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Post-Soviet farmland abandonment, forest recovery, and carbon sequestration in western Ukraine

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Abstract

Land use is a critical factor in the global carbon cycle, but land-use effects on carbon fluxes are poorly understood in many regions. One such region is Eastern Europe and the former Soviet Union, where land-use intensity decreased substantially after the collapse of socialism, and farmland abandonment and forest expansion have been widespread. Our goal was to examine how land-use trends affected net carbon fluxes in western Ukraine (57 000 km^2) and to assess the region's future carbon sequestration potential. Using satellite-based forest disturbance and farmland abandonment rates from 1988 to 2007, historic forest resource statistics, and a carbon bookkeeping model, we reconstructed carbon fluxes from land use in the 20th century and assessed potential future carbon fluxes until 2100 for a range of forest expansion and logging scenarios. Our results suggested that the low-point in forest cover occurred in the 1920s. Forest expansion between 1930 and 1970 turned the region from a carbon source to a sink, despite intensive logging during socialism. The collapse of the Soviet Union created a vast, but currently largely untapped carbon sequestration potential (up to ~150 Tg C in our study region). Future forest expansion will likely maintain or even increase the region's current sink strength of 1.48 Tg C yr^{-1}. This may offer substantial opportunities for offsetting industrial carbon emissions and for rural development in regions with otherwise diminishing income opportunities. Throughout Eastern Europe and the former Soviet Union, millions of hectares of farmland were abandoned after the collapse of socialism; thus similar reforestation opportunities may exist in other parts of this region.

Keywords: carbon flux, carbon sequestration potential, Carpathians, cropland abandonment, forest harvesting, forest transition, former Soviet Union, land-use legacies, postsocialist land-use change

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Introduction

Land use plays a critical role in the global carbon cycle and quantifying historic and potential future land-use effects on carbon fluxes is therefore a research priority (Houghton & Goodale, 2004; Bondeau *et al.*, 2007; Schulp *et al.*, 2008). Emissions from deforestation in the tropics have received much attention (DeFries *et al.*, 2002; Achard *et al.*, 2004), yet forests often recover during industrialization and urbanization, when farmland is abandoned (Kauppi *et al.*, 2006; Lambin & Meyfroidt, 2010). Such forest expansion (here: forest recovery on previously nonforested land such as agricultural land) can sequester large amounts of carbon, sometimes turning source regions into sinks (Grau *et al.*, 2004; Gimmi *et al.*, 2009; Rhemtulla *et al.*, 2009). However, farmland abandonment effects on carbon fluxes remain poorly understood in many regions of the world, partly because abandonment rates are unclear, rates and pathways of forest recovery are highly variable (Franklin *et al.*, 2002), and baseline information on historic forest cover is missing.

Vast areas of farmland were abandoned in Eastern Europe and the former Soviet Union after the collapse of

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socialism in 1989 (EBRD & FAO, 2008; Henebry, 2009). The shift from centralized toward market-oriented economies resulted in a fundamental restructuring of the region's agricultural sectors, including price liberalization for agricultural products and inputs (e.g., fertilizer), disappearing guaranteed markets within the Eastern Bloc, increasing foreign competition, and the privatization of land and capital assets (Ioffe *et al*., 2004; Lerman *et al*., 2004; Rozelle & Swinnen, 2004). The transition period was also characterized by large-scale outmigration from rural areas (Ioffe *et al*., 2004; Elbakidze & Angelstam, 2007). Altogether, this triggered farmland abandonment at unprecedented rates (Peterson & Aunap, 1998; Kuemmerle *et al*., 2008) in what has been called 'the most widespread and abrupt episode of land change in the 20th century' (Henebry, 2009).

Postsocialist land-use change likely affected the region's carbon dynamics in profound ways (Smith *et al*., 2007). Most aboveground biomass in farmland systems is harvested or consumed, and cultivation frequently reduces soil carbon stocks compared with natural ecosystems (Post & Kwon, 2000; Houghton & Goodale, 2004). Where farming ceases, significant amounts of carbon can be sequestered as succession replaces farmland with grasslands, shrublands, and finally forests (Houghton, 1999; Post & Kwon, 2000; Rhemtulla *et al*., 2009). Yet, despite widespread postsocialist farmland abandonment in Eastern Europe and the former Soviet Union, resulting carbon fluxes have so far only been assessed in two studies (Larionova *et al*., 2003; Vuichard *et al*., 2008). Focusing on soil carbon, a process-driven ecosystem model revealed that cropland–grassland conversions in European Russia resulted in a net carbon sink of up to 64 Tg C between 1991 and 2000 (Vuichard *et al*., 2008). Similarly, downscaling carbon sequestration rates measured in abandoned fields around Moscow suggest cropland abandonment may offset a significant amount of Russia's industrial CO_2 emissions (Larionova *et al*., 2003). Both prior studies focused solely on cropland–grassland conversions although carbon storage potential in regrowing forests may be much higher (Houghton, 2005; Luyssaert *et al*., 2008). No study in Eastern Europe has assessed carbon fluxes on farmland and in forests in tandem, which would be required for quantifying net fluxes. Moreover, existing studies only analyzed regions in European Russia, yet abandonment rates varied substantially across Eastern Europe and the former Soviet Union (Peterson & Aunap, 1998; Kuemmerle *et al*., 2008, 2009b). What is missing are regional-level accounts of net carbon fluxes from land-use change in the postsocialist period, particularly for areas outside Russia.

Land-use statistics from the postsocialist era are often of unknown quality or were derived inconsistently over time, and as a result there are large uncertainties regarding the rates of farmland abandonment in some Eastern European regions. Likewise, the reliability of forest harvesting statistics is sometimes uncertain (Houghton *et al*., 2007; Grainger, 2008). Forestry statistics also capture neither forest expansion on former farmland, nor illegal logging, which was widespread during the transition period (Nijnik & Van Kooten, 2000; Buksha, 2004; Kuemmerle *et al*., 2009a). Satellite remote sensing can mitigate some of these problems, because sensors with relatively long data records allow for reconstructing forest and farmland change in a consistent manner across large areas. Specifically, the Landsat image archive provides a continuous data record since the early 1970s (Cohen & Goward, 2004), making it valuable for quantifying postsocialist forest cover change (Bergen *et al*., 2008; Main-Knorn *et al*., 2009; Olofsson *et al*., 2010), and farmland abandonment (Peterson & Aunap, 1998; Kuemmerle *et al*., 2008).

A second obstacle for quantifying the net carbon flux from land use is the need to consider broad time scales. Past deforestation, forest expansion on abandoned farmland, and logging can have long-lasting legacies on today's carbon budgets, because carbon release can be gradual or lagged (Houghton, 1999; Foster *et al*., 2003), and because regenerating forests sequester carbon at a faster rate than mature forests (Houghton, 2005). Conversely, conversion from landscapes dominated by mature forest, with high carbon storage capacity, to agricultural or young-forest dominated landscapes results in net loss of carbon from the conversion site and a subsequent release of carbon to the atmosphere (Harmon *et al*., 1990). The low-point in forest cover in many western European countries occurred in the 19th century (Kauppi *et al*., 2006), but there is evidence that this turning point occurred substantially later in Europe's East (Mather, 1992; Turnock, 2002) and that long-term forest trends differed markedly among regions (Tsvetkov, 1957; Kozak *et al*., 2007). Moreover, forests were heavily exploited during socialism (Nijnik & Van Kooten, 2000; Turnock, 2002), possibly counteracting forest recovery. Overall, historic forest cover trends are uncertain in many regions in Eastern Europe, as are the effects of land-use change in the 20th century on the region's net carbon fluxes.

This is unfortunate, because a better understanding of recent carbon fluxes is urgently needed to quantify the region's future carbon sequestration potential. Farmland abandonment and subsequent forest expansion affect a range of ecosystem processes and services (DLG, 2005), improving some services (e.g., water quality, soil stability, carbon sequestration) while reducing others (e.g., agricultural production). The future of Eastern Europe's abandoned farmland is uncertain and competing land-use claims are likely (EBRD & FAO, 2008; Verburg & Overmars, 2009). Reforestation and afforestation of fallow farmland could be an attractive land use in light of incentives provided by carbon markets, particularly in areas where farming conditions are marginal. Quantifying carbon fluxes and future sequestration potential of abandoned farmland therefore has important policy implications and is a key component of identifying tradeoffs and synergies among competing land-use options.

Our goal was to reconstruct historic and recent carbon fluxes and to quantify carbon sequestration potential in western Ukraine, where forests have been heavily exploited in the 19th and 20th century (Nijnik & Van Kooten, 2000; Kuemmerle *et al*., 2009a), and where farmland abandonment was widespread after the collapse of the Soviet Union in 1991 (Turnock, 2002; Elbakidze & Angelstam, 2007). In previous work, we used satellite images to map forest harvesting, farmland abandonment, and forest expansion on former farmland (Kuemmerle *et al*., 2008, 2009a). Forest inventory statistics are available from both the socialist and Austro–Hungarian periods, forming a record from the mid 1800s to the present day. Specifically, we asked the following research questions:

1. How has land-use change affected the carbon balance in western Ukraine throughout the 20th century?
2. What are the legacies of socialist land-use practices for the net carbon flux from land use in the 21st century?
3. What is the future carbon storage potential on abandoned farmland in the study region?

Materials and methods

Study region

Our study region encompassed four Oblasts (i.e., states) in western Ukraine (Lvivska, Ivano-Frankivska, Zakarpatska, and Chernivitska Oblasts), an area of 56 600 km^2 (Fig. 1). The study region contains the entire Ukrainian Carpathians, running from west to southeast, and extends into the Polissian lowland in the north and east, and the Pannonian lowland in the southwest. Elevations range from 100 to 2061 m and climate in the region is mostly temperate continental with an average summer temperature of 6–20 °C (depending on elevation), average winter temperature of -10 to -3 °C, and average yearly precipitation of 600–1200 mm. In the Pannonian lowlands, slightly warmer and wetter climate prevails (Herenchuk, 1968; UNEP, 2007). Climate and topography result in five potential vegetation types that are distributed along an elevation gradient: plains ($<$200 m) dominated by oaks (*Quercus sp*) and beech (*Fagus sylvatica*) forests; foothills (200–600 m) dominated by oaks, beech, and hornbeam (*Carpinus betulus*); montane mixed forests with beech and silver fir (*Abies alba*) (600–1100 m); montane temperate and subalpine coniferous forests (up to 1500 m) dominated by Norway spruce (*Picea abies*) and stone pine (*Pinus cembra*); and an alpine zone above treeline (UNEP, 2007).

The region contains about 25% of Ukraine's forests. Especially the Carpathian forests are highly productive, with annual increments of up to 5 $m^3\,ha^{-1}$ and standing volumes of $>$300 $m^3\,ha^{-1}$ (Buksha, 2004; Nijnik, 2005). Forestry has thus long been an important economic activity and forests in the region were heavily exploited, both during socialism (Nijnik & Van Kooten, 2000; Buksha *et al*., 2003) and in the transition period when illegal logging increased (Buksha, 2004; Kuemmerle *et al*., 2009a). Average rotation age in the study region is around 100 years. Farming conditions vary and are relatively marginal in the mountains and in wide areas of the plains where poor soils dominate (e.g., gleysols, podzols), or groundwater levels are high (e.g., in the Dnister floodplains). In such areas, dairy, beef, oat, and potatoes are the main agricultural products. Where farming conditions are more favorable, major agricultural products include grain (e.g., winter wheat, buckwheat), corn, oil crops (e.g., rape, sunflowers), and dairy, and meat. Total population of the study region is 6.08 million, 49% of which live in urban areas (2008 census, http://www.ukrcensus.gov.ua).

Forestry statistics

Pre-World War I (WW I) forest cover estimates were available for the years 1872 (Orzechowski, 1872) and 1876 (Hołowkiewicz, 1877) for former counties (*powiaty*) of the Kingdom of Galicia and Lodomeria, covering the area of contemporary Lvivska and Ivano-Frankivskska Oblasts (the other two oblasts were not covered by these data). For the period between WW I and WW II, forest cover estimates were available for 1923 and 1928 (Miklaszewski, 1928) and 1937 (Mały Rocznik Statystyczny, 1939) for the same area. We estimated percent forest cover for the entire region by assuming main forest trends were comparable between the regions (i.e., the proportion of forest cover among the oblast remained stable during the 20th century) and then converted percent to area estimates. Forest cover before large-scale human disturbance was assumed to be 75% (Herenchuk, 1968), and we also assumed that large-scale forest clearing in the region did not start until the 17th century (Turnock, 2002; UNEP, 2007).

Forestry statistics from the Soviet period were acquired from the Statistical Yearbooks of the State Statistics Committee of Ukraine for the years 1946, 1970, 1973, and 1978. For 1946 forest cover data was only available as percent forest cover that we converted to area estimates. We also obtained detailed current age-distributions (10-year intervals) for each oblast in our study region from the State Forestry Committee of Ukraine (http://dklg.kmu.gov.ua). Age distributions were area estimates and covered all forests managed by state forest enterprises (about 81% of the total forest in the study region).

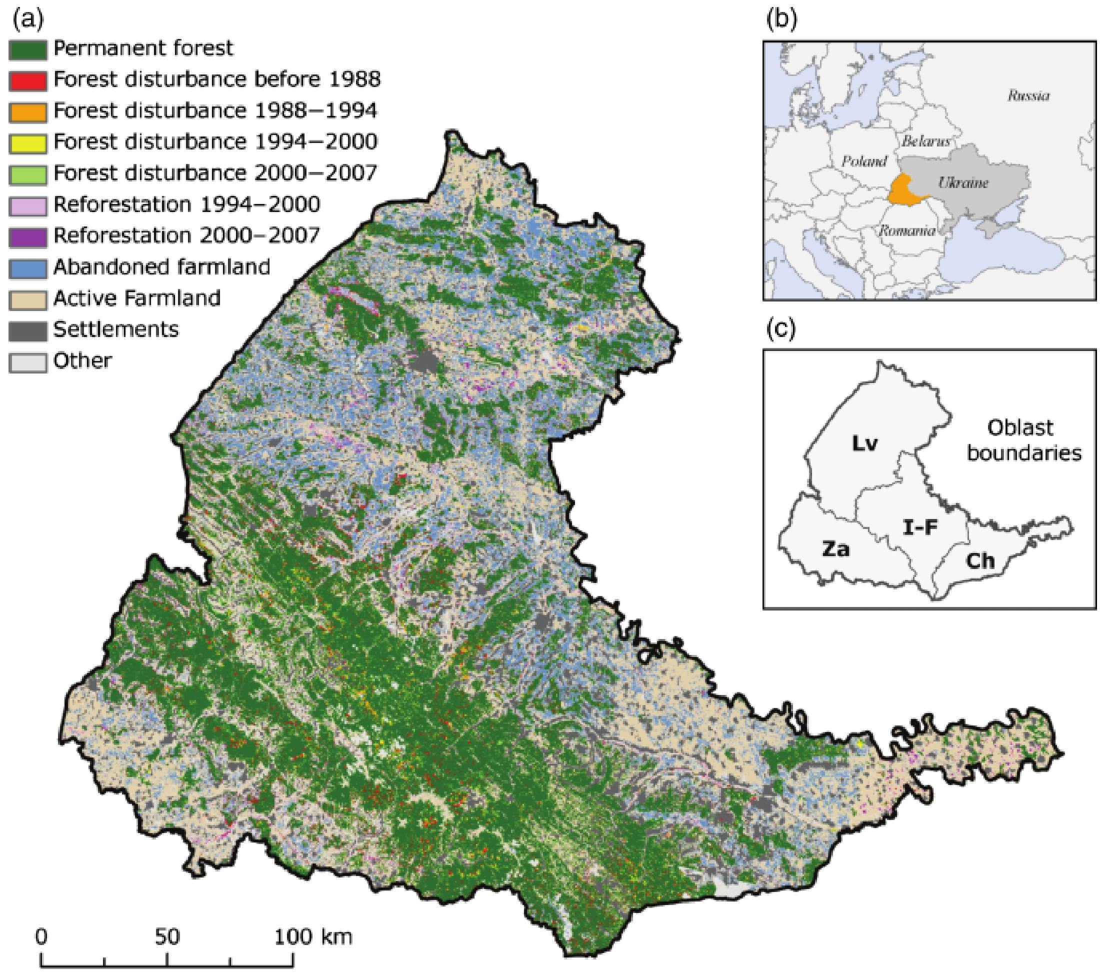

Fig. 1 (a) Forest cover changes and farmland abandonment patters between 1988 and 2007 in the study region. Land cover changes were mapped from Landsat TM and ETM + images. (b) Location of the study region in Eastern Europe. The study region (highlighted in orange) consists if four Ukrainian Oblasts (equivalent to states) (c) Administrative boundaries of Lvivska Oblast (Lv), Ivano-Frankivska Oblast (I-F), Zakarpatska Oblast (Za), and Chernivetska Oblast (Ch).

Remote sensing maps

A map of forest harvesting and forest expansion patterns between 1988 and 2007 was available from our previous research (Kuemmerle *et al.*, 2009a). This map covered about 55% of the study region and was derived from Landsat Thematic Mapper and Enhanced Thematic Mapper Plus (ETM +) images from 1988, 1994, 2000, and 2007 at a resolution of 30 m. We classified forest vs. nonforest for each image using ~1500 random ground truth points (obtained from high-resolution imagery interpretation) per image and a Support Vector Machines (SVM) classifier. Second, we derived forest change trajectories via postclassification comparison (i.e., stand replacing disturbance before 1988, during 1988–1994, 1994–2000, and 2000–2007, as well as forest expansion in 1988–2000 and 2000–2007). Forest regrowth following pre-1988 disturbance was distinguished from forest expansion on abandoned farmland based on differences in regeneration time and the spatial context of regeneration sites (Kuemmerle *et al.*, 2009a). Here, we extended the map to match the boundaries of our study region using the same methodology (three additional Landsat footprints). In total, we used 23 Landsat images. The mean accuracy of the individual forest/nonforest maps was 97.04% [standard deviation (SD) 1.39%] with a mean κ value of 0.94 (SD = 0.03) (see supporting information, Table S1). Change detection accuracy was assessed separately and exceeded 83% for all disturbance classes. The forest cover change map (Fig. 1) showed that about 155 800 ha of forest were harvested between 1988 and 2007, with annual forest harvesting rates of 5460 ha in 1988–1994, 6720 ha in 1994–2000, and 5950 ha in 2000–2007. About 87 400 ha had been logged before 1988 and regenerated in 1988–2007. Forest expansion on former farmland occurred on 64 400 ha.

Farmland abandonment was mapped between 1988 and 2007 using 32 Landsat images About 87 400 ha had been logged before 1988. Abandonment was defined as farmland (both cropland and managed grassland) in use during the late 1980s that converted to fallow or successional land (i.e., shrubland or young forest) by 2007. We used a two-step change-detection approach. First all active farmland during the last years of socialism was masked using 2–3 Landsat images per footprint. These images were selected to cover different seasons and consecutive years, to make use of phenology information that is important to separate farmland in use from abandoned areas (Kuemmerle *et al*., 2008; Baumann *et al*., under review). We used an SVM classifier and about 13 000 random ground truth points that we labeled based on high-resolution imagery available in Google Earth, topographic maps, and the Landsat images from the 1980s. Second, we mapped abandoned farmland using a multitemporal change classification based on SVM and a random sample of about 10 000 ground truth points (Baumann *et al*., under review). Classification accuracy was 93% (SD = 1.59%) with a κ value of 0.86 (SD = 0.03) for the farmland mask and 88.4% (SD = 8.03%) with a κ value of 0.74 (SD = 0.14) for the abandonment map (see supporting information, Tables S2 and S3). Farmland abandonment was widespread in the study region (Fig. 1), accounting for 32% of all farmland in use during the last years of socialism and covering about 728 400 ha (13% of the study region). We combined the forest disturbance map and the farmland abandonment map into a single change map, giving precedence to the prior in the rare case of conflict between the two maps.

The carbon bookkeeping model

To model net fluxes of carbon due to land-use change, we used a carbon bookkeeping model (Moore *et al*., 1981; Houghton *et al*., 1983; Houghton & Hackler, 2001). The model tracks year-to-year changes in carbon stocks due to forest harvesting followed by forest regeneration, permanent clearing of forest, and forest expansion on previously nonforested lands (Moore *et al*., 1981). For each event, the ecosystem response in terms of released and sequestered carbon (i.e., uptake) is calculated. Rates of harvesting, clearing, and forest expansion are provided as annual time-series, to track the net carbon flux over time (Houghton *et al*., 1983; Houghton & Hackler, 2001).

Forest harvesting is characterized by a simultaneous uptake and release of carbon [Eqn (1)] and the model assumes that forest regeneration follows harvesting. The model allocates all harvested wood into three different carbon pools. The carbon in the first pool is released immediately after harvest (i.e., within 1 year), mainly as firewood. Short-lived wood products (e.g., packaging material) end up in the second pool, where the fraction of the initial amount of carbon in the pool decays at a rate of 10% yr^{-1}. The third pool contains long-lived wood products (e.g., furniture, building material) where carbon decays at a rate of 1% yr^{-1}. Slash left on site gradually decays and is added to the total release of carbon to the atmosphere. In the event of permanent forest clearing (i.e., deforestation), carbon stored in both soil and vegetation is released [Eqn (2)]. Wood removed from the site is assigned to one of the three pools and released over time (immediate, short-term, and long-term release) and slash left on site gradually decays. In contrast to forest harvesting, which does not have consistent effects on the soil carbon flux (Johnson & Cutis, 2001), forest clearing for cultivation usually triggers an exponential loss of soil carbon (Yanai *et al*., 2003). In the event of forests expansion into previously nonforested lands, for example due to forest planting or natural succession on abandoned farmland, carbon is sequestered in both soil and vegetation [Eqn (3)]. No carbon is released in this event. Finally, the net carbon flux due to land-use change is calculated as the sum of the individual fluxes by the following equations:

$$\begin{aligned}\mathrm{Flux_{harvest}} = &\mathrm{Pool_{1\,year}} + \mathrm{Pool_{10\,years}} + \mathrm{Pool_{100\,years}} \\ &+ \mathrm{Slash} - \mathrm{Regrowth}\end{aligned}, \quad (1)$$

$$\begin{aligned}\mathrm{Flux_{clearing}} = &\mathrm{Pool_{1\,year}} + \mathrm{Pool_{10\,years}} + \mathrm{Pool_{100\,years}} \\ &+ \mathrm{Soil_{release}} + \mathrm{Slash}\end{aligned}, \quad (2)$$

$$\mathrm{Flux_{forest\,expansion}} = -\mathrm{Regrowth} - \mathrm{Soil_{uptake}}, \quad (3)$$

$$\mathrm{Flux_{final}} = \mathrm{Flux_{harvest}} + \mathrm{Flux_{clearing}} + \mathrm{Flux_{forest\,expansion}}. \quad (4)$$

This carbon bookkeeping model has been widely applied to assess land-use effects on carbon fluxes from regional to global scales (Houghton *et al*., 1985, 1999; Houghton, 1999; Houghton & Hackler, 2001). Whereas earlier applications of the model relied on forestry statistics to estimate land-use change, more recent applications used remotely sensed forest cover change data (Houghton *et al*., 2000; DeFries *et al*., 2002; Olofsson *et al*., 2010).

Model parameterization

We estimated forest harvesting, permanent clearing, and forest expansion from 1800 to 2007 based on the remote sensing maps, forestry statistics, and a current age distribution as input for the carbon bookkeeping model. For 1988–2007, annual rates were derived from the Landsat forest change map (Fig. 1). The forest change map also captured harvesting before 1988, but the exact time period of those harvests was unclear. The forest age distribution revealed annual harvesting of about 12 000 ha during the 1980s. This suggested that the pre-1988 forest harvesting measured in the satellite-based map represented the period 1982–1988, which matches well with the capacity of Landsat images to detect full canopy disturbances in temperate forests (Healey *et al*., 2005; Kuemmerle *et al*., 2007).

To reconstruct long-term forest cover trends from the forestry statistics, we made two assumptions. First, we assumed that forest cover changes documented in historic statistics represent either permanent clearing or forest expansion, and do not capture short-term forest cover changes before 1923 (the low-point in forest cover, see 'Results'). We assumed a linear forest cover decline, because population growth during the second half of the 19th century was relatively linear (Soja, 2008) and industrial logging did not start until the turn of the century (Augustyn, 2004). Second, we assumed that perma-

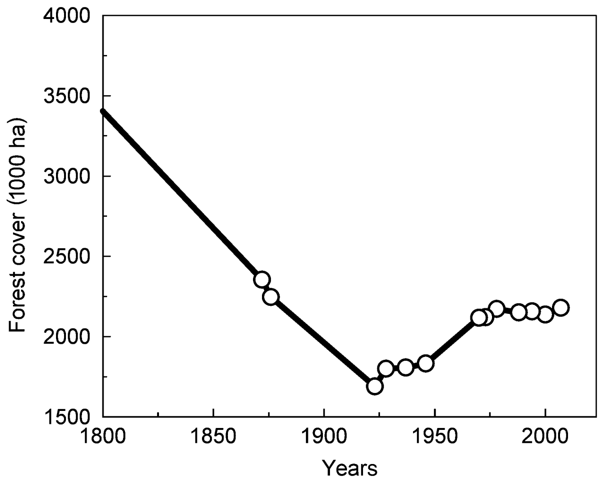

Fig. 2 Forest cover changes in western Ukraine between 1800 and 2007. Estimates are from historic land-use surveys (1872, 1876, 1923, 1928, 1937), statistical yearbooks (years 1946, 1970, 1973, 1978), and remote sensing images (1988, 1994, 2000, 2007). Presettlement forest cover for the study region was estimated at 75% (see 'Materials and methods' for details).

nent forest clearing was not widespread after 1923. This allowed us to calculate annual forest clearing rates (before 1923) and annual forest expansion rates (after 1923) for the entire time period not covered by the satellite images (Fig. 2). These assumptions are consistent with other accounts of historic forest change in the region (Mather, 1992; Turnock, 2002; Augustyn, 2004; Kozak *et al*., 2007).

Harvesting rates before 1982 were reconstructed from the age-distributions. We assumed the age distribution of state forest and total forest to be identical and rescaled the age distribution based on total forest cover measured from the satellite images. We then subtracted the total area of forest expansion for each 10-year interval to derive the area of forest regrowth due to forest disturbances. Large-scale natural disturbances in the region are infrequent, and salvage logging after windthrow and mortality caused by insects and disease is common (Lavnyy & Lässig, 2007; Kuemmerle *et al*., 2009a). We therefore assumed all disturbances to represent forest harvesting, which allowed calculating annual harvesting rates. We did not estimate harvesting rates before 1880, because large-scale logging did not start until the expansion of railway networks in the late 19th century (Augustyn, 2004), and pre-1880 harvesting rates only have a small affect on 20th century fluxes, and no effect on future carbon fluxes in our model. Forest cover and use time series from 1800 to 1900 were only used to spin up the model.

In addition to the time-series of forest change, the carbon bookkeeping model required several input parameters (Table 1), the slash ratio (fraction of carbon remaining on site), slash decay rate, and the fractions of carbon released after 1 year, and with annual decay rates of 0.1% and 0.01%. Regionalized estimates for slash ratio and decay rate were taken from Houghton & Hackler (2001). For forest harvesting, we estimated the three carbon pools based on wood production statistics for Ukraine (Buksha *et al*., 2003). For forest clearing, we used estimates from the Romanian Forest Service made for the Carpathian ecoregion (A. Baccini, V. Blujdea, V. Gancz, J. Hackler, R. Houghton, M. Ozdogan, C. E. Woodcock, unpublished results). Other parameters needed were the total carbon content of mature forest (per hectare), the carbon content of disturbed systems (i.e., after clearing or harvesting), and the recovery time of disturbed systems (Table 1). We used estimates from a previous study in the same ecoregion for these parameters (A. Baccini, V. Blujdea, V. Gancz, J. Hackler, R. Houghton, M. Ozdogan, C. E. Woodcock, unpublished results). Finally, we used the default soil carbon parameters for deciduous forest in the former Soviet Union (Houghton & Hackler, 2001, Table 1). To reconstruct historic carbon dynamics, we ran our model for the time period from 1900 to 2007, with a 100-year spin-up period. To test the robustness of our model toward changes in parameter estimates we varied the variables 'total carbon content of mature forest,' 'initial recovery time,' and 'full recovery time' by $\pm$ 5%, 10%, and 20% and compared carbon flux estimates. To assess the sensitivity of our results toward assumptions regarding our historic forest cover data, we varied the pre-1872 deforestation rate by $\pm$ 10% and $\pm$ 20%, and we shifted the low-point in forest cover by $\pm$ 5 and $\pm$ 10 years.

Future scenarios

The future of currently abandoned farmland in western Ukraine is uncertain, as are future logging rates and practices, meaning that simply extrapolating current land-use change rates would convey an incomplete picture of the region's potential future carbon dynamics. To analyze future land-use effects on the net carbon flux, we assessed a range of different forest harvesting and forest expansion scenarios. We used a baseline harvesting rate of 10 000 ha yr^{-1} (approximately the harvesting rate in the postsocialist period 1991–2007, see 'Results') and considered logging scenarios of 0%, 50%, 100%, 150%, and 200% relative to this rate. The modeling also assumed continuation of current harvesting practices, which are primarily rotational even-aged silviculture. Concerning forest expansion on former farmland, we considered one scenario assuming no forest expansion, six scenarios assuming different levels of forest expansion on currently abandoned farmland (10%, 20%, 30%, 40%, 50%, 75%, and 100% of all idle farmland), and two scenarios assuming additional farmland abandonment and subsequent forest expansion in the future (125% and 150%, i.e., $\sim$40% and 48% of all farmland in the study region). These five forest harvesting and ten forest expansion scenarios were compared in a fully factorial design, resulting in a total of 50 scenarios. All future scenarios assumed zero permanent forest clearing. All simulations covered the time period 2008–2100 and we compared carbon fluxes and the total amount of carbon accumulated (or released) for the different scenarios.

Results

Land use substantially affected carbon fluxes in western Ukraine during the last two centuries, mainly as a result

Table 1 Parameter estimates used in the carbon bookkeeping model

Parameter description	Estimate	Source
Fraction of C remaining on site (i.e. slash ratio) following clearing	0.33	Houghton & Hackler (2001)
Slash ratio following harvest	0.09	A. Baccini, V. Blujdea, V. Gancz, J. Hackler, R. Houghton, M. Ozdogan, C. E. Woodcock (unpublished results)
Slash decay rate	0.04	Houghton & Hackler (2001)
Fraction of initial C released within 1 year (clearing)	0.500	A. Baccini, V. Blujdea, V. Gancz, J. Hackler, R. Houghton, M. Ozdogan, C. E. Woodcock (unpublished results)
Fraction of initial C assigned a decay rate of 10% yr^{-1} (clearing)	0.100	A. Baccini, V. Blujdea, V. Gancz, J. Hackler, R. Houghton, M. Ozdogan, C. E. Woodcock (unpublished results)
Fraction of initial C assigned a decay rate of 1% yr^{-1} (clearing)	0.070	A. Baccini, V. Blujdea, V. Gancz, J. Hackler, R. Houghton, M. Ozdogan, C. E. Woodcock (unpublished results)
Fraction of initial C released within 1 year (harvesting)	0.180	Buksha *et al.* (2003) – wood used for fuel and energy
Fraction of initial C assigned a decay rate of 10% yr^{-1} (harvesting)	0.270	Buksha *et al.* (2003) – wood used for packaging
Fraction of initial C assigned a decay rate of 1% yr^{-1} (harvesting)	0.460	Buksha *et al.* (2003) – wood used for building, furniture, mining, etc.
C content of mature forest ($tC\,ha^{-1}$)	144	A. Baccini, V. Blujdea, V. Gancz, J. Hackler, R. Houghton, M. Ozdogan, C. E. Woodcock (unpublished results)
Minimum C content after disturbance ($tC\,ha^{-1}$)	5	A. Baccini, V. Blujdea, V. Gancz, J. Hackler, R. Houghton, M. Ozdogan, C. E. Woodcock (unpublished results)
Initial C content of disturbed system ($tC\,ha^{-1}$)	127	A. Baccini, V. Blujdea, V. Gancz, J. Hackler, R. Houghton, M. Ozdogan, C. E. Woodcock (unpublished results)
Initial recovery time (forest expansion) (year)	80	A. Baccini, V. Blujdea, V. Gancz, J. Hackler, R. Houghton, M. Ozdogan, C. E. Woodcock (unpublished results)
Full recovery time (forest expansion) (year)	100	A. Baccini, V. Blujdea, V. Gancz, J. Hackler, R. Houghton, M. Ozdogan, C. E. Woodcock (unpublished results)
Soil C content in undisturbed systems ($tC\,ha^{-1}$)	134	Houghton & Hackler (2001)
Soil C content after disturbance ($tC\,ha^{-1}$)	114	Houghton & Hackler (2001)
Minimum soil C content ($tC\,ha^{-1}$)	107	Houghton & Hackler (2001)
Time for soil C to recover after abandonment (year)	40	Houghton & Hackler (2001)

of historic deforestation and forest recovery in the 20th century. Forest cover in the Ukrainian Carpathians diminished rapidly during the 19th century (to $<40\%$ of the presettlement cover). The low point in forest cover was reached in the early 20th century (Fig. 2), when <1.7 million ha of forest remained (from previously >4.3 million ha). From 1930 to 1970, forests expanded rapidly at annual rates of up to 12 000 $ha\,yr^{-1}$. After 1970, the region's forest cover remained fairly stable, covering an area of about 2.1 million ha (Fig. 2). Surprisingly, forest cover did not increase substantially after the collapse of socialism, despite widespread farmland abandonment.

Forest harvesting was most intense during the first half of the 20th century, reaching its peak during the 1940s and 1950s with up to 30 000 ha of annual harvesting (Fig. 3). After 1960, harvesting rates were substantially lower and after a short episode of increased logging in the 1980s, harvesting rates decreased again markedly after Ukraine gained independence in 1991(to $<10\,000\ ha\,yr^{-1}$). Forest expansion rates were highest between 1940 and 1970, reaching up to 12 000 $ha\,yr^{-1}$ (Fig. 3). Forest expansion came to a halt in the 1980s, but increased again after the breakdown of the Soviet Union (about 2100 $ha\,yr^{-1}$ between 1994 and 2000). Between 2000 and 2007, forest expansion rates were almost identical to harvesting rates (i.e., annual forest cover increase of 8600 ha) (Fig. 3).

The observed land-use trends had marked effects on the region's modeled net carbon flux (Fig. 4). Deforestation and intensive logging resulted in the release of large amounts of carbon in the first half of the 20th century, with annual net emissions of up to 2.94 Tg C (in 1900). During socialism, the region turned from a net source to a net sink at around 1960 (Fig. 4), mainly due to forest expansion on abandoned farmland, both before and during the early years of socialism. Carbon emissions during socialism peaked immediately following western Ukraine's incorporation into the Soviet Union (1946) and the shift from source to sink occurred despite relatively high emission rates from forest harvesting (up to 2.67 Tg C between 1960 and 1970). Carbon sequestra-

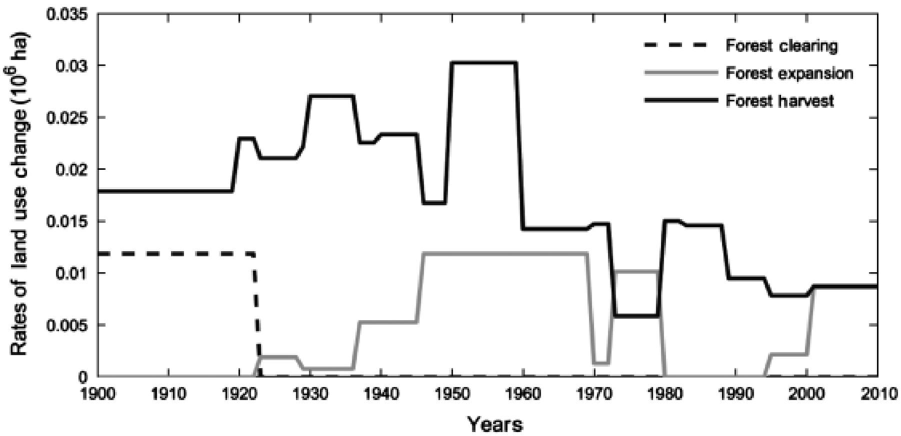

Fig. 3 Rates of permanent forest clearing, forest harvesting, and forest expansion for the time period 1900–2007 used as input data for the carbon bookkeeping model.

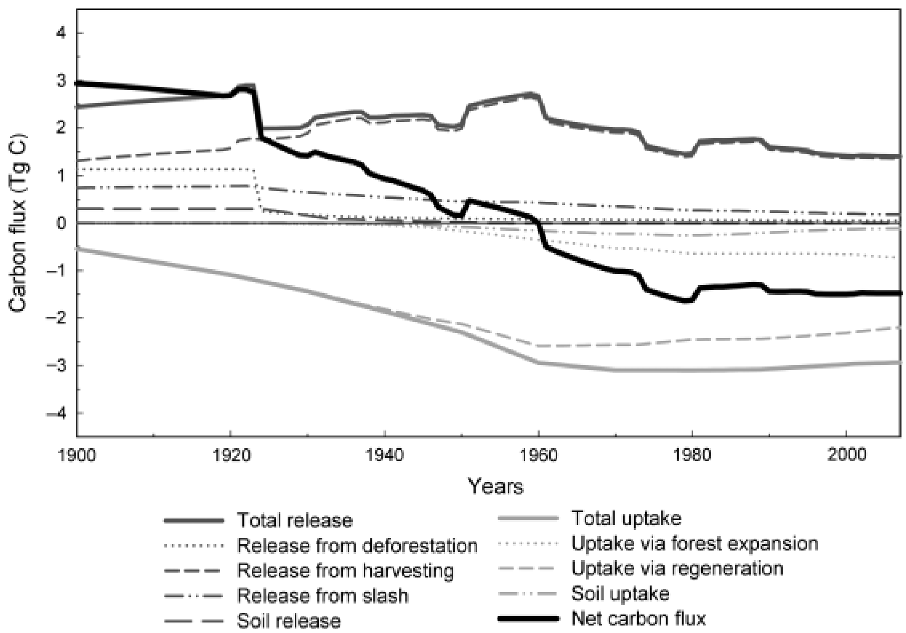

Fig. 4 Carbon fluxes due to land-use change in western Ukraine between 1900 and 2007. The net carbon flux is the total release of carbon (positive flux for emissions) minus the total uptake of carbon. Total release consists of carbon emissions following forest clearing or logging via biomass that is removed from a site (release from deforestation or from harvesting), via decaying biomass on site (release from slash), or from the soil carbon pool (soil release). Total uptake consists of carbon that is stored in regrowing vegetation on abandoned sites (uptake via forest expansion) or after harvesting (uptake via regeneration) and in the soil (soil uptake).

tion rates were highest from 1960 to 1980, with 3.10 Tg C on average captured annually. Modeled fluxes of soil carbon release and sequestered soil carbon did not affect the net carbon flux substantially (Fig. 4).

Western Ukraine remained a net carbon sink during the postsocialist period, although the sink strength decreased slightly to about 1.48 Tg C yr^{-1}. Carbon emissions from forest harvesting reached a low point after Ukraine gained independence in 1991 (5% decrease between 1980 and 2007). Despite higher forest expansion rates after independence, rates of carbon sequestration in regrowing forests decreased slightly after 1990 (by 5% between 1980 and 2007), because large areas of forests on farmland abandoned in the first half of the 20th century reached maturity (Fig. 4). Overall, forest expansion on abandoned farmland was the major land-use process affecting the net carbon flux in the transition period.

Our factorial design to explore alternative future scenarios of carbon dynamics suggests Western Ukraine

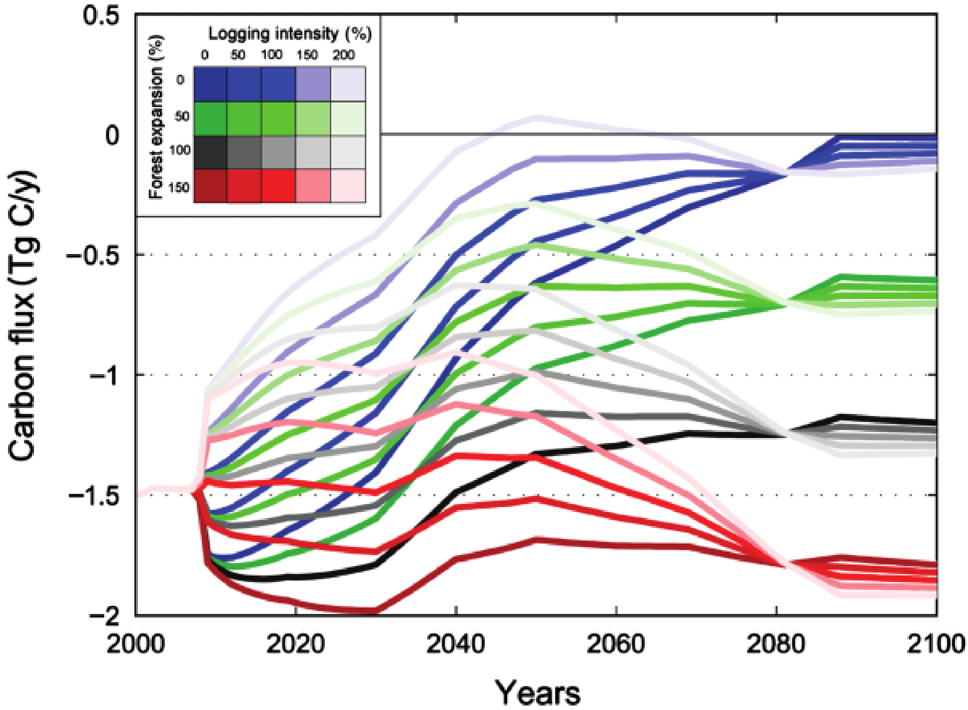

Fig. 5 Net carbon fluxes for different scenarios of logging intensity and forest expansion on currently unused farmland. Higher logging intensities lead to a higher initial release and higher sequestration in the second half of the simulation period (due to regrowing vegetation). Higher forest expansion rates result in more carbon being stored in vegetation and thus more negative net carbon fluxes.

will likely remain a carbon sink during the next 100 years (Fig. 5). Net carbon emissions from land-use activities only occurred in one out of 50 scenarios, and were very small ($<0.1\,\mathrm{Tg\,C\,yr^{-1}}$) and restricted to the time period 2040–2060. The carbon flux, however, differed substantially among the scenarios, ranging from a release of $0.07\,\mathrm{Tg\,C\,yr^{-1}}$ (lowest forest expansion scenario) to a sink of $-1.98\,\mathrm{Tg\,C\,yr^{-1}}$ (highest forest expansion scenario). Higher logging rates decreased sink strength at first, but forest regrowth on former logging sites added to the sink strength during the second half of our simulation period, resulting in higher rates of carbon uptake by 2100 for scenarios with higher logging rates when assuming the same forest expansion rates (Fig. 5). Constant fluxes were only attained by the end of our simulation period (despite constant logging and forest expansion on abandoned farmland rates) due the legacies of pre-2007 logging and abandonment (Fig. 5). Whereas different forest expansion rates determined the overall level of the net carbon flux, different harvesting rates determined the gradient (i.e., year-to-year changes) in the net carbon flux (Fig. 5).

The different scenarios suggest western Ukraine has vast potential for carbon sequestration (Fig. 6), with the total amount of potential carbon sequestration ranging from 22.37 Tg C (20 000 ha of annual forest harvesting

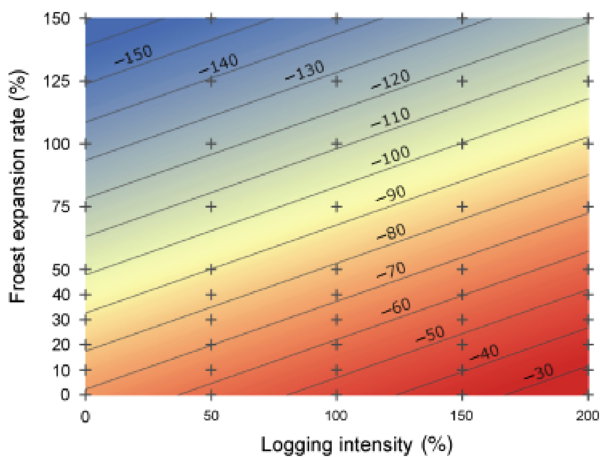

Fig. 6 Total carbon sink strength [Tg C] between 2008 and 2100 for different scenarios of logging intensity ($100\% = 5000\ \mathrm{ha\ yr^{-1}}$) and forest expansion (100% = all currently unused farmland ~728 000 ha). Crosshairs mark modeled scenarios; isolines denote identical sink strength across different scenarios.

and no further forest expansion) to 167.20 Tg C (no forest harvesting and a annual forest expansion rate of ~12 000 ha). Assuming that logging will continue at current rates and all currently idle farmland will revert back to forest until 2100, resulting in a net carbon sink of

111.24 Tg C. The difference in the total amount of carbon stored between scenarios with no forest harvesting and the highest forest harvesting rates was 46.11 Tg C and the difference between scenarios with the lowest and highest rate of forest expansion amounted to 98.71 Tg C (Fig. 6).

Several combinations of different forest harvesting and forest expansion rates resulted in identical amounts of carbon sequestered between 2008 and 2100 (Fig. 6). Generally, a 50% increase in logging rates (i.e., by 5000 ha yr^{-1}) required a 17.51% increase in the forest expansion rate (i.e., by 1400 ha yr^{-1}) to sequester the same amount of carbon by 2100. In other words, carbon emissions from harvesting 1 ha of forest would be compensated for by carbon sequestration of regrowing forest on 0.27 ha formerly nonforested land.

Table 2 Changes in current (2010) sink strength of the carbon bookkeeping model towards changes in the parameters *total amount of carbon in mature forest*, and *initial and full recovery times*

Relative change (%)	C content of mature forest (base value: 144 Tg C ha^{-1}) (Tg C yr^{-1})	Initial and full recovery times (base value: 80 and 100 years) (Tg C yr^{-1})
−20	1.2100	1.4523
−10	1.3467	1.4731
−5	1.4150	1.4785
0	1.4833	1.4833
+ 5	1.5517	1.4627
+ 10	1.6200	1.4439
+ 20	1.7567	1.3768

The sensitivity analyses showed that varying total carbon in mature forest had a moderate effect on the carbon release and sequestration fluxes, while slash and soil carbon fluxes remained relatively unaffected (Table 2). Increasing total carbon content increased current sink strength, for example from 1.48 to 1.55 Tg C yr^{-1} for a 10% increase in carbon content (from 144 to 158 Mg C ha^{-1}). Likewise, decreasing total carbon content yielded lower current sink strength (e.g., 1.35 Tg C yr^{-1} for a 10% decrease in carbon content). Model sensitivity toward changes in the parameters 'initial recovery time' and 'full recovery time' was small. Decreasing recovery time resulted in higher initial sink strength after disturbances followed by a quicker decline of carbon sequestration rates. Current sink strength increased slightly when assuming shorter initial and full recovery times (e.g., 1.45 Tg C for a 20% decrease in those parameters) and decreased for longer recovery times (e.g., 1.38 Tg C for a 20% increase in recovery time) (Table 2).

Varying deforestation rates before 1872 had a small effect on the 20th century net carbon flux (Fig. 7a). For example, the source strength in 1910 increased from 2.95 to 3.00 Tg C when assuming a 20% increase in deforestation rates. The net carbon flux after 1930 was only marginally affected by variations in pre-1872 deforestation rates. Varying the low-point in forest cover had a marked effect on net carbon fluxes from land use between 1910 and 1950 (Fig. 7b). Assuming an earlier forest transition (i.e., shift from net forest cover loss to net forest cover gain) resulted in an earlier and more rapid reduction of source strength and vice versa. Varying the low point in forest cover neither affected the net carbon flux after 1950 nor the timing of the region's shift from net source to net sink appreciably.

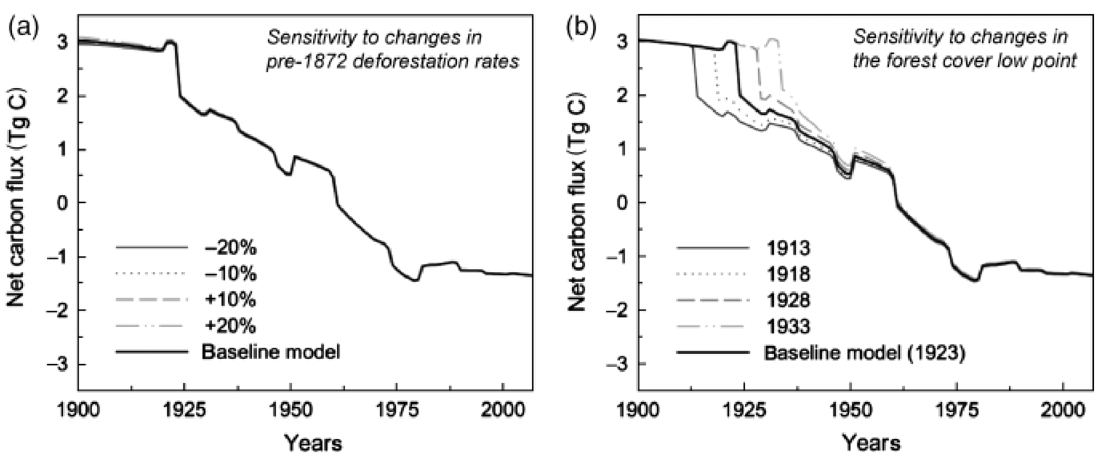

Fig. 7 Changes in the net carbon flux between 1900 and 2007 compared with the baseline model when varying pre-1872 deforestation rates by ± 10% and ± 20% (a) and when shifting the low point in forest cover by ± 5 and ± 10 years (b).

Discussion

Net carbon flux from land use in western Ukraine

Dynamics of carbon fluxes from land use in western Ukraine during the 20th century were strongly affected by several distinct phases of socioeconomic transformation. Before World War II and during the early Soviet period (before 1970), the region's industrialization triggered large-scale forest expansion, which gradually shifted the region from a net carbon source to a net sink, thus compensating for emissions from excessive Soviet forest harvesting during the same period. After 1970, our results suggest that Soviet land management retarded forest expansion, resulting in a period of relatively stable carbon fluxes. The widespread farmland abandonment that occurred after the collapse of socialism has to date only moderately affected carbon dynamics, because only a small proportion of all abandoned lands reverted to forests. Yet, future forest expansion on abandoned farmland provides great potential for additional carbon sequestration. Postsocialist farmland abandonment and subsequent forest recovery will likely increase the region's sink strength during the 21st century and this offers substantial opportunities to offset industrial carbon emissions and for providing additional rural income.

Forest expansion often occurs when agrarian societies undergo industrialization and urbanization, leading to farmland abandonment (Grau *et al*., 2004; Kauppi *et al*., 2006; Meyfroidt & Lambin, 2008), a process commonly referred to as the forest transition (Mather, 1992; Rudel *et al*., 2005; Barbier *et al*., 2009). Such a forest transition was the main driver of land-use-related carbon fluxes in western Ukraine during the 20th century, similar to the changes experienced by other European regions (Gingrich *et al*., 2007; Gimmi *et al*., 2009). Much forest had been converted to farmland during the Austro-Hungarian Empire (1772–1918) as populations grew and the railway system expanded (Turnock, 2002; UNEP, 2007), resulting in a period of high net carbon emissions (Fig. 4). This changed in the 1920s when forest area started to expand and the study region shifted to a net carbon sink. This forest expansion occurred very rapidly, in contrast to some western European regions (Mather, 1992; Kauppi *et al*., 2006), which is explained by three factors: First, agricultural expansion often occurred in areas only marginally suited for farming that were quickly abandoned at the onset of industrialization and urbanization (Turnock, 2002). Second, accelerated farmland abandonment occurred in some areas in western Ukraine during and after World War II due to depopulation and resettlement (Augustyn, 2004; Kozak *et al*., 2007). Third, large efforts were made to industrialize agriculture and rural societies after the region became part of the Soviet Union in 1945. Most farmland was collectivized and managed in large-scale, highly mechanized agricultural enterprises (Augustyn & Kozak, 1997; Ash & Wegren, 1998), decreasing the importance of subsistence farming.

The Soviet period was, however, also characterized by forest exploitation at high, often unsustainable rates, especially in the 1940s and 1950s (Nijnik & Van Kooten, 2000; Turnock, 2002). This resulted in a severely skewed age structure and considerable logging-related carbon emissions ($>2\,\mathrm{Tg\,C\,yr^{-1}}$). Surprisingly though, these emissions were more than compensated for by carbon sequestered in forest expanding on former farmland and the region even turned from a net source to a net sink during the period of heaviest logging (Fig. 4). A second interesting aspect is the relative stability of forest cover during the last two decades of socialism (1970–1990), when many Western European regions experienced continued forest expansion (Tasser *et al*., 2007; Gimmi *et al*., 2009). Command-and-control land management heavily subsidized farming (e.g., via guaranteed prices and markets) and maintained farming even when agricultural enterprises were not profitable. This likely explains the low abandonment rates during that period and suggests socialism has slowed down the trend in increasing forest cover since the forest transition (Kozak *et al*., 2007).

The collapse of the Soviet Union drastically changed this situation. Many state-owned farms went bankrupt, out-migration from rural areas became common, and widespread farmland abandonment occurred (Fig. 1). Yet carbon sink strength did not change noticeably and even declined slightly after 1991, partly because sequestration rates in regrowing forests decreased over time on areas abandoned during the mid-20th century. Moreover, forest expansion on former farmland in the postsocialist period has been slow (Kuemmerle *et al*., 2008), partly because forest expansion mainly occurs via natural succession (Turnock, 2002; Buksha, 2004). A third factor was that logging rates did not decline appreciably after 1991, mainly because illegal logging and sanitary clear-cutting compensated for declines in official harvests (Kuemmerle *et al*., 2009a).

On the other hand, the relatively slow forest expansion in the postsocialist period presents a vast potential for future carbon sequestration. Although current socioeconomic trends suggest that a major portion of the currently unused farmland will eventually revert back to forests, the future of Eastern Europe's farmland remains uncertain (DLG, 2005; Verburg & Overmars, 2009). For example, surging food prices and a growing biofuel demand could become incentives to farm abandoned lands again, whereas a continuing rural exodus or an increasing focus on second-generation biofuels could spur forest planting (Elbakidze & Angelstam, 2007; EBRD & FAO, 2008; Rudel, 2009). In exploring future scenarios, our goal was not to make a correct forecast, but to analyze the range of available options. Interestingly, the region remained a carbon sink throughout the 21st century in almost all of our scenarios, even if logging intensity would double (Fig. 5). Our model also showed that soil carbon accumulation, the only carbon flux that has so far been assessed in the context of postsocialist land-use change (Vuichard *et al*., 2008), was small compared with carbon sequestration in regrowing forests.

The large and currently untapped carbon sequestration potential may offer opportunities for offsetting some of Ukraine's carbon emissions. The region's current sink strength is $1.48\,\mathrm{Tg\,C\,yr^{-1}}$ and our scenarios suggest sequestration rates could be maintained or even increased, particularly when combined with adequate forest management practices. Carbon sequestration in our study region (about 9% of the country) already compensates for roughly 2% of Ukraine's total carbon emission of $94\,\mathrm{Tg\,C\,yr^{-1}}$ (UN, 2007) and increased forest planting on former farmland could be an attractive low-cost option to comply with international agreements such as the Kyoto Protocol (Nijnik, 2005; Nijnik & Bizikova, 2008). Moreover, if properly linked with nature conservation and rural development policies, increased carbon sequestration via forest planting on sites that would not reforest naturally could created win–win situations and provide additional income in otherwise increasingly depressed rural areas (Klooster & Masera, 2000; Nijnik, 2005). Implementing such schemes is however not easy and would require overcoming existing divides among the economic and environmental policy arenas, and a more integrated approach to forestry and agricultural land-use planning (Nijnik, 2005).

There is considerable potential for western Ukraine's carbon capacity to incentivize sustainable forest management activities that would have other environmental cobenefits. Ukraine is eligible for both, the Joint Implementation mechanism established under the Kyoto Protocol, and the Voluntary Carbon Standard, that include a range of options for the forest sector, including avoided deforestation, afforestation/reforestation, and improved forest management. All three options would enhance net carbon storage in the region (Keeton & Crow, 2009).

Model uncertainty

Our analyses used a robust and well-established carbon bookkeeping model that we adjusted to our local conditions using parameter estimates directly measured for our study region (e.g., input time series, age class distributions) or the same ecoregion (e.g., biophysical parameters). Our sensitivity analyses showed that the model was relatively robust toward small variations in important parameters (e.g., recovery time, total carbon stored), our reconstructions of past forest cover change are congruent with fine-scale studies from the same region (Kozak *et al*., 2007; Sitko & Troll, 2008), and satellite-based maps captured land-use change with high accuracy, all of which bolstered our confidence in our results. Moreover, our model results showing net carbon losses from terrestrial vegetation during the time period in which primary forests were largely converted to rotational plantations and as forest harvesting intensity increased is consistent with previous studies (Harmon *et al*., 1990; Harmon & Marks, 2002; Nunery & Keeton, 2010).

A few potential sources of uncertainty remain. First, we assumed no major deforestation during Soviet time. If some deforestation happened, we would have overestimated harvesting rates while underestimating deforestation and forest expansion rates, but this would not have affected our net carbon flux substantially. Second, we acknowledge the higher level of uncertainty of our historic forest cover data compared with statistics from Soviet times and remote sensing. Yet, our sensitivity analyses clearly suggest that possible uncertainty (e.g., regarding the timing of the low-point in forest cover or pre-1872 logging rates) does not affect carbon fluxes in the 20th century substantially, thus not challenging any of our main conclusions. Moreover, all of our main assumptions regarding the historic forest cover time series are well document in other, independent studies (Mather, 1992; Turnock, 2002; Augustyn, 2004; Kozak *et al*., 2007). Third, we cannot fully rule out that some stands logged in the 20th had been already been logged in the 19th century, which would have resulted in a reduced source strength in the early 20th century.

We did not consider carbon release from thinning and selective logging. Forest management uses thinning to avert mortality due to self-thinning, i.e., increasing competition as trees increase in size with higher stand age. Both thinning and self-thinning would result in rapid release of carbon either due to use (typically fire-wood or pulp), or to decay, which is fast for smaller diameter trees. Thinning was more widespread under the Soviet regime, when forest management was intensive (Keeton & Crow, 2009), yet carbon flux from thinning was likely small compared with regeneration harvests (or 'final fellings') which were primarily clearcuts. We also did not model possible future shifts from clear-cutting-based to partial harvesting systems or a shift to longer rotation times, both of which have been shown to increase net carbon storage over more intensive harvesting practices (Swanson, 2009; Nunery & Keeton, 2010).

Logging in the Carpathians converted large areas of uneven-aged primary forest to even-aged spruce plantations, particularly during the first half of the 20th century (Turnock, 2002). Conversion of old-growth forests can release large amounts of carbon (Harmon *et al.*, 1990), because older forests are structurally more complex and therefore have higher biomass than younger and intensively managed stands (Keeton *et al.*, 2010). Carbon storage potential of old-growth forests in the Carpathians is not well-understood due to the scarcity of such stands, and the extent of old-growth stands at the beginning the time period we studied is highly uncertain, both of which prevented us from modeling old-growth conversions explicitly. This could have resulted in an underestimation of carbon release rates during the 20th century. On the other hand, higher carbon storage potential in old-growth forests would also suggest even higher sink strength of Carpathian forests in the 21st century than predicted by our model, because many forests in the Carpathians likely currently store less carbon then they did historically and forests continue to sequester carbon for long-time periods of times (Luyssaert *et al.*, 2008). From this perspective, higher rates of logging will forgo the carbon storage (i.e., sink) potential that would accrue under less intensive forest management and conservation. Our model did not consider cropland–grassland transitions. Some carbon accumulation occurs in such an event, but pales compared with carbon stored in regrowing forests (Henebry, 2009). Nevertheless, we cannot fully rule out underestimation of postsocialist carbon sequestration rates.

Our modeling approach did not incorporate climate change scenarios or CO_2 fertilization effects on plant growth in predictions of future carbon fluxes. Though climate change and elevated ambient CO_2 levels are likely to affect forest carbon dynamics (Cramer *et al.*, 2001) and soil carbon stocks (Romanenkov *et al.*, 2007), rates and trajectories of change at subregional to regional scales remain uncertain (Xu *et al.*, 2009). This is especially true in terms of potential interactions between climate change impacts and forest management (Hyvönen *et al.*, 2007). While we recognize the potential for interactions between land use, climate change, and other anthropogenic stressors, we here focused on land-use effects on carbon dynamics in order to isolate the importance of these factors.

Conclusions

We used a comprehensive dataset of historic forest data and contemporary satellite images and a carbon-bookkeeping model to quantify recent and potential future carbon fluxes in western Ukraine. Our results clearly suggest that while socialism may have delayed forest recovery following the forest transition in the early 20th century, the breakdown of the Soviet Union has released a vast and currently largely unused potential for increased carbon sequestration. Postsocialist farmland abandonment was widespread throughout Eastern Europe and the former Soviet Union (up to 20 million ha, EBRD & FAO, 2008), suggesting similar potentials in many former socialist areas. If adequately supported by policy, forest expansion on former farmland could help mitigate climate change, benefit sustainable rural development, and conserve biodiversity. Our study also showed that land-use change before World War II was the dominating factor influencing carbon dynamics throughout the 20th century. The collapse of the Soviet Union may affect continued land-use-related carbon fluxes throughout the 21st century. This emphasizes the paramount importance of land-use legacies in determining ecosystem service flows, in Eastern Europe and elsewhere in the world.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Landsat TM/ETM + images used for mapping forest disturbance and forest expansion in Western Ukraine between 1988 and 2007, and accuracy measures for the individual forest (F)/non-forest (NF) maps. Details on the classification and accuracy assessment approach are provided in: Kuemmerle et al. (2009a, b) *Forest cover change and illegal logging in the Ukrainian Carpathians in the transition period from 1988 to 2007. Remote Sensing of Environment, 113, 1194–1207.*

Table S2. Landsat TM/ETM + images used for mapping the extent of socialist farmland in Western Ukraine in the late 1980s as well as accuracy measures for the 'farmland' (F) and 'non-farmland' (NF) classes.

Table S3. Additional Landsat TM/ETM + images used for mapping post-socialist farmland abandonment in Western Ukraine between 1988 and 2007 as well as accuracy measures for the 'farmland abandonment' (AB) and 'unchanged areas' (UC) classes. For each footprint 2–3 images centered around 1988 (see Table S2) and 2007 were stacked and a multi-temporal change classification was carried out.

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