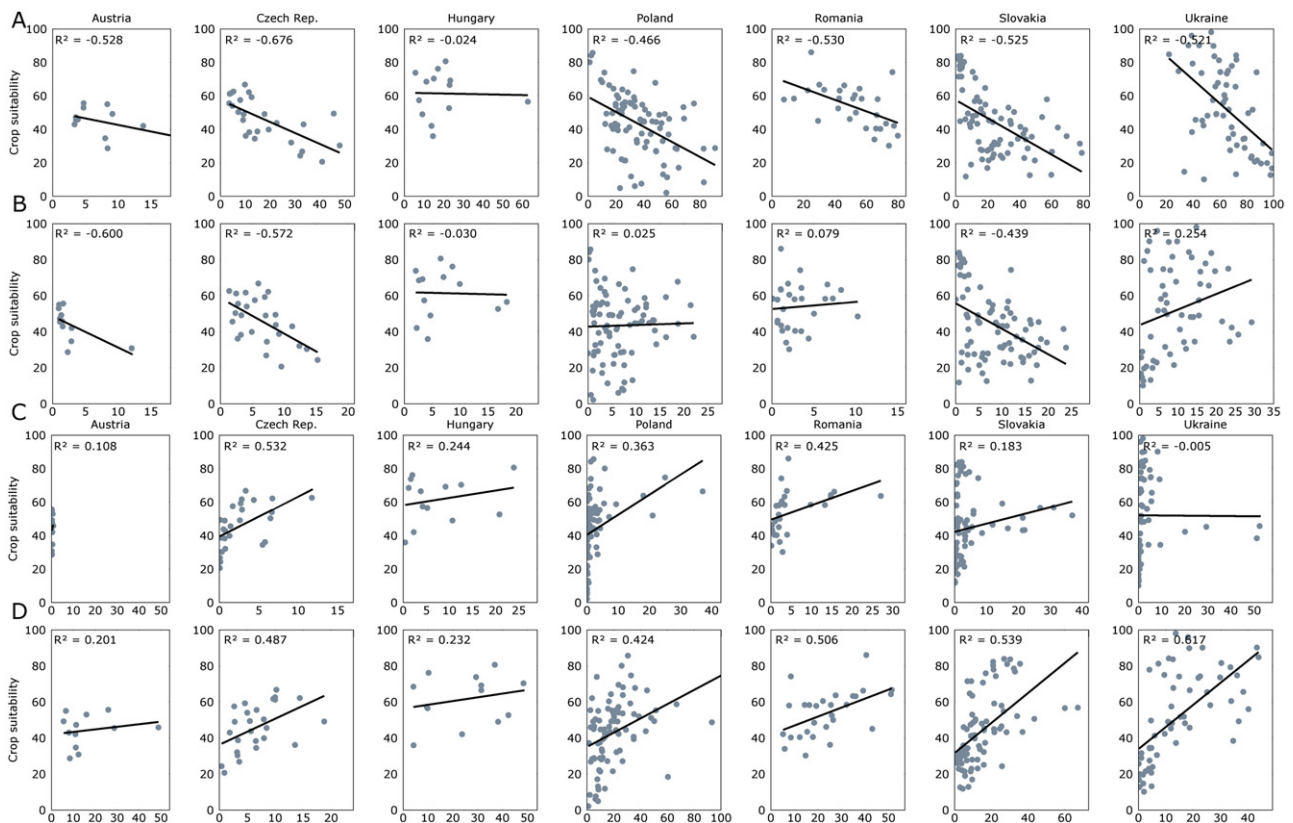


Figure 5. Comparison of the average crop suitability index (Y axis) and cropland abandonment rates (X axis) aggregated to administrative units, provided for (A) the transition period (1985–2000) and for (B) the EU accession period (2000–2010). Comparison of the average crop suitability index (Y axis) and recultivation rates (X axis) provided for (C) the transition period and for (D) the EU accession period.

suggest a large change in conversion rates for recent years (table 3).

Our change map had a relatively high accuracy despite complex change classes. This underlines the value of the Landsat archive and of the compositing approach, which allow assessing unprecedented detail of change patterns with

satellite data at regional scales. However, a few sources of uncertainty remain. Generally, our approach works very well as long as the landscape elements (e.g. agricultural fields) provide sufficient spectral contrast in the different seasonal composites. But many agricultural areas underwent substantial structural changes that led to the fragmentation of

Table 4. Validation results providing the confusion matrix as well as overall, user's and producer's accuracy for the change map derived from the analysis of the nine seasonal composites and spectral variance metrics. Columns show the reference samples while rows provide the classification results. The producer's accuracy relates to the number of reference samples correctly identified against all available reference points for that class, while the user's accuracy relates to the number of correctly classified samples against all samples classified as that class. (Note: the producer's accuracy was obtained from the area adjusted error assessment.)

Classification	Reference														User's accuracy (%)		
	90.29%	CCC	CCF	CCG	CFF	CGC	CGF	CGG	BBB	GGG	GCC	GFF	GGC	GGF		WWW	FFF
Overall accuracy																	
CCC	39	1	2	—	—	—	—	1	—	—	1	—	—	—	—	—	88.64
CCF	3	20	—	4	—	—	—	—	—	—	—	1	—	—	—	—	54.05
CCG	7	—	26	—	—	—	5	—	—	3	1	—	—	—	—	—	61.90
CFF	—	—	—	23	—	—	2	—	—	3	—	12	—	—	—	—	50.00
CGC	19	—	—	—	13	—	1	—	—	3	—	—	1	—	—	—	34.21
CGF	—	2	—	2	—	16	2	—	—	4	—	3	—	7	—	—	44.44
CGG	5	—	5	—	2	—	30	—	—	4	—	—	—	—	—	—	65.22
BBB	—	—	—	—	—	—	1	—	41	3	—	—	—	—	2	—	87.23
GGG	—	—	—	—	—	—	1	—	—	43	—	—	—	1	—	—	95.56
GCC	11	—	2	—	—	—	2	1	—	3	20	—	1	—	—	—	50.00
GFF	—	—	—	—	—	—	—	—	—	—	—	48	—	—	1	—	96.00
GGC	3	—	—	—	—	—	—	—	—	14	2	—	20	—	—	—	51.28
GGF	—	—	1	—	—	—	1	—	—	2	—	8	—	32	—	—	72.73
WWW	—	—	—	—	—	—	—	—	—	—	—	—	—	—	46	—	100.00
FFF	—	—	—	—	—	—	—	—	—	—	—	—	—	—	49	—	100.00
Producer's accuracy (%)	86.75	10.50	36.58	78.01	69.58	86.22	85.56	77.93	93.75	54.34	87.48	55.71	41.25	82.62	99.94		

large collectively managed cropland plots, accompanied by a diversification of ownership and crop types within small areas. If a large cropland plot in 1985 experienced such fragmentation, the reflectance signal subsequently becomes a mixture of different components (e.g. soil, grass, crop), which compromises accurate detection (Ozdogan and Woodcock 2006). In these cases, our approach may have detected some of the decrease in spectral contrast as, for example, a change from cropland to grassland.

Overall though, our results corroborate the extensive land changes that occurred throughout the Carpathians between 1985 and 2010. Cropland abandonment was most widespread and 24% of the 1985 cropland and a further 11% of the 2000 cropland were no longer cultivated in 2000 and 2010, respectively. According to our expectations, agro-ecological suitability showed strong linkages with agricultural abandonment and recultivation. The highest abandonment rates generally occurred on lands that are marginally suited for farming and in the years immediately following the collapse of socialism, as observed elsewhere in Eastern Europe (Mueller and Munroe 2008, Mueller *et al* 2009, Prishchepov *et al* 2013). This suggests that post-socialist cropland abandonment in the Carpathians was strongly contingent on socialist farming strategies that subsidized substantial expansion of agricultural land use in order to increase outputs. As a result, most cultivable land was used for farming, including marginal areas. The collapse of socialism led to a massive drop in state support for agriculture as well as adjustments in input and output prices (Rozelle and Swinnen 2004). Moreover, land reforms led to the privatization and restitution of agricultural land resulting in a large number of small fragmented farms particularly in mountainous regions (Lerman *et al* 2004). Combined, these changes grossly affected agricultural production and caused significant amounts of cropland abandonment throughout the Carpathians.

Interestingly, the rates of cropland abandonment tend to be higher in countries of the former Soviet Union than in Eastern Europe, similar to results from other studies. For example, cropland abandonment rates of up to 50% were found in the Baltics and in the Russian enclave of Kaliningrad (Nikodemus *et al* 2005), but abandonment was much lower in neighboring Poland (Prishchepov *et al* 2012a) and in the non-Soviet countries in our study region (all except Ukraine). Arguably, more determined support for agriculture during socialism in the former Soviet Union, including the nationalization of land, contributed to the extensive adaptation of land use after the collapse of socialism (Prishchepov *et al* 2013).

Recultivation concentrated in areas favorable for farming (as forecasted by Lakes *et al* (2009) for Southern Romania). Increasing profit opportunities in agriculture due to rising commodity prices since 2007 are likely the key underlying driver for the recultivation of cropland. Possibly, support through EU CAP contributed additional incentives for recent recultivation. In the coming years, expected further increases in agricultural commodity prices will likely provide additional incentives for recultivation of areas suitable for agricultural

production. Furthermore, future biofuel production and the increasing demand for food, feed and fiber will compete with the requirement for nature protection in pristine landscapes like many parts of the Carpathian ecoregion. However, most future changes in land systems may not manifest in categorical changes of land use, as we have assessed, but in land use modifications (e.g. growing capital inputs in agriculture (Kuemmerle *et al* 2013)), which still pose considerable challenges for remote sensing based monitoring approaches (Lambin and Linderman 2006). Because crop yields are still modest in many areas of the Carpathian ecoregion, increasing land use intensity may translate into considerable production gains on currently used lands (Kuemmerle *et al* 2013).

Our results underline the value of the open Landsat archive for retrospective land change assessments and specifically the potential of seasonally tuned compositing approaches for mapping agricultural land change. This allowed assessing the major agricultural land change processes in an Eastern European setting, including cropland abandonment and recultivation. Both processes need to be equally considered here, as abandonment today only rarely represents a finite state of land change (Munroe *et al* 2013).

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References

- Baumann M, Kuemmerle T, Elbakidze M, Ozdogan M, Radeloff V C, Keuler N S, Prishchepov A V, Kruhlov I and Hostert P 2011 Patterns and drivers of post-socialist farmland abandonment in Western Ukraine *Land Use Policy* **28** 552–62
- Biró M, Czúcz B, Horváth F, Révész A, Csatári B and Molnár Z 2013 Drivers of grassland loss in Hungary during the post-socialist transformation (1987–1999) *Landsc. Ecol.* **28** 789–803 (in English)
- Card D H 1982 Using known map category marginal frequencies to improve estimates of thematic map accuracy *Photogramm. Eng. Remote Sens.* **48** 431–9
- CERI 2001 The status of the Carpathians *WWF—Danube-Carpathian Programme* (Vienna: Carpathian Ecoregion Initiative)
- Csaki C 1990 Agricultural changes in Eastern-Europe at the beginning of the 1990s *Am. J. Agric. Econ.* **72** 1233–42
- Deininger K 2011 Challenges posed by the new wave of farmland investment *J. Peasant Stud.* **38** 217–47
- Foley J A *et al* 2005 Global consequences of land use *Science* **309** 570–4
- Foley J A *et al* 2011 Solutions for a cultivated planet *Nature* **478** 337–42
- Google 2013 *StreetView* [online] available from: <http://maps.google.com/help/maps/streetview/> [accessed 11 June 2013]

- Griffiths P, Kuemmerle T, Baumann M, Radeloff V C, Abrudan I V, Lieskovský J, Muntenau C, Ostapowicz K and Hostert P 2013a Forest disturbances, forest recovery, and changes in forest types across the Carpathian ecoregion from 1985 to 2010 based on Landsat image composites *Remote Sens. Environ.* at press doi:10.1016/j.rse.2013.04.022
- Griffiths P, van der Linden S, Kuemmerle T and Hostert P 2013b A pixel-based Landsat compositing algorithm for large area land cover mapping *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **6** 2088–101
- Henebry G M 2009 Global change—carbon in idle croplands *Nature* **457** 1089–90
- Hostert P, Kuemmerle T, Prishchepov A, Sieber A, Lambin E F and Radeloff V C 2011 Rapid land use change after socio-economic disturbances: the collapse of the Soviet Union versus Chernobyl *Environ. Res. Lett.* **6** 045201
- IIASA, & FAO 2012 *Global Agro-ecological Zones (GAEZ v3.0)* (Laxenburg: International Institute for Applied Systems Analysis) IIASA (Ed.)
- Ioffe G, Nefedova T and Kirsten D B 2012 Land abandonment in Russia *Eurasian Geogr. Econom.* **53** 527–49
- Kozak J 2010 Forest cover changes and their drivers in the Polish Carpathian Mountains since 1800 *Reforestation Landscapes Linking Pattern and Process* ed H Nagendra and J Southworth (Berlin: Springer) pp 253–73
- Kuemmerle T, Muller D, Griffiths P and Rusu M 2009 Land use change in Southern Romania after the collapse of socialism *Reg. Environ. Change* **9** 1–12
- Kuemmerle T et al 2013 Challenges and opportunities in mapping land use intensity globally *Curr. Opin. Environ. Sustain.* **5** 484–93
- Lakes T, Mueller D and Krueger C 2009 Cropland change in Southern Romania: a comparison of logistic regressions and artificial neural networks *Landsc. Ecol.* **24** 1195–206
- Lambin E F and Linderman M 2006 Time series of remote sensing data for land change science *IEEE Trans. Geosci. Remote Sens.* **44** 1926–8
- Lerman Z 1999 Land reform and farm restructuring: what has been accomplished to date? *Am. Econ. Rev.* **89** 271–5
- Lerman Z, Csaki C and Feder G 2002 Land policies and evolving farm structures in transition countries *Policy Research Working Paper 2794* (Washington, DC: World Bank Development Research Group)
- Lerman Z, Csaki C and Feder G 2004 Evolving farm structures and land-use patterns in former socialist countries *Q. J. Int. Agric.* **43** 309–35
- MacDonald D, Crabtree J R, Wiesinger G, Dax T, Stamou N, Fleury P, Lazpita J G and Gibon A 2000 Agricultural abandonment in mountain areas of Europe: environmental consequences and policy response *J. Environ. Manag.* **59** 47–69
- Mueller D, Kuemmerle T, Rusu M and Griffiths P 2009 Lost in transition: determinants of post-socialist cropland abandonment in Romania *J. Land Use Sci.* **4** 109–29
- Mueller D and Munroe D K 2008 Changing rural landscapes in Albania: cropland abandonment and forest clearing in the postsocialist transition *Ann. Assoc. Am. Geogr.* **98** 855–76
- Munroe D K, van Berkel D B, Verburg P H and Olson J L 2013 Alternative trajectories of land abandonment: causes, consequences and research challenges *Curr. Opin. Environ. Sustain.* **5** 471–6
- Nikodemus O, Bell S, Grine I and Liepins I 2005 The impact of economic, social and political factors on the landscape structure of the Vidzeme Uplands in Latvia *Landsc. Urban Plann.* **70** 57–67
- Olofsson P, Foody G M, Stehman S V and Woodcock C 2013 Making better use of accuracy data in land change studies: estimating accuracy and area and quantifying uncertainty using stratified estimation *Remote Sens. Environ.* **129** 122–31
- Ozdogan M and Woodcock C E 2006 Resolution dependent errors in remote sensing of cultivated areas *Remote Sens. Environ.* **103** 203–17
- Prishchepov A V, Mueller D, Dubinin M, Baumann M and Radeloff V C 2013 Determinants of agricultural land abandonment in post-Soviet European Russia *Land Use Policy* **30** 873–84
- Prishchepov A V, Radeloff V C, Baumann M, Kuemmerle T and Mueller D 2012a Effects of institutional changes on land use: agricultural land abandonment during the transition from state-command to market-driven economies in post-Soviet Eastern Europe *Environ. Res. Lett.* **7** 024021
- Prishchepov A V, Radeloff V C, Dubinin M and Alcantara C 2012b The effect of Landsat ETM/ETM plus image acquisition dates on the detection of agricultural land abandonment in Eastern Europe *Remote Sens. Environ.* **126** 195–209
- Ramankutty N, Heller E and Rhemtulla J 2010 Prevailing myths about agricultural abandonment and forest regrowth in the United States *Ann. Assoc. Am. Geogr.* **100** 502–12
- Rozelle S and Swinnen J F M 2004 Success and failure of reform: insights from the transition of agriculture *J. Econ. Lit.* **42** 404–56
- Sala O E et al 2000 Biodiversity—global biodiversity scenarios for the year 2100 *Science* **287** 1770–4
- Sarris A H, Doucha T and Mathijs E 1999 Agricultural restructuring in central and eastern Europe: implications for competitiveness and rural development *Eur. Rev. Agric. Econ.* **26** 305–29
- Schierhorn F, Müller D, Prishchepov A and Balmann A 2012 Grain potentials on abandoned cropland in European Russia *Ann. World Bank Conf. on Land and Poverty* (Washington, DC: World Bank)
- Taff G N, Mueller D, Kuemmerle T, Ozdeneral E and Walsh S 2010 Reforestation in Central and Eastern Europe after the breakdown of socialism *Reforestation Landscapes: Linking Pattern and Process* ed H Nagendra and J Southworth (Eindhoven: Springer) pp 121–47
- Tilman D, Cassman K G, Matson P A, Naylor R and Polasky S 2002 Agricultural sustainability and intensive production practices *Nature* **418** 671–7
- Turnock D 2002 Ecoregion-based conservation in the Carpathians and the land-use implications *Land Use Policy* **19** 47–63
- van der Werf G R, Morton D C, DeFries R S, Olivier J G J, Kasibhatla P S, Jackson R B, Collatz G J and Randerson J T 2009 CO₂ emissions from forest loss *Nature Geosci.* **2** 737–8
- Visser O and Spoor M 2011 Land grabbing in post-Soviet Eurasia: the world's largest agricultural land reserves at stake *J. Peasant Stud.* **38** 299–323
- Vuichard N, Ciais P, Beletti L, Smith P and Valentini R 2008 Carbon sequestration due to the abandonment of agriculture in the former USSR since 1990 *Glob. Biogeochem. Cycles* **22** GB4018
- Waske B, van der Linden S, Oldenburg C, Jakimow B, Rabe A and Hostert P 2012 ImageRF—a user-oriented implementation for remote sensing image analysis with random forests *Environ. Modelling Softw.* **35** 192–3
- Wulder M A, Masek J G, Cohen W B, Loveland T R and Woodcock C E 2012 Opening the archive: how free data has enabled the science and monitoring promise of Landsat *Remote Sens. Environ.* **122** 2–10 (in English)