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Cross-border Comparison of Post-socialist Farmland Abandonment in the Carpathians

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Abstract

Agricultural areas are declining in many areas of the world, often because socio-economic and political changes make agriculture less profitable. The transition from centralized to market-oriented economies in Eastern Europe and the former Soviet Union after 1989 represented major economic and political changes, yet the resulting rates and spatial pattern of post-socialist farmland abandonment remain largely unknown. Remote sensing offers unique opportunities to map farmland abandonment, but automated assessments are challenging because phenology and crop types often vary substantially. We developed a change detection method based on support vector machines (SVM) to map farmland abandonment in the border triangle of Poland, Slovakia, and Ukraine in the Carpathians from Landsat TM/ETM+ images from 1986, 1988, and 2000. Our SVM-based approach yielded an accurate change map (overall accuracy = 90.9%; kappa = 0.82), underpinning the potential of SVM to map complex land-use change processes such as farmland abandonment. Farmland abandonment was widespread in the study area (16.1% of the farmland used in socialist times), likely due to decreasing profitability of agriculture after 1989. We also found substantial differences in abandonment among the countries (13.9% in Poland, 20.7% in Slovakia, and 13.3% in Ukraine), and between previously collectivized farmland and farmland that remained private during socialism in Poland. These differences are likely due to differences in socialist land ownership patterns, post-socialist land reform strategies, and rural population density.

Key words: agricultural abandonment; cropland; forest transition; Carpathians; land use and land cover change; land reform; transition economies; change detection; support vector machines (SVM); remote sensing.

Introduction

Human pressure is decreasing in many rural areas in the world due to urbanization, industrialization, and declining populations (Rudel 1998). These demographic changes often result in farmland abandonment, especially where farming conditions are marginal (Baldock and others 1996; Ramankutty and others 2002; Lepers and others 2005). Abandoned farmlands may revert back to forests (Rudel and others 2005) and this offers unique opportunities to restore some services of natural ecosystems, such as soil stability (Tasser and others

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2003) and water quality (Hunsaker and Levine 1995). Forest expansion on former farmland may also allow forest biodiversity to recover (Bowen and others 2007), and may help mitigate climate change through increased carbon sequestration (Silver and others 2000; Grau and others 2004). Information about the rates and spatial pattern of abandoned farmland is thus important to assess its consequences for ecosystem services and biodiversity. Unfortunately, little is known about rates and spatial patterns of farmland abandonment, particularly outside Western Europe and North America.

Farmland abandonment is often triggered by changing socio-economics, institutions, and land management policies (Grau and others 2004; DLG 2005; Yeloff and van Geel 2007). The economic and political transitions that occurred in eastern Europe and the former Soviet Union after the fall of the Iron Curtain in 1989 is a prime example of this process. During socialism, all eastern European countries collectivized farmland—albeit at different rates—and intensified agricultural production (Turnock 1998; Lerman and others 2004). Agriculture was heavily subsidized and production was mainly targeted at socialist markets. The situation changed drastically after 1989. Prices were liberalized and old markets diminished. New markets became accessible (for example, the European Union), but there was also much stronger competition with foreign producers (Turnock 1998; Trzeciak-Duval 1999). Most eastern European countries carried out land reforms to restructure the farming sector, individualize land use, and privatize farmland (Swinnen and others 1997; Lerman and others 2004). However, former landowners were in many cases urban dwellers not interested in farming (Mathijs and Swinnen 1998; DLG 2005), and young people migrated to cities (Ioffe and others 2004; Palang and others 2006). Altogether, these processes resulted in widespread farmland abandonment across eastern Europe in the post-socialist period (Bicik and others 2001; Nikodemus and others 2005; Müller and Sikor 2006). The problem is that although general trends in farmland abandonment are acknowledged, detailed information on these trends is lacking and the consequences of farmland abandonment on eastern Europe's ecosystems remains poorly understood.

Quantifying farmland abandonment in eastern Europe is not easy, because detailed agricultural census data are lacking or of unknown accuracy (Peterson and Aunap 1998; Filer and Hanousek 2002; DLG 2005). Remotely sensed data from before and after 1989 exist, but have rarely been used to study post-socialist farmland abandonment. Visual assessment of a Landsat image and historic maps revealed patterns of both farmland abandonment and agricultural intensification in southeast Poland (Angelstam and others 2003). In Albania, a 7% cropland decline was found based on visual interpretation of Landsat images, and abandonment rates were highest in the first years of the transition (Müller and Sikor 2006; Müller and Munroe 2008). Aerial photo interpretation showed that 50% of the farmland used in socialist times had been abandoned in a Latvian study site by 1999 (Nikodemus and others 2005). Only one study used automated change detection to map farmland abandonment for larger areas. In an assessment of Estonia's farmland, a rule-based classification of Landsat Multispectral Scanner images revealed a 30% abandonment between 1990 and 1993 (Peterson and Aunap 1998).

The lack of automated assessments of farmland abandonment is not surprising, because most change detection methodologies are not well suited to detect changes in land cover classes that are not spectrally stable (Coppin and others 2004). In the case of agriculture, phenology and crop type variability may give false impressions of change, and multiple images for each time period are necessary to separate farmland in use from abandoned lands with high accuracy (Peterson and Aunap 1998; Oetter and others 2001; Kuemmerle and others 2006). Such multitemporal datasets can be analyzed by classifying all images simultaneously in a single change classification (Coppin and others 2004). Change classes, however, are frequently characterized by complex distributions (for example, multi-modal, non-normal) and many-to-one relationships (that is, different crop types prior to abandonment all revert to one land cover type). Classifiers that do not assume specific class distributions, such as artificial neural networks (Benediktsson and others 1990), or decision trees (Friedl and Brodley 1997), are most appropriate in such situations (Seto and Liu 2003). Recently developed support vector machines (SVM) classifiers have the additional advantage that they require only a relatively low number of training samples while performing equally well or better than other non-parametric approaches (Huang and others 2002; Foody and Mathur 2004; Pal and Mather 2005). However, despite their potential advantages, SVM have to our knowledge not yet been used for automated land-use change detection.

We developed an SVM-based method to map post-socialist farmland abandonment in eastern Europe based on Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) satellite images. We focused on a study region in the

Carpathian mountains, because of the region's exceptional ecological value as a biodiversity hotspot and Europe's largest temperate forest ecosystem (Webster and others 2001). Farmland abandonment and forest expansion provide threats and opportunities for the region's biodiversity and ecosystems. For example, forest regrowth increases habitat availability and connectivity for forest dwelling species (Bowen and others 2007), especially benefiting area-demanding top carnivores and herbivores that are still numerous in the Carpathians (Turnock 2002). Abandoned farmland could be afforested and the region may have considerable carbon sequestration potential (Nijnik and Van Kooten 2000). On the other hand, farmland abandonment threatens traditional cultural landscapes and their unique biodiversity (Cremene and others 2005; Baur and others 2006; Elbakidze and Angelstam 2007). Despite the widespread effects of post-socialist farmland abandonment on ecosystems and biodiversity in the Carpathians, little is known about abandonment rates and spatial patterns.

Studying farmland abandonment in the Carpathians may also help understand the role of socio-economics, policies, and institutions for land-use change. Such broad-scale factors are key for land-use decisions (GLP 2005; Lambin and Geist 2006) and determine the profitability of farming (Baldock and others 1996; MacDonald and others 2000). However, little is known about their relative importance, because these factors are usually constant over times, or change only gradually, and they are often fairly uniform within a given study area. The rapid political and economic transition in eastern Europe offers a unique "natural experiment" to study broad-scale determinants. Farmland abandonment may be among the largest land-use changes in the European Union in the future (Verburg and others 2006) and assessing farmland abandonment in post-socialist eastern Europe may reveal important insights into drivers of abandonment and its consequences for ecosystems. Studying rates and spatial patterns of farmland abandonment in border regions in the Carpathians is particularly interesting, because trans-boundary comparisons may reveal how differences in land management policies, land ownership, and institutional change affect abandonment (Kuemmerle and others 2006). However, to our knowledge, no study to date has compared rates and spatial patterns of post-socialist farmland abandonment among countries in eastern Europe.

In summary, this study served two overarching goals: first, to use SVM to map farmland abandonment in the Carpathian border region of Poland, Slovakia, and Ukraine based on Landsat TM and ETM+ satellite images; and second to compare farmland abandonment among countries to better understand how socio-economic and institutional change affects land-use change. Our specific objectives were:

(1) to develop a digital change detection approach based on multitemporal image classification using SVM;
(2) to quantify the extent, rates and spatial patterns of farmland abandonment for our study area between 1988 and 2000;
(3) to compare farmland abandonment rates and spatial patterns among the three countries Poland, Slovakia, and Ukraine, and at different elevations and slopes; and
(4) to relate differences in farmland abandonment to differences in land reforms and socio-economic conditions between the countries.

Study Area

Our study area was the border triangle of Poland, Slovakia, and Ukraine in the Carpathian mountains (Figure 1). We selected an area of 17,800 km^2 based on administrative boundaries, landscape features such as rivers and valleys, as well as the extent of one Landsat TM scene (path/row, 186/26). The region is characterized by mountainous terrain and altitudes vary from 200 to 1,480 m above sea level. Carpathian flysh (sandstone and shale) is the main bedrock component (Denisiuk and Stoyko 2000), but some andesite-basalts are found in the southwest of the study area (Herenchuk 1968). Dominating soils include cambisols and podzols in the mountainous regions; podzoluvisols, greysems, and gleysols in the plains; and fluvisols in alluvial plains.

Climate in the study area is moderately cool and humid. Average annual precipitation amounts to 1,100–1,200 mm, mean annual temperature is 5.9°C (at 300 m), and the growing season ranges from more than 270 days below 500 m altitude to less than 220 days above 800 m (Zarzycki and Glowacinski 1970; Augustyn 2004). The potential natural vegetation can be stratified into three main altitudinal zones: a foothill zone (<600 m) where broadleaved species dominate, particularly beech (*Fagus sylvatica*) and oak (*Quercus robur, Quercus petraea*); a montane zone (600–1,100 m) with beech, silver fir (*Abies alba*), sycamore (*Acer pseudoplatanus*), and alder (*Alnus incana*); and alpine meadows with dwarfed beech (*F. sylvatica*) above the treeline (1,100–1,200 m, Denisiuk and Stoyko 2000). Farming conditions vary in the study area and are relatively marginal in the montane zone (Dolishniy

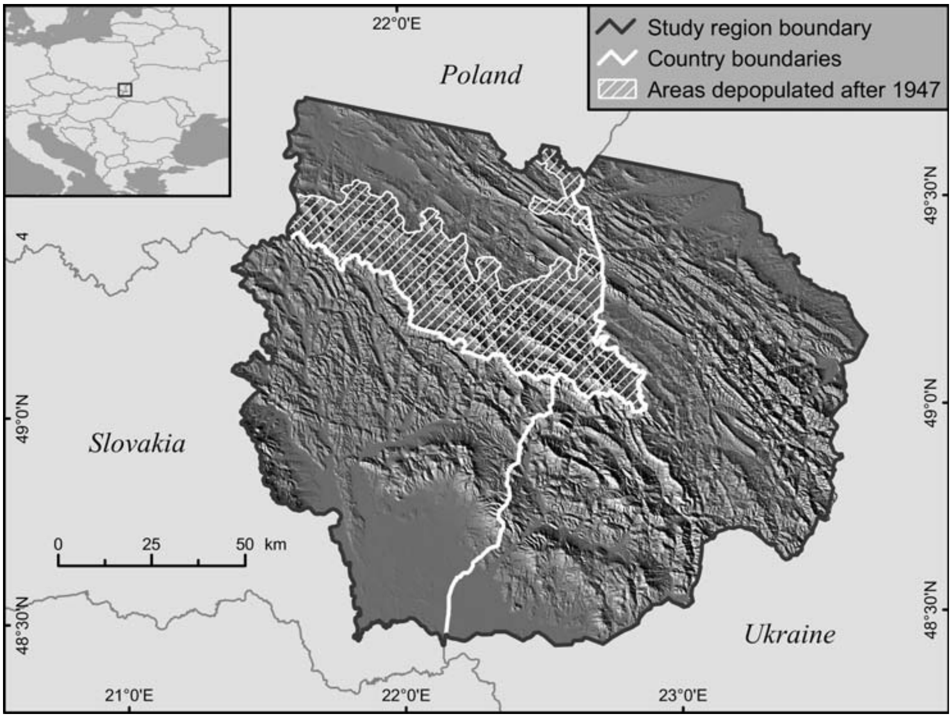

Figure 1. The border triangle of Poland, Slovakia, and Ukraine in the Carpathians. Farmland in the hatched region in Poland was mostly collectivized during socialism.

1988; Turnock 2002). Dairy products, cattle, flax, oat, and potatoes are the main agricultural products here. In the foothill zone (including the plains in the north and south of the study area), farming conditions are more favorable, allowing for cultivation of a diversity of crops, including grain (for example, winter wheat, buckwheat), oil crops (for example, rape, sunflowers), sugar beets, corn, and potatoes. Milk, cheese, and meat production are also significant agricultural activities in the foothill zone.

The region was part of the Austro-Hungarian Empire for a period of approximately 150 years until 1918. During that period, land use intensified markedly, mainly due to technological advancements and population growth (Turnock 2002; Augustyn 2004). The region's forests were largely converted to farmland, particularly in mountain valleys and in the densely settled foothills and plains (Turnock 2002; Kozak and others 2007), whereas forests remained dominant in the montane zone (>60%, Kuemmerle and others 2006). During socialist rule, great efforts were made to intensify agriculture in all three countries. However, land ownership and land management differed among the Polish, Slovak, and Ukrainian region of the study area. In Poland, most farmland was never collectivized (Lerman and others 2004). Yet, many areas in the study area were owned and managed by the state, because these lands had been depopulated following border changes between the Soviet Union and Poland in 1947 (Figure 1), and large-scale farming enterprises were established in these areas (Turnock 2002; Augustyn 2004). In Slovakia, almost all farmland was collectivized and managed in state-controlled cooperatives, but landowners retained property rights to their fields (Lerman 1999; Csaki and others 2003). This was different in Ukraine, where all land was owned by the state and managed in large-scale agricultural enterprises (collectives or state farms). After the demise of the Soviet Union, Slovakia, Poland, and Ukraine launched land reforms to privatize farmland and to individualize land use (Mathijs and Swinnen 1998). The land reform strategy largely depended on the land ownership pattern in socialist times, and thus differed among the three countries. Poland auctioned formerly state-owned farmland, Slovakia restituted farmland to previous owners, and Ukraine distributed farmland among the workers of the agricultural enterprises (Lerman and others 2004). This makes the study area particularly well suited for comparing rates and spatial patterns of farmland abandonment among countries, and for exploring how differences in land ownership and land reforms relate to differences in farmland abandonment.

Datasets Used and Methods

Datasets Used

To map farmland abandonment in the study area, we used Landsat TM and ETM+ images (path/row, 186/26) from the last socialist years (2nd October

1986, 27th July 1988) and from 2000 (10th June, 20th August). We used two images per time period because initial tests suggested better separability of active and abandoned farmland compared to only using a single image (Kuemmerle and others 2006). Thermal bands were not retained due to their coarser resolution. All images were geometrically rectified, corrected for relief displacement using the Space Shuttle Radar Topography Mission (Slater and others 2006) digital elevation model, and co-registered to the Universal Transverse Mercator coordinate system (see Kuemmerle and others 2006). Removing atmospheric influence and illumination variations due to topography improves change detection accuracy (Song and others 2001) and we transferred all images to surface reflectance using a 5S radiative transfer model that incorporated a terrain-dependent illumination correction (Hill and Mehl 2003). All forests (in 1988), water bodies, and built-up areas were masked out based on earlier classifications (Kuemmerle and others 2006, 2007). The 1988 image contained some clouds (<0.01% of the study area), which we excluded from the analysis. We also masked areas above 1,000 m altitude, because farming is not carried out at these altitudes in the study area. In total, 56% of the study area was masked. The four masked images were stacked into one multitemporal dataset.

Ground-truth points for training and validation purposes were collected in the field and from high-resolution satellite images. Field mapping was carried out in the summer of 2004, spring of 2005, and spring of 2006 using non-differential Global Positioning System receivers. We considered only locally homogeneous areas (that is, 90×90 m^2 or 3×3 Landsat pixels) to rule out erroneous assignments due to positional uncertainty. To cover wide areas, we photo-documented some sites (for example, remote valleys) from viewpoints (for example, mountain ridges). Viewpoints were georeferenced, and the view angle and distance of the area depicted in the photo were registered. Thus, we were able to digitize ground-truth points on screen using topographic maps, high-resolution images, and the Landsat images as reference maps (Kuemmerle and others 2006, 2007). We also digitized additional ground truth points from 16 Quickbird images available in Google Earth™ (http://earth.google.com) for the Slovak and Ukrainian region of our study area, and we obtained three IKONOS images for the Polish region. All high-resolution images were acquired between 2003 and 2005 and had a spatial resolution of 1 m or finer. Ground-truth points were digitized on screen using the same criteria that were applied in the field and photo mapping.

We categorized all ground-truth plots into the classes 'unchanged areas,' 'fallow land,' and 'reforestation.' A field was considered fallow land if crops or managed grasslands (that is, cut or intensively grazed) had been replaced by unmanaged grasslands or successional shrubland. Reforestation denotes the natural or artificial reestablishment of forest cover in areas that had been converted to some other land use (EEA 2007). Thus, the class 'reforestation' included all areas used for farming in 1986 and 1988 (crops and managed grassland) that had a closed forest canopy by 2000. Abandoned farmland was defined as the sum of fallow land and reforestation. Due to the time span among Landsat image acquisition (1986–2000), field campaigns (2004–2006), and high-resolution imagery (2003–2005), we determined the approximate time of abandonment based on the estimated age of successional shrubs, questioning of local farmers, and visual assessment of the Landsat images. We labeled all locations where abandonment occurred after 2000 as unchanged. Field visits and visual assessment of the Landsat images suggest no conversions from forests or fallow land to cropland between 1986 and 2000. In total, we gathered 1,652 ground-truth points (481 based on ground visits and 1,171 from high-resolution remote sensing data).

Mapping Farmland Abandonment Using SVM Change Detection

Image classifications with SVM discriminate classes by fitting separating hyperplanes in the feature space based on training samples (Huang and others 2002; Foody and Mathur 2004). The hyperplane that best discriminates two classes is constructed by maximizing the distance between the hyperplane and the closest training samples—the so-called support vectors (Burges 1998; Pal and Mather 2006). Thus, SVMs use only training samples that characterize class boundaries and perform well with a relatively small number of training samples (Foody and Mathur 2006). For classes that are linearly not separable, a kernel function is used to transform training data into a higher dimensional space where a separating linear hyperplane can be fitted (Huang and others 2002; Pal and Mather 2005). This allows SVM to handle complex class distributions and SVM should therefore be well suited for separating classes in a multitemporal feature space. SVMs were originally developed for binary classification problems and two main strategies exist to extend the approach to multi-class problems (Huang and others 2002; Foody and Mathur 2004). The one-against-one strategy applies a set of individual classifiers to all possible class pairs and performs a majority vote to assign the winning class. The one-against-all strategy uses binary classifiers to separate each class from the rest and the final class label is determined by the maximum decision value, that is, the distance to the hyperplane (Huang and others 2002). Both strategies result in comparable classifications (Melgani and Bruzzone 2004).

We used a one-against-all strategy to fit SVM for mapping farmland abandonment in our study area, because it is the simpler and more commonly used strategy. Two-thirds of the ground-truth points (1,079 points) were randomly selected to be used in the training phase of the SVM. Successful SVM training requires inclusion of pixels at the class boundaries (Foody and Mathur 2006). To account for this, we established buffer zones with a 45 m (1.5 Landsat TM/ETM+ pixels) radius around the 1,079 training point locations and included all pixels with more than 50% area inside these buffers. Such a sampling strategy is efficient for selecting a sufficiently large training set while ensuring the inclusion of boundary pixels (that is, mixed pixels) that are important for delineating the separating hyperplanes (Foody and Mathur 2006). In total, we used 7,789 training pixels based on 1,079 ground truth locations: 5,100 pixels (704 points) for unchanged areas, 2,332 (326) for fallow land, and 357 (49) for afforested areas.

A Gaussian kernel function was used to construct the three hyperplanes to separate each of the change classes from all other training samples (one-against-all). The Gaussian kernel function requires two parameters: γ controlling the kernel width, and C determining the magnitude of penalty given to misclassified training samples. To find the best parameter set for each hyperplane and to avoid overfitting, we systematically tested a wide range of γ and C combinations and compared them based on cross-validation errors. Once optimal parameters were found for all binary problems, we used the resulting SVM to classify the multitemporal stack of four images and to derive a map of farmland abandonment for our study area. To eliminate isolated pixels likely representing misclassifications (that is, salt-and-pepper effect common to pixel-based classifications), we applied a 3×3 majority filter and assigned all patches smaller than 0.63 ha (7 pixels) to the surrounding dominant class. The accuracy of the farmland abandonment map was based on the remaining 573 ground-truth samples not used in the training of the SVM. We calculated an error matrix, overall and class-specific classification accuracies, and the kappa value (Foody 2002). SVM training (including kernel function parameter estimation), classification, and accuracy assessment were carried out with imageSVM (Janz and others 2007).

Cross-border Comparison of Farmland Abandonment

Based on the change map, we summarized the area of farmland abandonment (that is, sum of fallow farmland and reforestation) for each country. To calculate abandonment rates, we divided the sum of fallow land and afforested areas by the total unmasked area. We also calculated reforestation rates separately for each country. To assess whether farmland abandonment varied along the altitudinal gradient in the study area, the DEM was categorized into 50-m wide elevation classes and we calculated fallow land and reforestation rates for each country. We also calculated the slope from the DEM (in percent; 100% = 45°) and summarized abandonment rates for 20 slope classes defined using 5% breaks. In addition, we separated farmland in Poland that had been collectivized and farmland that was privately owned and managed in socialist times (Figure 1). To assess whether farmland abandonment differed, we calculated abandonment and reforestation rates for each farmland type. We determined the boundary between state-owned and private farmland under consideration of topographic maps that included the locations of former state farms (scale: 1:50,000) and in collaboration with a local historian (M. Augustyn, personal communication).

To assess the spatial pattern of farmland abandonment, we calculated landscape indices (O'Neill and others 1988; Turner and Gardner 1991). We derived mean patch size, area-weighted mean patch size, and patch density for the classes fallow land and reforestation. The area-weighted mean patch size equals the sum across all patch areas while weighting each patch according to its relative abundance in the class (McGarigal 1994). Patch density was calculated as the number of patches per square kilometer of all unmasked areas. To assess the level of spatial aggregation of abandoned farmland patches, we also derived the aggregation index (AI) for both abandonment classes. The AI assumes that pixels in a class with the highest level of aggregation (AI = 1) share the maximum number of possible edges (that is, the class is clumped into a single compact patch). A class whose pixels share no edges is completely disaggregated (AI = 0) (McGarigal 1994).

Results

The change detection approach based on multitemporal image classification using SVM resulted in

Table 1. Accuracy Assessment of the Change Classification

Classified data	Reference data				
	Unchanged areas	Fallow farmland	Reforestation	σ	User's accuracy (%)
Unchanged areas	349	19	4	372	93.82
Fallow farmland	24	136	1	161	84.47
Reforestation	3	1	36	40	90.00
σ	376	156	41	573	
Producer's accuracy (%)	92.82	87.18	87.80		

a farmland abandonment map with an overall accuracy of 90.9% and a kappa of 0.82. Unchanged areas had highest producer's and user's accuracies, whereas accuracies were slightly lower for the fallow land and reforestation classes (Table 1). Classification uncertainty was mainly due to confusion between unchanged areas and one of the two change classes, whereas confusion among fallow land and reforestation was negligible. Post-classification image processing (that is, majority filter, and the removal of small patches) increased overall accuracy by 3.1%.

Farmland abandonment was widespread in the border triangle of Poland, Slovakia, and Ukraine between 1988 and 2000 (Figure 2). In total, 16.1% (1,285 km^2) of the farmland in socialist times was abandoned after the system change (that is, the sum of fallow land and afforested areas) and 12.5% (161 km^2) of the abandoned farmland had already reverted back to forests. Abandoned fields were not distributed uniformly across the study area and showed a highly clustered pattern, particularly in the plains in the south of the study area and in some mountain valleys (Figure 2).

The change map revealed substantial differences in the rates and spatial pattern of post-socialist farmland abandonment among the Polish, Slovak, and Ukrainian regions of the study area. In Poland,

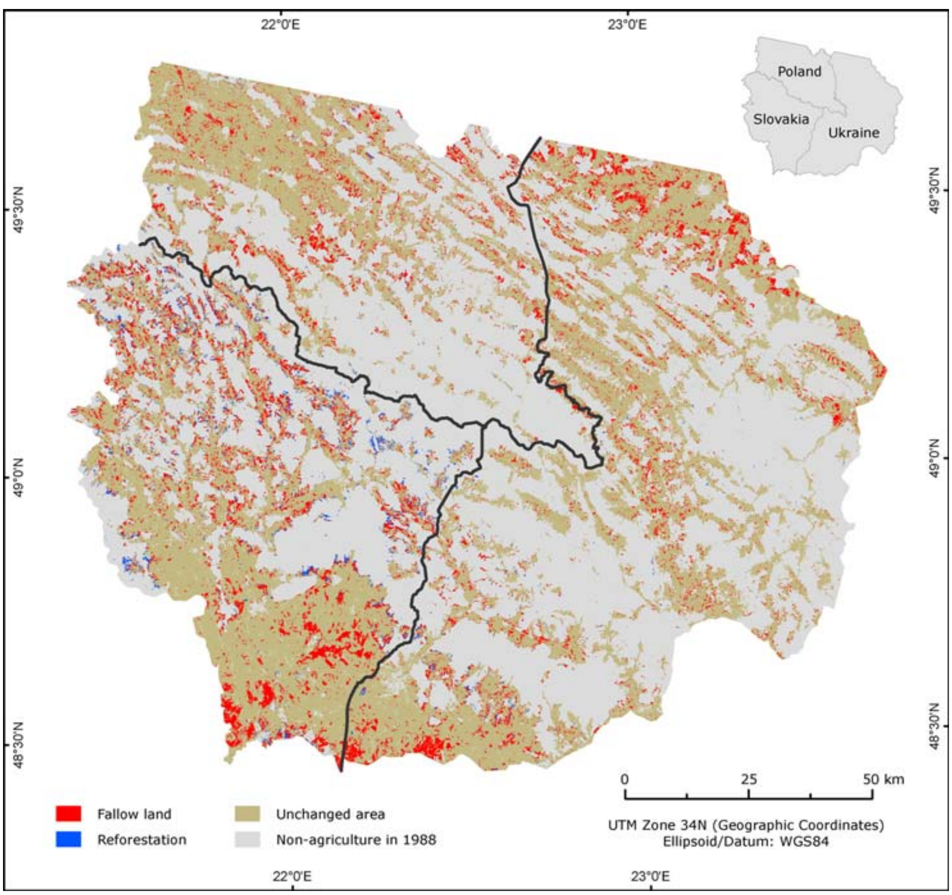

Figure 2. Farmland abandonment from 1986 to 2000 in the study area.

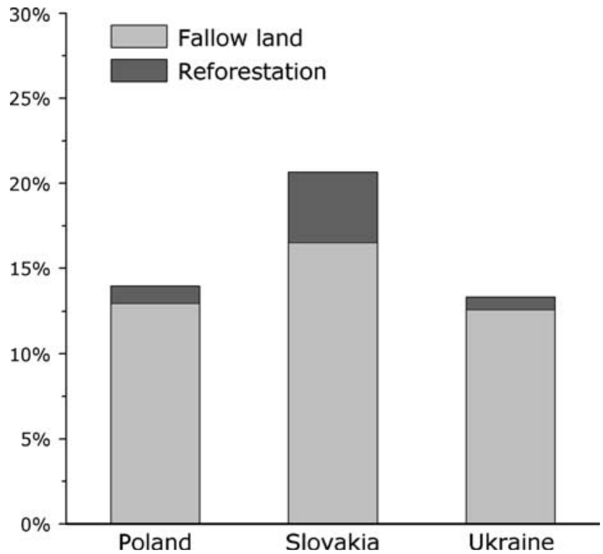

Figure 3. Comparison of fallow land and reforestation rates (1986/1988–2000) among the Polish, Slovak, and Ukrainian portions of the study area.

13.9% (sum of fallow land and afforested areas) of the farmland used in 1988 was abandoned by 2000 (240 km^2, Figure 3). Abandoned lands were concentrated in the valleys along the Polish–Slovak and the Polish–Ukrainian border (Figure 2), although some clusters of abandoned fields also occurred in the north-western plain. Highest abandonment rates were found at altitudes between 350 and 550 m (Figure 4) and where intermediate slopes prevailed (Figure 5), whereas abandonment rates were lower in the plains and in altitudes above 700 m. Reforestation was not extensive in Poland, overall accounting for only 1.0% of the former farmland (17 km^2). Most reforestations occurred in mountain valleys at intermediate altitudes between 350 and 550 m (Figure 4), and at steeper slopes (Figure 5). We found marked differences in abandonment rates on farmland managed by large-scale farming organizations during socialism, and farmland that had always been owned and managed by private farmers. Abandonment rates were two times higher

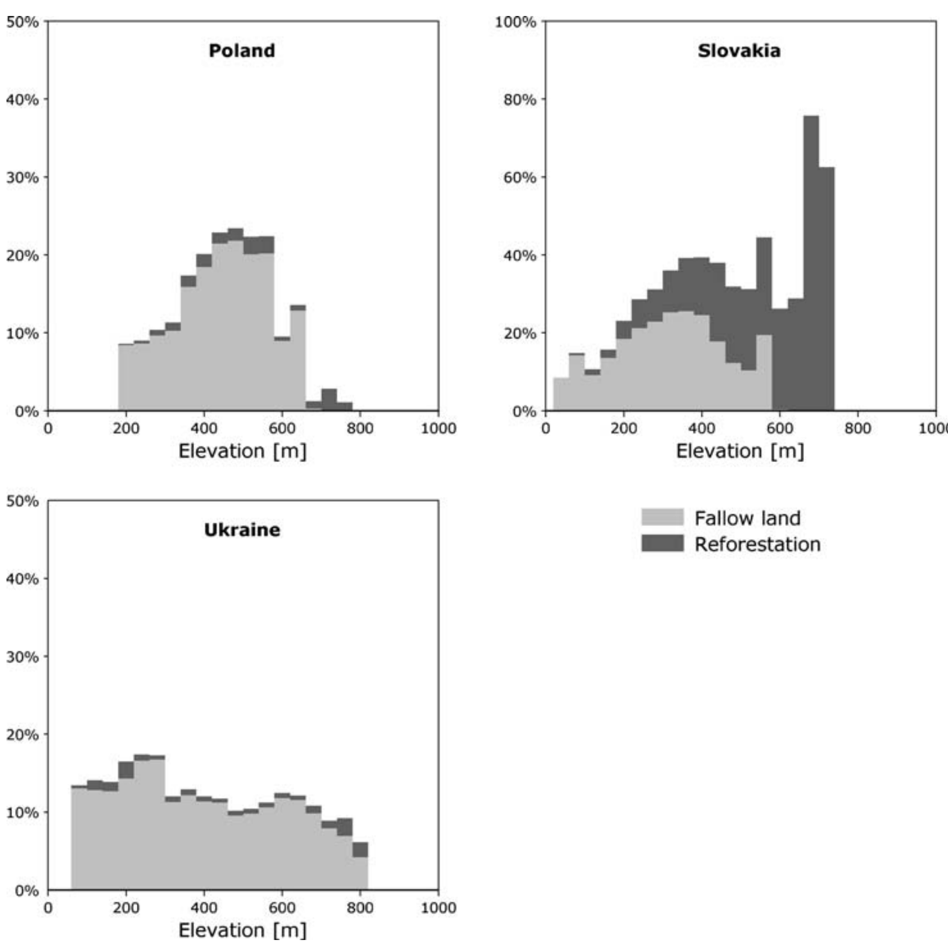

Figure 4. Rates of fallow land and reforestation (1986/1988–2000) by elevation class (50 m elevation increase per class, histogram bars are stacked).

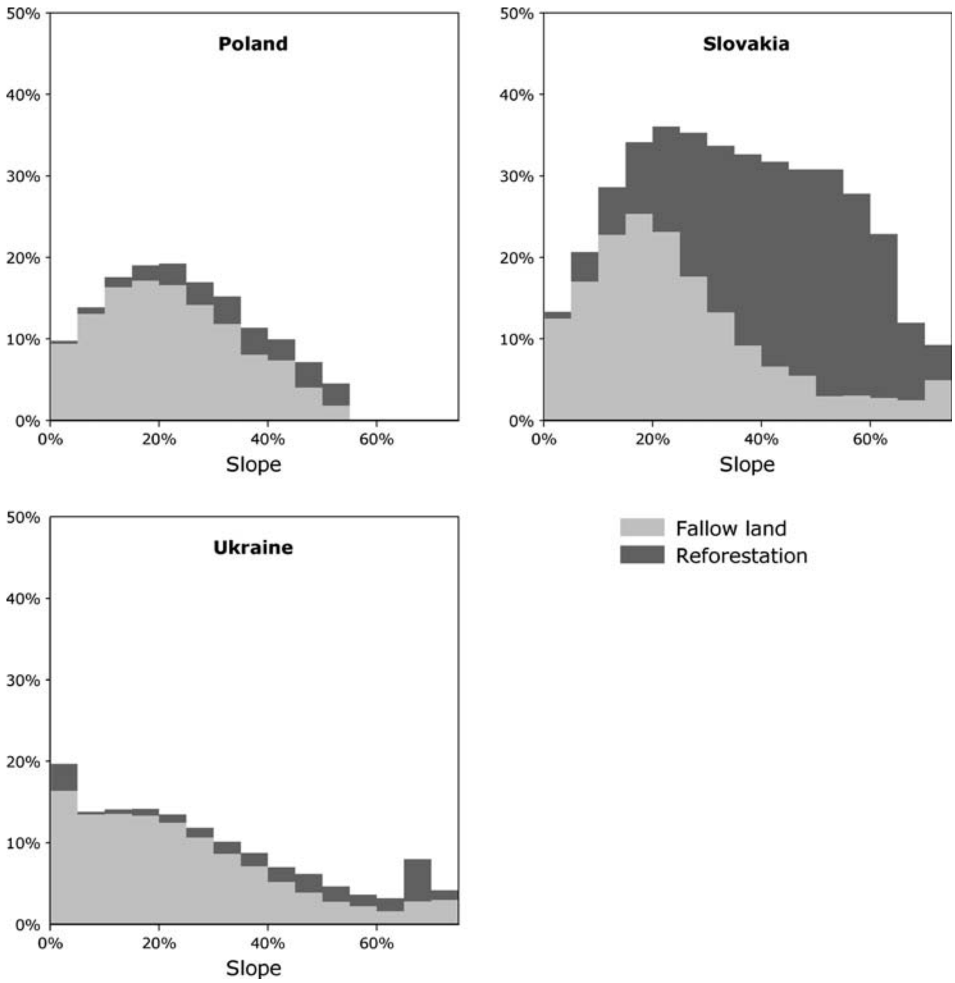

Figure 5. Rates of fallow land and reforestation (1986/1988–2000) by slope class (5% slope per class; histogram bars are stacked).

than on former state-owned land (21.8 vs. 10.8%) and reforestation was more widespread where land had been collectivized (Figure 6).

Farmland abandonment was most extensive in Slovakia among the three countries in our study area with an overall abandonment rate (that is, the combination of fallow land and afforested areas) of 20.7% (590 km^2, Figure 3). Slovakia contained almost 46% of all abandoned lands in the study area. The spatial pattern of farmland abandonment in Slovakia was highly heterogeneous and characterized by some very large patches of fallow land in the southern plains as well as a high number of abandoned fields (fallow or afforested) in mountainous areas (Figure 2). Farmland abandonment rates were lower at lower altitudes and increased with elevation, exceeding 40% at 350–450 m. Abandonment rates in Slovakia were higher than in Poland and Ukraine at all altitudes (Figure 4). Reforestation was extensive in Slovakia, covering 20.2% (119 km^2) of all abandoned lands, exceeding Polish and Ukrainian rates by a factor of 4.3 and

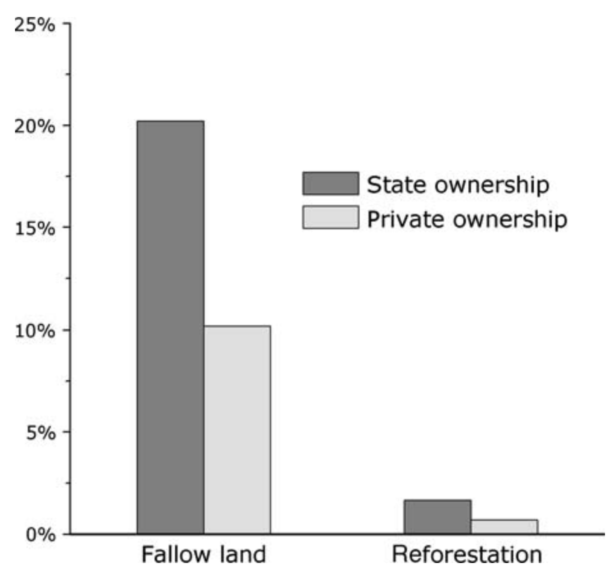

Figure 6. Comparison of farmland abandonment rates (1986/1988–2000) of lands managed by the state during socialism and lands that were never collectivized in the Polish region of the study area.

5.7, respectively. Conversion of farmland to forests was especially widespread in mountain valleys (~80% of all afforested areas occurred between 200 and 500 m elevation) and reforestation rates were particularly high at higher altitudes (up to 80% at elevations above 700 m). Whereas the rates of fallow lands were highest at intermediate slopes, reforestation occurred dominantly at steeper slopes (Figure 5) and at the forest fringe (Figure 2).

In Ukraine, 13.3% (fallow land and reforestation) of all unmasked areas were abandoned between 1988 and 2000 (455 km^2). Abandonment patches were highly clustered in the plains in the north and south of the study area, whereas abandonment was more dispersed in mountainous areas (Figure 2). Thus, the location and spatial pattern of farmland abandoned differed considerably among the Polish and Ukrainian regions of the study area although both countries had similar abandonment rates. Moreover, abandonment rates in Ukraine did not vary substantially with altitude unlike in Poland and Slovakia. We found higher rates at lower elevations and 50% of all abandoned land was located at altitudes below 350 m. However, abandonment rates decreased only slightly with altitude and abandonment was still substantial at altitudes above 750 m (Figure 4). In contrast to Poland and Slovakia, the highest abandonment rates occurred on gentle slopes (Figure 5). Among the three countries, reforestation was lowest in Ukraine (0.7%, Figure 3), mostly at lower altitudes (<200 m) and above 750 m elevation (Figure 4).

The size and the spatial pattern of abandoned patches also differed among the three countries (Table 2). Patches of fallow land were on average larger in Slovakia compared to Poland and Ukraine. The same was true for afforested areas: the area-weighted mean patch size for Slovak reforestation patches was up to a factor of 6.7 larger. Patch density of fallow lands was highest in Ukraine (1.4 times higher than in Poland and Slovakia), whereas the density of reforestation patches was 3.6 times higher in Slovakia than in Poland and Ukraine. Abandoned patches tended to be spatially aggregated, with AI values of above 0.8 for fallow land and approximately 0.7 for afforested areas. Patches of fallow land were slightly more clustered in Slovakia (AI = 0.85) compared to Poland (AI = 0.79) and Ukraine (AI = 0.82), and fallow land was characterized by a higher spatial aggregation than afforested areas.

Discussion

Mapping Farmland Abandonment Using SVM

To our knowledge, this is the first study that used SVM for land-use change detection. The SVM separated active and abandoned farmland with high accuracy and were well suited to handle complex multitemporal many-to-one classes (that is, when different types of cropland were abandoned and all reverted to forests), which would have been difficult using parametric classifiers (for example, maximum likelihood, Seto and Liu 2003). The relatively low number of training samples required, and inclusion of multiple pixels per location as training data were strong advantages of the SVM. Classification with other (parametric or non-parametric) classifiers would have required gathering substantially more training data and splitting complex change classes into many subclasses. The SVM was also successful in separating managed and unmanaged grasslands, which is crucial for accurately mapping land abandonment, yet, can be difficult using traditional approaches (Peterson and Aunap 1998).

Overall, classification accuracy was high, some classification errors remain, and there may be several reasons for those. First, there was a time lag between Landsat image acquisition and ground truth collected in the field and from very high-resolution images. Cross-checking all ground-truth points with Landsat data was helpful (for example, where farmland abandonment occurred after 2000),

Table 2. Mean Patch Size (mean), Area-Weighted Mean Patch Size (AMean), Patch Density (PD), and AI for the Fallow Farmland and Reforestation Classes of the Polish, Slovak, and Ukrainian Region of the Study Area

	Mean	AMean	PD	AI
Fallow farmland (Poland)	3.79	26.53	1.42	78.92
Fallow farmland (Slovakia)	7.78	178.73	1.16	84.78
Fallow farmland (Ukraine)	4.95	124.65	1.07	81.84
Reforestation (Poland)	1.51	2.98	0.27	67.39
Reforestation (Slovakia)	2.90	11.85	0.78	75.22
Reforestation (Ukraine)	2.13	5.40	0.14	72.93

but we cannot rule out mislabeled ground-truth points. Second, the minimum mapping unit of 7 pixels may have omitted small abandoned fields, even though this threshold removed noise due to misclassifications and thus improved the overall accuracy. Third and last, defining abandonment in itself is not easy (DLG 2005). We considered a field abandoned if intensive management during socialism (cropping, mowing, or high grazing pressure) ceased after 1990. Thus, our analysis cannot separate fully abandoned lands from areas used for occasional grazing or areas that lie fallow within a crop rotation cycle. However, extensive field visits and expert interviews between 2004 and 2006 confirmed that most fallow land in the study region was permanently abandoned and low-intensity grazing was only carried out in a few areas, suggesting that abandonment rates were not positively biased.

Farmland Abandonment in the Border Region of Poland, Slovakia, and Ukraine

Farmland abandonment was extensive in our study area. We suggest this is mainly due to three factors: declining profitability of agriculture under free markets, restructuring of the agricultural sector, and societal change in eastern Europe's rural landscapes. Whereas the first factor likely had a strong effect on farmland abandonment in all three countries that we studied, differences in land reforms and rural populations (factors 2 and 3) likely explain differences in post-socialist farmland abandonment rates among countries.

In socialist times, agricultural intensification and farmland expansion occurred even in marginal areas (for example, characterized by steep slopes, or limited market access), thanks to subsidies and capital investment by the state (Turnock 1998; Ramankutty and others 2002). State support diminished after the breakdown of the Soviet Union, prices were no longer fixed, and export markets in other socialist countries disappeared. Many eastern European farmers were not able to compete under these conditions. Altogether, this decreased the profitability of agriculture substantially, particularly in marginal regions such as the Carpathians (DLG 2005) and resulted in a steep decline in agricultural production in the early 1990s (on average 31% in eastern Europe, Trzeciak-Duval 1999). In our study area, conditions for farming are best in the plains and worst in the mountains (for example, access to markets, terrain ruggedness, and so on). Abandonment rates reflected this gradient, particularly in Poland and Slovakia (Figures 4 and 5), and abandoned patches were highly clustered (Table 2). Similar to other European mountain regions, post-socialist farmland abandonment in our study area was connected to topography (Poyatos and others 2003; Gellrich and others 2007; Tasser and others 2007). Yet, the rapid and extensive abandonment that occurred right after the system change (>16% in a period of only 12 years) emphasizes that socio-economic conditions are powerful determinants of land-use marginality (Baldock and others 1996; Grau and others 2004).

The rates and spatial pattern of farmland abandonment differed substantially among the Polish, Slovak, and Ukrainian regions of our study area. These differences cannot be solely explained by differences in the marginality of farming, because the region is environmentally relatively homogenous and the three countries faced similar economic challenges in the transition period. Instead, differences among countries appear to be most strongly related to differences in land-ownership patterns, land-reform strategies, and societal developments (for example, rural population density and emigration).

In Poland, abandonment rates were twice as high on former state-owned land compared to collectivized land. State farms were only established in mountain valleys that had been depopulated after 1947 (Turnock 2002) and these areas still have a very low population density (for example, 22 persons/km^2 in the Bieszczady County in 2000, SOR 2002). When Poland chose to auction off former state land after the system change, some farmland was acquired by the Polish Forest Service, but most was purchased by investors for speculative purposes rather than by local farmers. As a result, farmland in these areas was almost completely set-aside (Augustyn 2004), explaining the high abandonment and reforestation rates at intermediate altitudes and slopes, and the large clusters of abandoned lands we found in mountain valleys. The situation was different for private farmland. In these areas, population density is relatively high and economic difficulties and high unemployment in the early 1990s forced many people into farming (Gorz and Kurek 1998). Abandonment rates were lowest in these areas (Figure 6), the spatial pattern of abandonment was highly dispersed (for example, lowest AI and highest patch density among the three countries), and abandoned patches were smallest (Table 2 and Figure 2). We therefore suggest that abandonment in these areas was not triggered by increased land-use marginality, but can be attributed to societal changes in the transition period (for example, aging of rural populations, Gorz and Kurek 1998; SOR 2002; Palang and others 2006).

High abandonment rates in Slovakia (Figure 3) can largely be attributed to the slow pace of land privatization and farm restructuring (Csaki and others 2003). Slovakia restituted all farmland (Lerman and others 2004). Yet, land tenure is highly fragmented, identifying former owners often proved difficult, and many of them were not interested in farming anymore, resulting in much unclaimed farmland (Mathijs and Swinnen 1998; van Dijk 2003; DLG 2005). This led to a twofold pattern of farmland abandonment. In the plains, owners leased their land to large-scale farming organizations and the socialist farming structure largely survived (Csaki and others 2003; Lerman and others 2004). Abandonment was mainly clustered in areas of poor farming conditions, for example in marshlands (Figure 2). Farmland abandonment rates were higher in Slovak mountain valleys where production is limited by environmental conditions (for example, at high altitudes, steep slopes, and so on) and where considerable emigration to urban areas occurred in the post-socialist period (Izakovicova and Oszlany 2007). The twofold concentration of abandonment (that is, in mountain valleys and along floodplains) also explains the high level of aggregation and the larger size of abandonment patches we found in Slovakia. Reforestation was especially widespread in protected areas that were established in the post-socialist period (Kuemmerle and others 2007) and around the Starina water reservoir, which was constructed in the late 1980s.

In Ukraine, many state-owned agricultural enterprises were not able to operate under market conditions and went bankrupt after 1989 (Ash and Wegren 1998; Augustyn 2004). Farmland was distributed among the workers of the former agricultural enterprises, but they lacked funds and machines, and a functioning land market did not exist until 2005 (Lerman and others 2004). Altogether, this explains the high farmland abandonment rates in Ukraine. As in Slovakia, abandonment patches were highly clustered (Table 2) especially in areas with high ground water tables and less fertile soils, for example, in the northeastern foothill zone where podzols and gleysols dominate, or in the alluvial plain of the Tisza river in the southwest (Figure 2). Farmland abandonment was almost absent in the vicinity of larger settlements, but abandoned areas were widespread in the foothill zone. Farmland abandonment rates in Ukrainian mountain valleys did not differ substantially from rates in the plains and were sometimes even lower (Figure 4). In contrast to Polish and Slovak mountain valleys, rural population density is high in Ukrainian valleys (for example, 2.8 times higher in Lviv Oblast compared to the Polish Bieszczady County, SOR 2002), and many people depend on subsistence farming. Despite difficult farming conditions much former state land was converted to household plots in the mountains, thereby explaining the absence of an elevation gradient in farmland abandonment and decreasing abandonment rates with increasing slopes. Some abandonment occurred where livestock farms operated in socialist times, because most animals were slaughtered after the system change and were never replaced (DLG 2005). Reforestation rates were low in Ukraine, partly due to the high human pressure in mountain areas, but mostly because active forest planting essentially stopped after the system change (Buksha and others 2003).

Overall, only a small proportion (~12%) of the abandoned farmland had been converted to forests by 2000. This offers much potential for additional rapid carbon sequestration, especially because Carpathian forests are highly productive and sequestration rates are highest in young forests (MASR 2003; Grau and others 2004). Reforestation potential is especially high in Ukraine, where forest cover is substantially lower than in Poland and Slovakia (Kuemmerle and others 2006), but funds for afforesting abandoned farmland are limited (Nijnik and Van Kooten 2000; Buksha and others 2003). Although conversions from farmland to forests may be beneficial for carbon sequestration and soil protection (Rudel and others 2005), they are of little value for biodiversity conservation in the Carpathians. Area-sensitive top carnivores and herbivores may benefit from increased forest cover and decreasing human pressure in rural areas. In some areas in eastern Europe, these circumstances have led to increasing populations (L. Baskin, personal communication). However, much of the Carpathian's unique biodiversity is dependent on semi-natural grasslands at intermediate and high elevations (Baur and others 2006). In these regions, we found highest abandonment rates in Poland and Slovakia. If these lands revert back to forests, much of the biodiversity found in cultural landscapes in the Carpathians would be lost (Cremene and others 2005).

Conclusion

We found extensive farmland abandonment in the border region of Poland, Slovakia, and Ukraine between 1986/1988 and 2000. In total, 16.1% of the farmland used before 1990 was no longer used in

2000. Our results suggest that the political and economic changes following the breakdown of the Soviet Union had profound impacts on the profitability of farming in the region. As elsewhere in the world, farmland abandonment was also connected to physiographic factors affecting farmland marginality, for example, elevation and slope. However, we also found strong differences in the rates and spatial pattern of farmland abandonment among the three countries in our study area. We suggest that these differences are related to differences in socialist land-ownership patterns, post-socialist land-reform strategies, and rural population density. In Poland, abandonment rates were twice as high on collectivized land compared to areas that were always privately farmed, emphasizing the importance of land-use legacies for land-use change. Farmland abandonment in the Carpathians threatens cultural landscapes and their biodiversity, vbut offers opportunities for increased carbon sequestration, especially in Ukraine where forest cover is low and most abandoned farmland has not yet been afforested. Considering broad-scale political, economic, and societal conditions was essential to understand farmland abandonment in our study area and we suggest that these factors may be equally important land-use determinants in marginal regions in other parts of the world.

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