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Rapid land use change after socio-economic disturbances: the collapse of the Soviet Union versus Chernobyl

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Abstract

Land use change is a principal force and inherent element of global environmental change, threatening biodiversity, natural ecosystems, and their services. However, our ability to anticipate future land use change is severely limited by a lack of understanding of how major socio-economic disturbances (e.g., wars, revolutions, policy changes, and economic crises) affect land use. Here we explored to what extent socio-economic disturbances can shift land use systems onto a different trajectory, and whether this can result in less intensive land use. Our results show that the collapse of the Soviet Union in 1991 caused a major reorganization in land use systems. The effects of this socio-economic disturbance were at least as drastic as those of the nuclear disaster in the Chernobyl region in 1986. While the magnitudes of land abandonment were similar in Ukraine and Belarus in the case of the nuclear disaster (28% and 36% of previously farmed land, respectively), the rates of land abandonment after the collapse of the Soviet Union in Ukraine were twice as high as those in Belarus. This highlights that national policies and institutions play an important role in mediating effects of socio-economic disturbances. The socio-economic disturbance that we studied caused major hardship for local populations, yet also presents opportunities for conservation, as natural ecosystems are recovering on large areas of former farmland. Our results illustrate the potential of socio-economic disturbances to revert land use intensification and the important role institutions and policies play in determining land use systems' resilience against such socio-economic disturbances.

Keywords: coupled human–natural systems, socio-economic disturbance, Chernobyl nuclear disaster, post-socialist land use change, transition economies, Soviet Union

1. Introduction

Coupled human–natural systems in general, and land use systems in particular may display nonlinear responses to stressors, cascading effects, and tipping points that can shift systems onto a new trajectory (Liu *et al* 2007, Scheffer 2010). Land system dynamics may thus be characterized as a sequence of periods of relative stability followed by rapid changes with potentially long-lasting effects (Dearing *et al* 2010, Lambin and Meyfroidt 2010). The challenge is to better understand the triggers that can reorganize land use systems and modify long-term land use trajectories (NSF 2009, Scheffer 2010). In natural systems, disturbance is considered an intrinsic component resulting in rapid and sometimes drastic change of ecosystem structure and functioning. We ask here whether the same applies to land use systems: to what extent can large socio-economic disturbances such as wars, revolutions, recessions, and changes in political systems trigger a fundamental change in land use systems and how do different institutional settings affect the outcomes of such socio-economic disturbances?

A reorganization in land use systems can be defined as a process whereby the structural character of land use transforms as a result of a set of connected changes. This may be triggered by slow drivers of change (e.g., demographic changes or industrialization), fast ones (e.g., revolutions, wars, disease outbreaks, economic crises, technological breakthroughs), or both (Aide and Grau 2004, Rudel *et al* 2005, Geist *et al* 2006, Machlis and Hanson 2008). The effects of fast drivers on land use transitions are not well understood, even though they may strongly affect a systems' state and future trajectories (Dearing *et al* 2010). Moreover, related transitions may result in either higher (Zak *et al* 2008, Hansen *et al* 2009) or lower land use intensities (Rudel *et al* 2005, Yeloff and Van Geel 2007, Pongratz *et al* 2011).

We here use the term 'disturbance' in an ecological and socio-economic context to underline the coupling of human and environmental systems and define socio-economic disturbances as rapid and sweeping changes in social, political, or economic systems. To evaluate the effects of such disturbances on land use experimentally is rarely feasible, but natural experiments (*sensu* Diamond 2001) can identify real-world situations that approximate experimental conditions. Such natural experiments can occur in the form of discontinuities in time, i.e., brief periods during which one aspect of a system changes (e.g., the political system), while other aspects of the system (e.g., climate) remain constant and can thus be controlled for (Geist *et al* 2006). Natural experiments can also exploit discontinuities in space, e.g., cross-border situations where political systems differ between two neighboring countries while environmental conditions are similar (Homewood *et al* 2001, Kuemmerle *et al* 2008).

Our goal here was to assess to which extent a major socio-economic disturbance can cause a fundamental reorganization in land use systems. In particular, we were interested in the potential of a socio-economic disturbance to revert a land system toward less intensive use. We studied land change associated with two major events that took place in Central

and Eastern Europe in the 1980s and 1990s. The main socio-economic disturbance that we studied was the collapse of the Soviet Union in 1991. To provide a reference against which to evaluate land use impacts of that socio-economic disturbance, we also studied the effect of a major technological disturbance that affected the same region a few years earlier, i.e., the nuclear disaster in Chernobyl.

The collapse of the Soviet Union in 1991 meant that the largest country in the world switched from a socialist to a capitalist society and this resulted in substantial institutional changes, large-scale rural–urban migrations, massive privatization, and deep economic perturbations as command economies transitioned toward free markets. Agriculture had been heavily subsidized and intensified during the socialist period, but the post-socialist period was characterized by a drastically lower profitability of farming, unsecure land tenure, and decreasing agricultural workforces (Swinnen 1997, Lerman *et al* 2004). As a consequence, millions of hectares of farmland were abandoned (Ioffe *et al* 2004, Kuemmerle *et al* 2008, Kovalsky and Henebry 2009, Baumann *et al* 2011).

The reference disturbance to evaluate the magnitude of land use impacts of this socio-economic disturbance was a technological disturbance: the meltdown of the nuclear reactor in Chernobyl on 26 April 1986, resulting in massive contamination, and enormous effects on human health and ecosystems (Anspaugh *et al* 1988, Baverstock and Williams 2003, IAEA 2006, Møller and Mousseau 2006). The Soviet administration evacuated the local population within a 30 km exclusion zone around the reactor, and implemented additional large-scale relocation schemes for local residents based on cesium (^{137}Cs) contamination patterns (IAEA 2006). The evacuation of local populations and resulting land abandonment after the Chernobyl meltdown provided a clear benchmark for assessing the effects of a massive socio-economic disturbance, i.e., the collapse of the Soviet Union.

We selected these two disturbances because they affected the same region and took place within a few years. Thus other potential drivers of land use decisions such as technological, cultural, and biophysical factors remained constant. Both disturbances also occurred more than two decades ago, allowing us to assess whether these disturbances set land use systems into different long-term trajectories. Last but not least, both disturbances affected the border region of Belarus and Ukraine, which allowed us to exploit differences among the two countries' responses to the disturbances.

2. Materials and methods

2.1. Study area

Our study region (figure 1) covered an 80 km radius around the reactor in the limits of one Landsat footprint. This ensured that the study region included the 30 km evacuation zone around the reactor and the entire relocation zones related to the post-meltdown ^{137}Cs contamination in Ukraine and Belarus. The study area is part of the Polesse lowlands in the eastern European plain along the Pripyat River. Sandy and peat soils

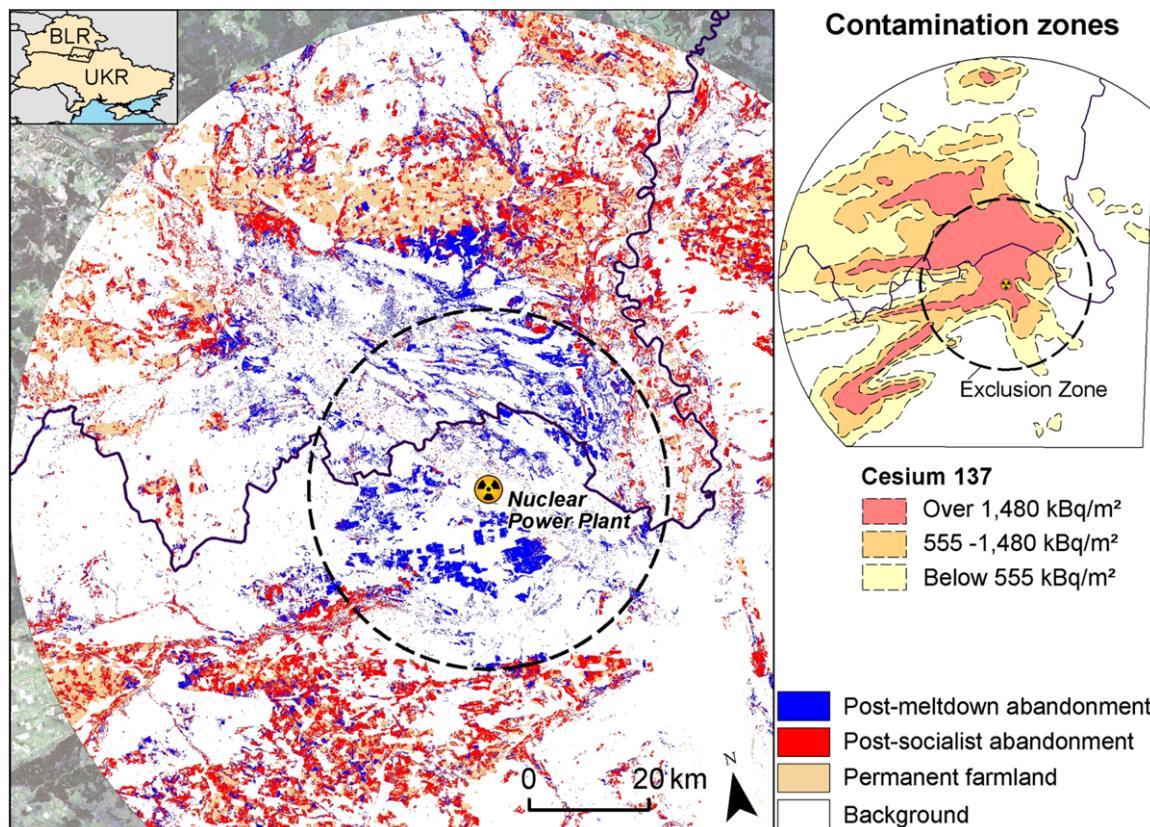


Figure 1. Land use changes and radioactive contamination. Farmland abandonment and re-cultivation in the Chernobyl region between 1986 and 2006 (main map) in the Ukrainian–Belarus border region (inset top-left). The post-meltdown period was from 1986 to 1992, post-socialist period from 1992 to 2006, recent re-cultivation refers to areas abandoned from 1986 to 1999, but farmed again by 2006. Contamination zones based on cesium 137 radiation after the reactor meltdown are shown (upper right).

dominate the region and farmland includes a high share of managed grasslands. Agriculture was traditionally dominated by dairy and meat production that account for 80–85% of the total agricultural output. Industrial meat production and dairy farming relied on extensive fodder production on managed grasslands in our study region. Grain, potato and flax were traditionally secondary products. Agricultural land was greatly expanded in the former Soviet Union during the 1980s and marginal land was put under agricultural production.

2.2. Data preparation

Remote sensing is a powerful tool to map rates and patterns of post-socialist land use and land cover change (Houghton *et al* 2007, Kovalsky and Henebry 2009, Kuemmerle *et al* 2011, Potapov *et al* 2011). We analyzed a time series of Landsat satellite images to monitor land use change after the Chernobyl disaster and after the breakdown of the Soviet Union. Landsat thematic mapper (TM) data provide consistent satellite imagery since the 1980s with almost complete global coverage. Data availability for our study region was somewhat limited though, and only single cloud-free images were available for individual years of interest. Our analyses were hence based on four TM scenes from May 31st 1986, July 26th 1992, October 2nd 1999, and September 27th

2006, covering the Ukrainian–Belarus border region around Chernobyl (path/row 182/25).

Robust change analyses require accurate spatial co-referencing of the analyzed data (Lu *et al* 2004). The 1999 satellite image was ortho-corrected by the global land cover facility (GLCF) and served as spatial reference for the other images. We employed an automated orthorectification approach based on correlation windows to determine between 800 and 1300 ground control points per image. These were used for ortho-correction that employed a space resection derived Landsat model and Shuttle Radar Topography Mission (SRTM) elevation data. Validation based on independent control points confirmed positional accuracies between 0.2 and 0.3 pixels (~6–9 m). We then performed a relative radiometric normalization of our imagery based on dark object subtraction using a water spectrum as dark object. The four pre-processed images were combined in one image stack and we applied the 80 km radius of our area of interest. We digitized clouds and cloud shadows and excluded these areas from further analysis. Similarly, we delineated and masked out all settlements based on topographic maps, because the small and strongly vegetated villages in the study area would potentially have introduced uncertainty in the change detection.

We also digitized cesium (¹³⁷Cs) contamination maps as a proxy for the evacuation zones around the Chernobyl reactor (De Cort *et al* 1998). These maps were used to stratify

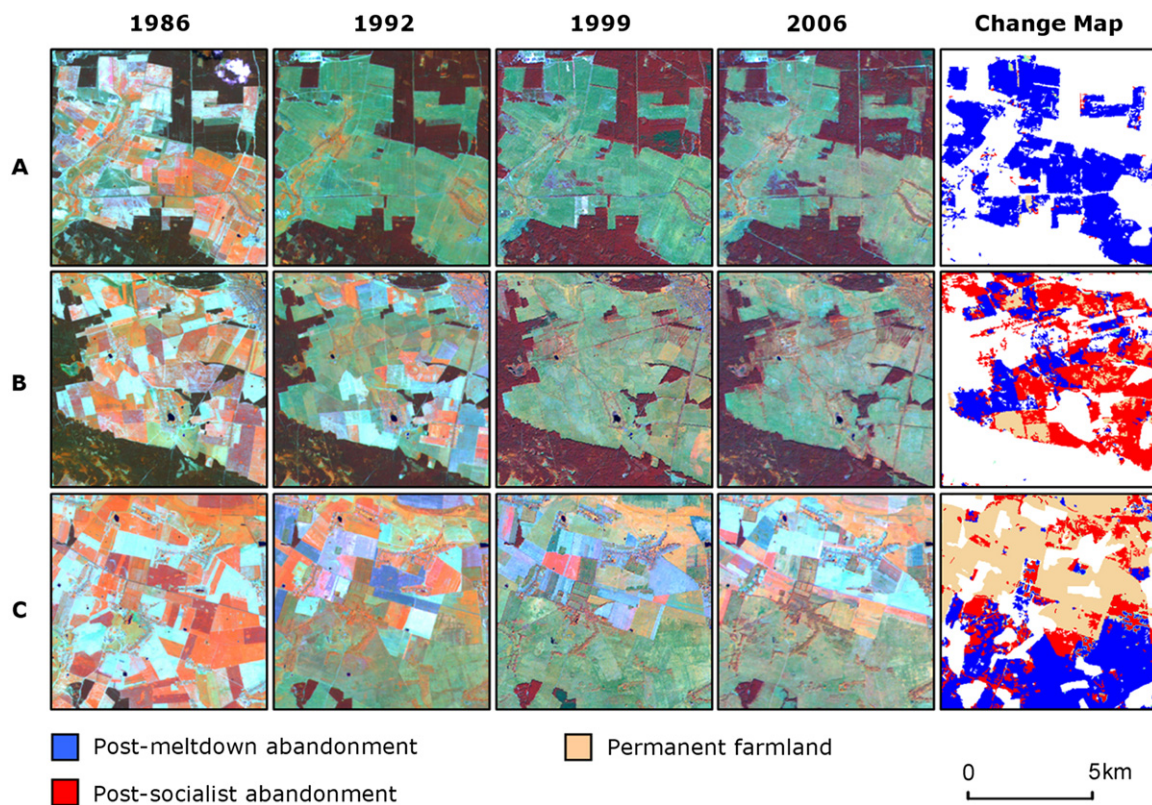


Figure 2. Farmland development between 1986 and 2006. Examples of post-meltdown farmland abandonment (A), post-meltdown and post-Soviet farmland abandonment ((B) and (C)). Columns 1–4 show the appearance in Landsat false color imagery, with forests in dark brown, photosynthetic active vegetation in orange, open soils in light blue, and abandoned fields in green colors. Mapping results are shown in the last column.

our results and to advance our understanding how governance and planning influenced land use change after the Chernobyl disaster.

2.3. Data analysis

We conducted a multi-temporal classification of Landsat thematic mapper (TM) and Enhanced Thematic (ETM+) data to analyze farmland change from 1986 to 1992 (post-meltdown period) and after 1992 (post-Soviet period). We identified changes among the land cover classes farmland, grassland, forest, and water. Farmland was defined to include both, arable land and managed grasslands. We considered an area abandoned if it was only farmed in the earlier satellite image of the respective time period.

Farmland abandonment is spectrally complex due to crop-type variability, phenology, and different vegetation succession stages following farmland abandonment. We therefore chose a support vector machine (SVM) for our classifications, because machine-learning classifiers perform well given such complexity, often outperforming traditional statistical classifiers (Huang *et al* 2002, Foody and Mathur 2004). SVM discriminate classes by fitting a separating hyperplane between two classes in the feature space based on training samples (Huang *et al* 2002) and have been successfully applied to analyze land use changes, including

farmland abandonment from Landsat data (Kuemmerle *et al* 2008, Baumann *et al* 2011).

We digitized 167 polygons covering the classes ‘post-meltdown abandonment’, ‘post-socialist abandonment’, ‘permanent farmland’, and ‘background’ (permanent forests and water, along with the previously digitized clouds, cloud shadows, and settlements) and randomly collected 200 pixels per class as training samples for the SVM classifier. We used the SVM classifier implementation ImageSVM (www.hu-geomatics.de). ImageSVM uses a Gaussian kernel function that requires setting the kernel width (γ) and the parameter C determining the error penalty for misclassified training data (Pal and Mather 2005). We systematically tested a wide range of γ and C combinations via a grid search and compared them based on tenfold cross-validation error estimates. Once optimal γ and C were found, we classified the multi-temporal image stack based on a one-against-one SVM scheme.

Once a farmland abandonment map was classified, we eliminated patches of five or less pixels (~ 0.5 ha) of any given class. We validated the resulting map based on an independent sample of 400 random points. Each sample had a minimum distance of 4 km from any neighboring sample to avoid spatial autocorrelation. Area-adjusted overall accuracy, user’s and producer’s accuracies and kappa statistics yielded were then calculated (Card 1982, Stehman 1996).

SVM were well suited to map farmland abandonment in our study region (figure 2). Our change map had an

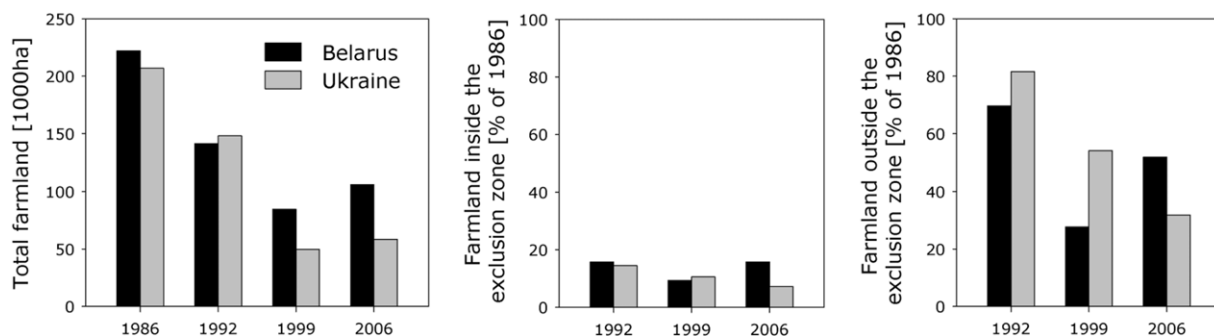


Figure 3. Development of farmland in Belarus and Ukraine. Total farmland in the study region (left) and proportions of farmland remaining inside (middle) and outside (right) of the 30 km exclusion zone in 1992, 1999, and 2006.

Table 1. Area-adjusted accuracy assessment (%).

	Producer's accuracy	User's accuracy	Error of commission	Error of omission
Post-meltdown abandonment	50.85	50.00	49.15	50.00
Post-socialist abandonment	35.19	36.00	64.81	64.00
Permanent farmland	89.98	86.00	10.02	14.00
Background	80.54	88.00	19.46	12.00

overall accuracy of 80.43% and a kappa value of 0.80. Class-wise user's and producer's accuracies were highest for the permanent farmland and background classes, whereas these accuracy measures were lower for the abandonment classes (table 1). For the change classes, user's and producer's accuracy were also well-balanced, suggesting no bias for our comparisons among regions, countries, or time periods. We generally assume that our farmland abandonment estimates after the Chernobyl disaster and the breakdown of the Soviet Union represent conservative. We finally summarized the area of farmland abandonment for the 30 km exclusion zone around the reactor and the different ¹³⁷Cs contamination zones for each country separately.

3. Results

The Chernobyl meltdown and associated relocation of local dwellers resulted in high farmland abandonment rates across the study region. Before the 1986 meltdown, farming patterns were similar in Belarus and Ukraine with 222 000 and 207 000 ha of farmland in the study region, respectively. In total, cultivation of 32.5% of all farmland ceased after the nuclear disaster until 1992 (figure 1). Approximately half of the farmland in both countries was located within the evacuation and relocation zones designated after the Chernobyl meltdown. Relocation of local dwellers depended on ¹³⁷Cs contamination levels, with a total of 120 900 ha of farmland subject to mandatory relocation (contamination >555 kBq m⁻²). Abandonment rates were very high in the regions that were subject to mandatory relocation, where more than 64.5% of all farmland was abandoned by 1992 (figure 3). In contrast, areas only designated for optional relocation

(contamination >185 and <555 kBq m⁻², 95 400 ha in total) exhibited lower farmland abandonment rates between 1986 and 1992. Post-Chernobyl abandonment in these zones was again similar in Belarus (24.9%) and Ukraine (23.0%, table 2). Land use outside heavily contaminated areas (≤185 kBq m⁻²) did not change substantially in the post-meltdown period (figure 1). The high rates of abandonment in the contaminated areas highlighted the magnitude of the effects that a major technological disturbance, such as the Chernobyl disaster, can have on land use (figure 3). In other words, given the severity of the reactor meltdown and the radioactive contamination, high rates of farmland abandonment were not surprising and make Chernobyl a sound benchmark for land use effects of an extreme socio-economic disturbance event.

What was surprising, however, was that the collapse of the Soviet Union resulted in abandonment rates that were even slightly higher (36% at the study region level) than those caused by the Chernobyl meltdown (33%). Post-Soviet agricultural abandonment was spatially not associated to ¹³⁷Cs contamination patterns from the Chernobyl disaster, i.e., it was related to processes after the collapse of the Soviet Union and not to long-term effects of the Chernobyl meltdown. Affected areas covered the whole range of field sizes and appeared across the entire study region.

The cross-border comparison further highlighted the magnitude of land use changes that followed the collapse of socialism. In Ukraine, abandonment rates reached 55.4% of all farmland in uncontaminated regions (i.e., outside the evacuation and relocation zones), compared to only 14.8% in the post-Chernobyl period. In Belarus, abandonment rates in uncontaminated areas were considerably lower (32.8% and 23.6% in the post-socialist and post-meltdown periods, respectively). In other words, the same trigger, i.e., the collapse of socialism, resulted in a much stronger land use change in one country than the other (figure 3).

4. Discussion

The main result of our study is that the effect of the socio-economic disturbance, the collapse of the Soviet Union, on land use systems was at least as drastic as that of the technological disturbance of the Chernobyl nuclear disaster. Both disturbances resulted in less intensive land use and

Table 2. Post-Soviet land abandonment (percentages relative to total farmland outside areas affected by Chernobyl disaster).

	Belarus		Ukraine		Both countries	
	ha	%	ha	%	ha	%
Early post-Soviet period outside relocation zones 1992–1999	25 934	37.74	74 029	62.51	99 963	53.42
Comparison 1986–1992	18 630	23.56	19 774	14.80	38 404	18.06

farmland abandonment, but the major difference between these disturbances was that effects of the Chernobyl disaster on land use systems were fairly local, whereas the collapse of the Soviet Union affected land use systems across one sixth of the planet's land surface (Ioffe *et al* 2004, EBRD and FAO 2008, Kuemmerle *et al* 2008, Henebry 2009). Moreover, our results suggest that institutions play important roles in mitigating the impact of socio-economic disturbances and may be able to increase the resilience of land use systems. While the dismantling of the Soviet Union had drastic effects on land use systems in both Ukraine and Belarus, continuing state-support for agriculture and a stronger institutional inertia resulted in substantially lower abandonment rates in Belarus compared to Ukraine.

Brief events, such as the Chernobyl meltdown and the collapse of the Soviet Union affected land use patterns for at least two decades thereafter. After the initial wave of farmland abandonment, land use in the region remained relatively stable since the nuclear disaster and the collapse of the Soviet Union. Twenty-five years after of the Chernobyl disaster and nearly 20 after the collapse of the Soviet Union, most abandoned lands continue to lie idle and are slowly reforesting. Only a small proportion of initially abandoned land has been re-cultivated, similar to other areas in the former Soviet Bloc (Henebry 2009, Baumann *et al* 2011). Once forests regrow on former farmland, it becomes economically very costly to revert back to agricultural land. This suggests that the socio-economic disturbances we studied indeed shifted land use systems in Central and Eastern Europe onto new trajectories.

Forests have regrown on many of the former farm fields, providing ecosystem services such as increased water quality, soil stability, and carbon sequestration, as well as additional habitat for wildlife (Pekarova and Pekar 1996, Tasser *et al* 2007, Vuichard *et al* 2009). Both the Chernobyl disaster and the collapse of the Soviet Union thus caused inadvertently a 'rewilding', i.e., the return of semi-natural vegetation across large areas that were previously farmed. However, while our examples both resulted in less intensive land use, socio-economic disturbances can also result in an intensification and possibly unsustainable states. For example, economic crises may have lead to increasing deforestation for oil palm expansion in Indonesia (Sunderlin *et al* 2001) and may have contributed to the rampant forest loss in the Argentine Chaco region (Zak *et al* 2008). Similarly, warfare, revolutions, or failing states can weaken institutions and the effectiveness of law enforcement, or increase poverty, all of which may result in a predatory exploitation of natural resources (Irland 2008). Indeed, the collapse of the Soviet Union also spurred an increase in illegal logging and poaching (Kuemmerle *et al* 2009).

We also infer from our findings that national policies can exacerbate or limit the effects of socio-economic disturbances and therefore increase the resilience of land use systems. Belarus and Ukraine followed very different strategies to deal with the aftermath of the collapse of the Soviet Union, and this resulted in different land abandonment rates in the post-socialist period. Ukraine, on the one hand, allowed privatization of all farmland, but implemented land reforms slowly (Lerman *et al* 2004). Tenure insecurity was high during the early post-Soviet years, land markets were not functioning, and price liberalization and the lack of capital limited the economic viability of farms. It is striking how weak institutions, a diminishing support for agriculture, and a lack of investments translated into widespread agricultural land abandonment during the 1990s in Ukraine (figure 1). Belarus, on the other hand, did not change its agricultural policies nearly as much. Farmland was not privatized and government support for agriculture continued after the collapse of the Soviet Union (Lerman *et al* 2004). As a result, land systems in Belarus were more resilient against the effects of the socio-economic disturbance caused by the collapse of the Soviet Union. Our cross-border comparison between Ukraine and Belarus thus highlights that institutions and policies may indeed mitigate or avert fundamental reorganization in land use systems, even after major socio-economic disturbances have occurred.

The marked differences in farmland abandonment rates between the two countries highlighted the challenges involved in understanding how a socio-economic disturbance will affect a particular land use system. While land use in our study site remained stable after the initial changes in response to the disturbances, and field observations indicate that the changes we found have persisted until today, it is difficult to forecast how long-lasting our observed land use changes will be. Evidence from other areas suggests that farmland abandonment may persist for a long time. Major socio-economic disturbances such as wars (Machlis and Hanson 2008, Witmer and O'loughlin 2009), economic crises (Sunderlin *et al* 2001), failing states (Irland 2008), revolutions, institutional changes (Sikor 2004), and globalization (Aide and Grau 2004) have triggered rapid and widespread land use changes elsewhere, too. They have set entire regions into new land use change trajectories. Among the studies that examined land use for half a century or more, some also found permanent land use change, e.g., in response to institutional change (Diamond 2005, Lambin and Meyfroidt 2010), or colonization by European settlers (Radeloff *et al* 1999, Pongratz *et al* 2011). Whether or not socio-economic disturbances result in permanent reorganization of land use systems will ultimately depend upon the resilience of land use systems (i.e., a system's distance to a tipping point) and on the nature of the threshold

(i.e., the irreversibility of a fundamental shift). Furthermore, less intensive land use trajectories in one region might trigger land use intensification in others. Globalization and global teleconnections can result in net land use intensification if leakage effects stimulate land use expansion or intensification elsewhere (Lambin and Meyfroidt 2011).

Irrespective of the duration of land use changes and potential leakage effects, coupled human–natural systems are inherently dynamic (Liu et al 2007) and land use theory needs to account for the effects of socio-economic disturbances to better understand land use trajectories, and thus to identify pathways toward sustainable land use systems. The interactions of socio-economic disturbances and the accelerating and powerful forces, such as climate change and globalization, that increasingly drive land-systems dynamics, will likely bring about ‘imaginable surprises’ (sensu Schneider et al 1998).

Human societies are rarely prepared for surprises and the rapid changes that socio-economic disturbances entail. Socio-economic disturbances may thus cause grave human suffering (Stuckler et al 2009), and societies should strive to limit their impacts on people and communities. On the other hand, our results suggest that socio-economic disturbances not necessarily put land use systems toward intensification trajectories and may allow landscapes to ‘rewild’, and as such represent opportunities for conservation. ‘A crisis is a terrible opportunity to waste’ (P Romer), and understanding socio-economic disturbance effects as both threats and opportunities is scientifically important and highly policy relevant.

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