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Carbon implications of forest restitution in post-socialist Romania

P Olofsson[1], T Kuemmerle[2], P Griffiths[3], J Knorn[3], A Baccini[4], V Gancz[5], V Blujdea[6], R A Houghton[4], I V Abrudan[7] and C E Woodcock[1]

[1] Department of Geography and Environment, Boston University, 675 Commonwealth Avenue, Boston, MA 02215, USA
[2] Earth System Analysis, Potsdam Institute for Climate Impact Research (PIK), Telegraphenberg A62, D-14412 Potsdam, Germany
[3] Department of Geography, Humboldt-University Berlin, Unter den Linden 6, 10099 Berlin, Germany
[4] Woods Hole Research Center, 149 Woods Hole Road, Falmouth, MA 02540, USA
[5] Forest Research and Management Institute (ICAS), Sos. Stefanesti 128, 077190 Voluntari, Bucharest, Romania
[6] European Commission, Joint Research Centre, Institute for Environment and Sustainability, Climate Change and Air Quality Unit, Via Fermi, 21027 Ispra, Italy
[7] Faculty of Silviculture and Forest Engineering, Transylvania University of Brasov, Street Sirul Beethoven, nr. 1, Brasov, Romania

E-mail: olofsson@bu.edu

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Abstract

The collapse of socialism in 1989 triggered a phase of institutional restructuring in Central and Eastern Europe. Several countries chose to privatize forests or to return them to pre-socialist owners. Here, we assess the implications of forest restitution on the terrestrial carbon balance. New forest owners have strong incentives to immediately clearcut their forests, resulting in increased terrestrial emissions. On the other hand, logging generally decreased after 1989 and forests are expanding on unused or abandoned farmland, both of which may offset increased logging on restituted forests. We mapped changes in forest cover for the entire country of Romania using Landsat satellite images from 1990 to 2010. We use our satellite estimates, together with historic data on logging rates and changes in forest cover, to parameterize a carbon book-keeping model for estimating the terrestrial carbon flux (above and below ground) as a consequence of land use change and forest harvest. High logging rates during socialism resulted in substantial terrestrial carbon emissions and Romania was a net carbon source until the 1980s. After the collapse of the Soviet Union forest harvest rates decreased dramatically, but since restitution laws were implemented they have increased by 60% (from $15\,122 \pm 5397$ ha y^{-1} in 2000 to $23\,884 \pm 11\,510$ ha y^{-1} in 2010), but still remain lower than prior to 1989. Romania currently remains a terrestrial carbon sink, offsetting $7.6\% \pm 2.5\%$ of anthropogenic carbon emissions. A further increase in logging could result in net emissions from terrestrial ecosystems during the coming decades. However, forest expansion on degraded land and abandoned farmland offers great potential for carbon sequestration.

Keywords: carbon flux, restitution, Romania, farmland abandonment, forest harvesting, forest transition, logging, post-socialist, land-use change

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1. Introduction

Changes in land use are an important factor in the global carbon cycle (Houghton and Goodale 2004, Bondeau *et al* 2007), yet there are substantial uncertainties regarding the magnitude of carbon fluxes related to land use (Houghton 2010). While emissions from tropical forest clearing have received much attention (Houghton *et al* 2000, DeFries *et al* 2002, Archard *et al* 2002, Hansen *et al* 2008), land use effects on terrestrial carbon budgets in other regions undergoing rapid land use change remain uncertain. One such region is Central and Eastern Europe (Henebry 2009, Kuemmerle *et al* 2011), where the breakdown of socialism in 1989 triggered fundamental institutional and socio-economic changes and a deep restructuring of the region's forestry and agriculture sectors (Lerman *et al* 2004, Rozelle and Swinnen 2004, Torniainen *et al* 2006).

Forest harvesting generally declined during the 1990s as timber markets collapsed, state support diminished, and institutional changes caused uncertainty (UNECE 2005, Leinonen *et al* 2008). Since 2000, harvesting rates have been recovering, sometimes reaching or even exceeding late-socialist rates in some areas. In some regions, illegal logging has also increased in the post-socialist period as a result of rising poverty, institutional decay, and weaker law enforcement (Vandergert and Newell 2003, Henry and Douhovnikoff 2008, Kuemmerle *et al* 2009). In the agricultural sector, price liberalization, diminishing markets for agricultural products, declining rural populations, and tenure insecurity have resulted in the abandonment of more than 2 million hectares of farmland (Ioffe *et al* 2004, Henebry 2009, Baumann *et al* 2011). Reforestation (forest recovery on previously non-forested land such as farmland) on these former farmlands is now common across Eastern Europe and the former Soviet Union (Peterson and Aunap 1998, Leinonen *et al* 2008, Kuemmerle *et al* 2011).

Although these land use trends likely altered carbon budgets profoundly, the net terrestrial carbon flux during the post-socialist era remains unclear. The few existing studies have primarily focused on single land use processes, for example cropland–grassland conversions (Larionova *et al* 2003, Vuichard *et al* 2008, 2009) or logging (Bergen *et al* 2003, Krankina *et al* 2004). Likewise, most studies assess carbon fluxes in European Russia, while rates of land use change vary substantially across Eastern Europe (Ioffe *et al* 2004, Knorn *et al* 2009, Baumann *et al* 2011). Finally, existing work has mainly relied on extrapolating field measurements over short time intervals. Because the legacies of past land use can be strong, understanding changes in carbon budgets in the post-socialist period requires reconstructing carbon fluxes over longer time periods (Gimmi *et al* 2009, Rhemtulla *et al* 2009).

A major problem for assessing carbon fluxes in Eastern Europe is incomplete knowledge about the rates and spatial patterns of post-socialist land use changes. Forest inventory data from the region are sometimes of low or unknown reliability (Nijnik and Van Kooten 2006, Houghton *et al* 2007), and these data often neither account for illegal logging nor reforestation on former farmland. Likewise, estimates of the extent of abandoned farmland vary drastically among different sources (Ioffe *et al* 2004, EBRD, FAO 2008). Remote sensing can provide robust assessments of both forest cover change and farmland abandonment (Bergen *et al* 2003, Kuemmerle *et al* 2008, Kovalskyy and Henebry 2009), but we are only aware of two studies from our own previous work that have used remote sensing to reconstruct carbon dynamics in Eastern Europe. Both studies combined Landsat-based change detection with historic land use statistics to parameterize a carbon book-keeping model, revealing that farmland abandonment resulted in vast carbon sequestration in the Ukrainian Carpathians (Kuemmerle *et al* 2011), and that Georgia's forests remain a strong carbon sink despite surging fuelwood use (Olofsson *et al* 2010). While these studies highlight the useful insights such approaches can provide, they also emphasize that country-specific policies and institutions strongly affect carbon fluxes. Additional studies focusing on different institutional settings are urgently needed to better understand the carbon dynamics of Eastern Europe in the post-socialist era.

Most importantly, several Eastern European countries chose to return forest to former owners (Sikor 2004, Bouriaud and Schmithuesen 2005b, Ioras and Abrudan 2006, Salka *et al* 2006), but the effect of forest restitution on carbon fluxes remains unassessed. Romania is a prime example of a country that chose to restitute its forests, (Lawrence and Szabo 2005, Ioras and Abrudan 2006, Lawrence 2009). This process included three phases: the first restitution law (18/1991) returned a total of 350 000 ha (Vasile and Mantescu 2009), the second law (1/2000) targeted another 2 million ha, and the third and final law (247/2005) restituted all remaining forests that were privately owned prior to World War II. Together, 70% of all Romanian forestland has been or will be transferred into non-state ownership, doubling the number of individual forest owners from >400 000 in 2000 (Ioras and Abrudan 2006, Abrudan *et al* 2009). Romania's forest restitution process proved complex and the transition period was characterized by substantial economic hardships and tenure insecurity. The incentive of new owners to clearcut their forests is high and supporting institutions and forest law enforcement are weak. As a result, much concern has been expressed about surging forest exploitation by new forest owners (Bouriaud 2005, Nichiforel and Schanz 2009, Strimbu *et al* 2005). On the other hand, forest harvesting rates in state forests were relatively high during socialism and have declined since (Turnock 2002), and much farmland was abandoned in post-socialist Romania (Baur *et al* 2006, Kuemmerle *et al* 2009b). Both of these effects increase carbon storage in terrestrial ecosystems and potentially counteract anthropogenic carbon emissions from burning fossil fuels. Furthermore, Romania became a member of the European Union in 2007, requiring new forest legislation and management practices, and a substantial enlargement of its protected area network. How institutional changes in the post-socialist period have affected forest cover and thus carbon fluxes remains unclear.

Our aim was to assess the effect of forest restitution in Romania on the terrestrial carbon balance. Our first goal was to map changes in forest cover for the entire country of Romania between 1990 and 2010 using Landsat satellite images. Second, we combined satellite-based estimates of land use change with historical data on land use to assess carbon dynamics for the last 200 years using a book-keeping model (Houghton *et al* 1983). Our third goal was to assess potential future land use effects on Romania's terrestrial carbon budget for a range of plausible scenarios of forest harvesting and reforestation.

2. Methodology

2.1. Remote sensing

Forest cover loss was mapped across Romania between 1990–2000 and 2005–10 using 17 Landsat TM/ETM+ images at a spatial resolution of 28.5 m. The 1990–2000 map was generated using a neural network classifier as described in detail in Olofsson *et al* (2010) and Woodcock *et al* (2001). The 2005–10 map was generated by mapping the forest areas of Romania in 2005 and 2010 using a support vector machines classifier and chain classification, and then overlaying these maps to find forest change. A detailed description of this approach is provided in Kuemmerle *et al* (2009b) and Knorn *et al* (2009). The map categories considered were stable forest, stable non-forest, forest to non-forest, non-forest to forest and other including cloud, cloud shadow and snow. Regrowing forest (non-forest to forest) was excluded from the analysis because of low accuracy and difficulty of detection using Landsat data. Both maps were subject to rigorous accuracy assessments, based on a stratified random sample of ground reference points independent from the training data (1368 and 1143 samples for the 1990–2000 and 2005–10 maps, respectively). The samples were interpreted using Google Earth™ high-resolution imagery in combination with the original Landsat imagery, and user's and producer's accuracy were calculated. Forest change estimates were adjusted according to the error matrix and 95% confidence intervals were calculated for each map category (Cochran 1977, Card 1982).

2.2. Carbon modeling

We employed a well-established carbon book-keeping model to estimate the effect of land use change on Romania's terrestrial carbon budget. The model tracks changes in carbon stocks (terrestrial and soil carbon) over time as a consequence of three land use events: (1) deforestation, (2) forest expansion, and (3) logging (and subsequent recovery), each of which is connected to specific release and uptake functions. In addition, parameterizing the book-keeping model requires characterizing the carbon content of mature and disturbed forest systems, specifying growth curves for forest regeneration, and decay functions for different carbon pools. A detailed description of the model is available (Moore *et al* 1981, Houghton 1987, Houghton and Hackler 1999, DeFries *et al* 2002). Model parameterization is described in Kuemmerle *et al* (2011).

The model requires annual rates of three kinds of land use events. Rates of forest harvest were obtained from the remote sensing maps for 1990–2010. We assumed that the forest loss observed in these maps is due to harvesting (natural disturbances occur, but salvage logging is almost always carried out), which implies that logged forests regenerate. We see little evidence of conversion of logged forests to other land uses. Forest harvesting rates for 1950–89 were estimated from forestry statistics (using the area of post-logging forest regeneration as a proxy) (MAPDR 2009, Untaru *et al* 2011, Marin and Barbu 2011). The statistical reports (SILV. 1–5) are released annually and contain data on harvested volumes and cutting areas. Harvest rates prior to 1950 were not available and we therefore inferred these rates from forest inventory data (ICAS 1984) for average forest biomass, age structure and average growth rate (ICAS 1984) contains values for forest inventory parameters and, unlike the statistical reports, is not updated on a regular basis.

Second, we derived historical logging rates that would result in the current age distribution of forests (Romania had an even age class distribution in 1990). The estimated rate in 1950 was exactly the same (60 000 ha y^{-1}) as the harvesting rate from the regeneration data, adding confidence to our approach. Based on this result, we defined a growth curve which allows young forest to grow from 5 to 127 Mg C ha^{-1} in the first 80 years, and from 127 to 144 Mg C ha^{-1} in the next 100 years. Values for recovery times and carbon contents of disturbed and recovered ecosystems were taken from ICAS (1984).

Rates of deforestation and forest expansion on previously non-forested lands were estimated using data on forest area back to 1800 (MAPDR 1990, 1998, Toader and Dumitru 2004, Sofletea and Curtu 2007, Anca 2011). Romania experienced several phases of drastic deforestation, most importantly during the 19th century, when forest areas were reduced by 0.5 million ha; in 1919–30, when about 1.3 million ha of forest were converted to agricultural land; and after World War II, when about 300 000 ha of forest were cleared. In contrast, forest expansion on abandoned farmland has not been extensive during the 20th century, and has been observed only recently. Together, this allowed us to estimate annual rates of deforestation and forest expansion between 1800 and 2010. While our remote sensing analysis covered all of Romania, the official forestry statistics only referred to land managed by the state (the 'forest fund'), which in 2000 consisted of about 6.4 million ha of forest. Our remote sensing estimate of forest area in 2000 was 7.3 million ha, and we therefore rescaled all pre-1990 rates to the entire forest area (i.e., assuming that forest changes on state managed land were also representative outside these areas).

Three different carbon decay pools determine the rate of release of the carbon from logged or cleared forest (Moore *et al* 1981). Wood in the first pool is consumed immediately (e.g. firewood), and its carbon released within one year after harvest. The second pool contains short-lived wood products, which decay at a rate of 10% a year (e.g. pulpwood, paper and paperboard). Long-lived wood products, such as furniture and building materials, end up in the third pool and are assumed to decay at a rate of 1% y^{-1}. To distribute harvested wood among these pools, we used national forest production statistics from the FAO (FAOSTATS 2011), yielding a distribution of 30.7%, 7.2% and 53.1% among the three pools (the remaining 9% was assumed to end up as slash left on site following harvest).

2.3. Scenarios

To explore the effects of alternative plausible futures, we defined a range of scenarios reflecting a number of different logging and forest expansion rates. A major proportion of Romania's forest has been or will be restituted to former owners. How that affects logging rates is unknown, but incentives for new owners for generating immediate income from restituted forest land are high. Thus, although forest harvesting has decreased in Romania after the collapse of socialism, forest restitution could augment logging rates in the coming decades. Using the current (2005–10) logging rate as our base rate, we explored five levels of future logging rates for the period 2011–100: 0% (no logging), 50% (half the current logging rate), 100% (current logging rate), 200%, and 300%. Much of the farmland in Romania was abandoned after the collapse of socialism or is currently unused. The Romanian Ministry of Agriculture and Rural Development recently reported that 2.9 million ha of farmland is abandoned or currently fallow (MADR 2009). It is unclear how much of this area will eventually revert to forest, but this estimate is extremely important to future carbon fluxes in Romania. Here we include scenarios of 0%, 10%, 20%, 50% and 75% of forest expansion on the 2.9 million ha of abandoned farmland from 2011 and 2100. The carbon implications of these scenarios were investigated in a full factorial design, resulting in 25 different combinations of logging and forest expansion rates for which the model was run.

3. Results

The annual logging rate estimated from the remote sensing analyses was 15 122 ± 5397 ha y^{-1} (95% confidence intervals) in 1990–2000 which increased by almost 60% to 23 884 ± 11 510 ha y^{-1} in 2005–10. The forest area in 2000 based on our remote sensing analysis was 7 335 448 ± 379 520 ha. Assuming that the 2005–10 logging rate was representative for 2000–5, the projected forest area in 2010 is 7 096 608 ha, thus resembling closely the forest area in the 2005–10 map of 6 943 535 ± 280 693 ha in 2010. The change map revealed clusters of forest harvesting throughout Romania, especially in Northern Romania (figure 1).

The remote sensing analyses yielded reliable forest cover change maps, and the stable forest and non-forest classes were derived with high user's and producer's accuracies in both maps (tables 1 and 2). The logging class had a higher accuracy in the 1990–2000 map (88% user's accuracy) than the 2005–10 map (51% user's accuracy), likely a result of the post-classification map comparison approach. However, omission errors in the logging class were low for both maps. Because of the relatively small area of logging (<1%), omission errors have a larger impact on the final area estimates, and will result in large confidence intervals. As a result, the confidence intervals for the logging estimates (36% and 48%, respectively) are similar for both change maps.

Even though we found a significant increase in logging since 2000, current logging rates are substantially lower than logging rates from socialist times. Forest harvesting was especially widespread during the late 1960s and 1970s, when almost 60 000 ha of forest were logged annually (figure 2).

The area of forest in Romania decreased substantially from 1800 until the 1970s (>2 million ha) when the forest cover reached its minimum. The forest cover has remained more or less stable since then (figure 2). Forest area decreased throughout the 19th and 20th centuries, except for a small gain just before the collapse of the Soviet Union.

The baseline rates of logging and forest change between 1800 and 2010 are shown in figure 3.

Reconstructing carbon fluxes due to land use change and logging revealed that Romania has been a net carbon source throughout much of the 20th century (figure 4). Terrestrial emissions were highest in 1920–30, as a result of the massive deforestation at that time. During socialism, terrestrial emissions gradually declined despite relatively high logging rates—mainly because of carbon sequestration in regenerating forests. The terrestrial carbon balance shifted from a source to a sink in the 1980s, and has remained a net sink throughout the post-socialist period. However, increased logging in the post-socialist period is reflected in the carbon flux by diminished strength of the sink after 2000 (figure 4). Currently (2010), Romania's net terrestrial carbon sink is 1.64 Tg C y^{-1} (figure 4), an 7.6% offset of Romania's anthropogenic carbon emissions (US Energy Information Administration 2011). The lower and upper confidence intervals of the logging estimates generate sinks in 2010 ranging from 1.10 to 2.18 Tg C y^{-1}, which corresponds to anthropogenic emissions offsets of 5% and 10%. Thus, we estimate the current terrestrial carbon sink to be 1.64 ± 0.54 Tg y^{-1} which equals an offset of 7.6% ± 2.5%.

Alternative scenarios of future logging rates and forest expansion rates on currently unused lands show significant effects on net flux of carbon for the period 2011–100 (figure 5). Romania remained a carbon sink throughout the 21st century for many of the 25 scenarios we assessed, especially if logging rates remain at current levels or lower (figure 5). In contrast, higher logging rates would shift Romania from a sink to a source within the next few decades. Forest expansion on currently unused land (either by way of natural succession or afforestation) could substantially offset higher terrestrial emissions from logging. For example, assuming a logging rate twice the current rate (figure 5(b)), could either result in net carbon emissions (e.g., if only 10% of all unused land reverts to forest, second lightest gray line) or sequestration (e.g., if forests regrow on 50% of all currently unused land, second darkest gray line in figure 5(b)). Assuming no logging and no forest expansion throughout the 21st century would result in a source of 0.76 Tg C y^{-1} in 2100 but a total sink of 56 Tg C between 2011 and 2100 (figure 5(e)). In contrast, a threefold increase of the 2005–10 logging rates after 2011 in combination with no forest expansion would result in a net carbon sink of up to 0.019 Tg C y^{-1} in 2100 but a total source of 84 Tg C between 2011–100 (figure 5(a)). Assuming that the observed rates of logging and forest change remain constant throughout the 21st century would result in a sink until about 2050 after which it would turn to a source, and a total sink of 9 Tg C for the remainder of the

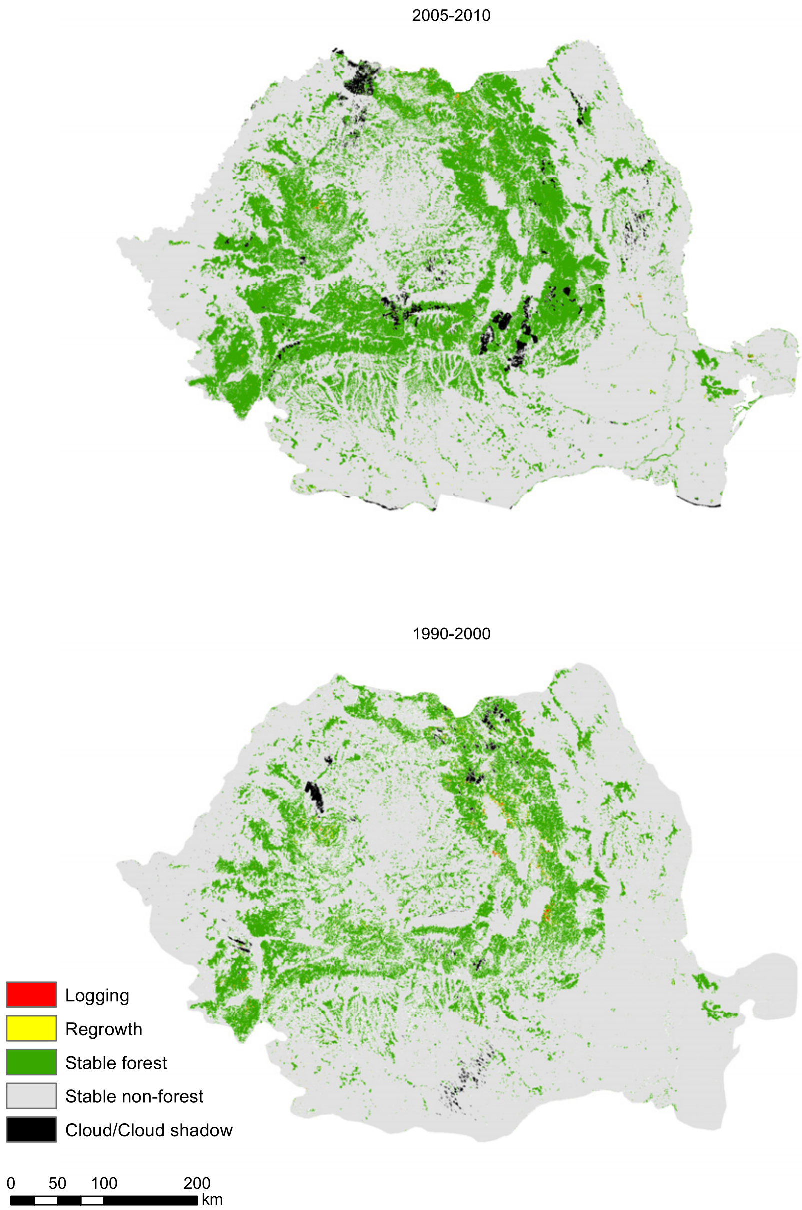

Figure 1. The two change maps which provided the baseline logging rates between 1990 and 2010. The regrowth class was omitted in the analysis.

Table 1. The resulting error matrix for the first change map (1990–2000) together with the mapped and adjusted areas and the 95% confidence intervals.

	Logging	Forest	Non-forest	User's acc	N samples		
Logging	161	11	10	88%	182		
Forest	0	559	4	99%	563		
Non-forest	1	49	573	92%	623		
Prod's acc	99%	90%	98%		1368		
	1990–2000				Annual (ha y^{-1})		
	Map area (ha)	Adj area (ha)	±95% CI (ha)	±95% CI (%)	Adj area	Lower CI	Upper CI
Logging	147 290	158 335	56 513	36	15 122	9725	20 519
Forest	5 995 217	7 335 448	379 520	5			
Non-forest	17 468 455	16 117 180	382 991	2			

Table 2. As figure 1 but for the second change map (2005–10).

	Logging	Forest	Non-forest	User's acc	*N* samples
Logging	127	66	54	51%	247
Forest	2	322	17	94%	341
Non-forest	0	15	540	97%	555
Prod's acc	98%	80%	88%		1143

	2005–10				Annual (ha y^{-1})		
	Map area (ha)	Adj area (ha)	±95% CI (ha)	±95% CI (%)	Adj area	Lower CI	Upper CI
Logging	154 159	119 420	57 550	48	23 884	12 374	35 394
Forest	6 846 562	6 943 535	280 693	4			
Non-forest	16 178 659	16 116 425	275 474	2			

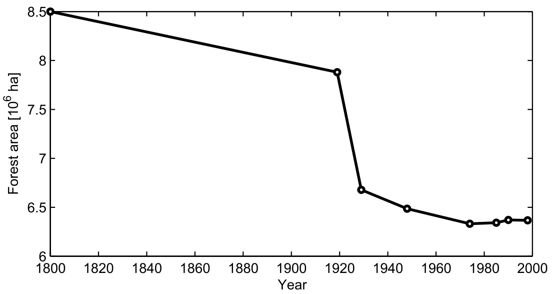

Figure 2. The forest area of Romania between 1800 and 2000.

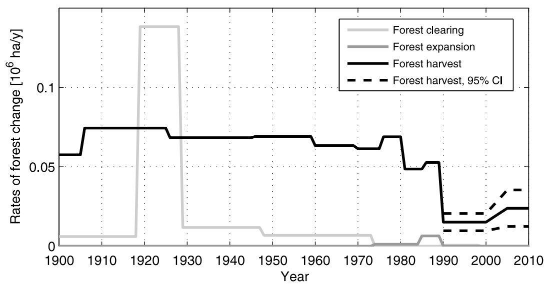

Figure 3. Baseline input to the carbon book-keeping model. The dashed lines are the 95% confidence intervals for the logging rates estimated from satellite data.

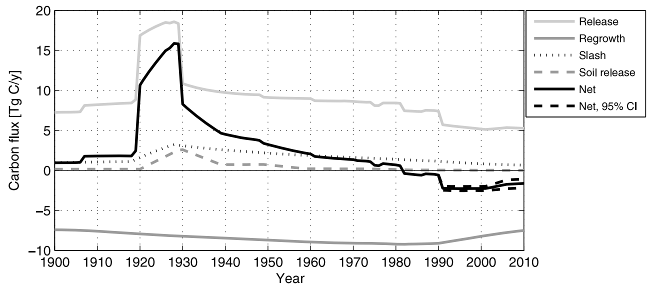

Figure 4. Terrestrial carbon flux in Romania as a result of the baseline rates in figure 2. As the model only associates release and uptake of soil carbon with permanent forest loss and gain, the soil carbon flux is close to zero and therefore not plotted. (A positive flux equals terrestrial emissions.)

Table 3. The offset in 2050 for the 25 different scenarios using the current anthropogenic carbon emissions.

	Forest expansion				
Logging	0%	10%	20%	50%	75%
300%	—	—	—	—	3%
200%	—	—	—	3%	6%
Obs	—	1%	3%	7%	10%
50%	2%	3%	4%	8%	11%
0%	4%	5%	6%	10%	13%

century (figure 5(c)). Depending on the harvesting and forest expansion rate, Romania's forests could compensate for up to 13% of the country's anthropogenic carbon emissions (table 3).

4. Discussion

The collapse of socialism profoundly affected Romania's land use systems, and in turn, the terrestrial carbon budget. Romania implemented one of the most dramatic forest restitution policies across Central and Eastern Europe, transferring up to 70% of all forests from state into private ownership. Our results suggest that these ownership transfers resulted in a 60% increase in logging rates, and a measurable effect on the countries net carbon flux from land use. Our study thus provides further support to previous studies that report that changes in forest property rights can trigger excessive resource use (Mena *et al* 2006, Deacon 1999, Strimbu *et al* 2005). Three factors explain increased logging rates after forest restitution laws were implemented. First, the transition period was characterized by substantial economic hardships (e.g. Romania's GDP has not recovered to pre-1989 levels) providing an incentive to many new owners to immediately clearcut their forests for short-term returns (Ioras and Abrudan 2006, Strimbu *et al* 2005). Second, Romania's forest restitution was a slow and complex process, with many new owners fearing that their property rights were not permanent (Ioras and Abrudan 2006, Sikor *et al* 2009). Third, the post-socialist period in Romania was, as elsewhere in Eastern Europe, characterized by decreasing transparency, lower institutional strength, and weak law enforcement, resulting in increasing illegal logging (e.g., timber theft) and a lack of conformity with forest laws (e.g., over harvesting, harvesting inside protected areas) (Ioja *et al* 2010, Ioras and Abrudan 2006, Strimbu *et al* 2005, Turnock 2002, Irland 2008).

The carbon implications of restitution of forest to pre-World War II owners was small compared to terrestrial

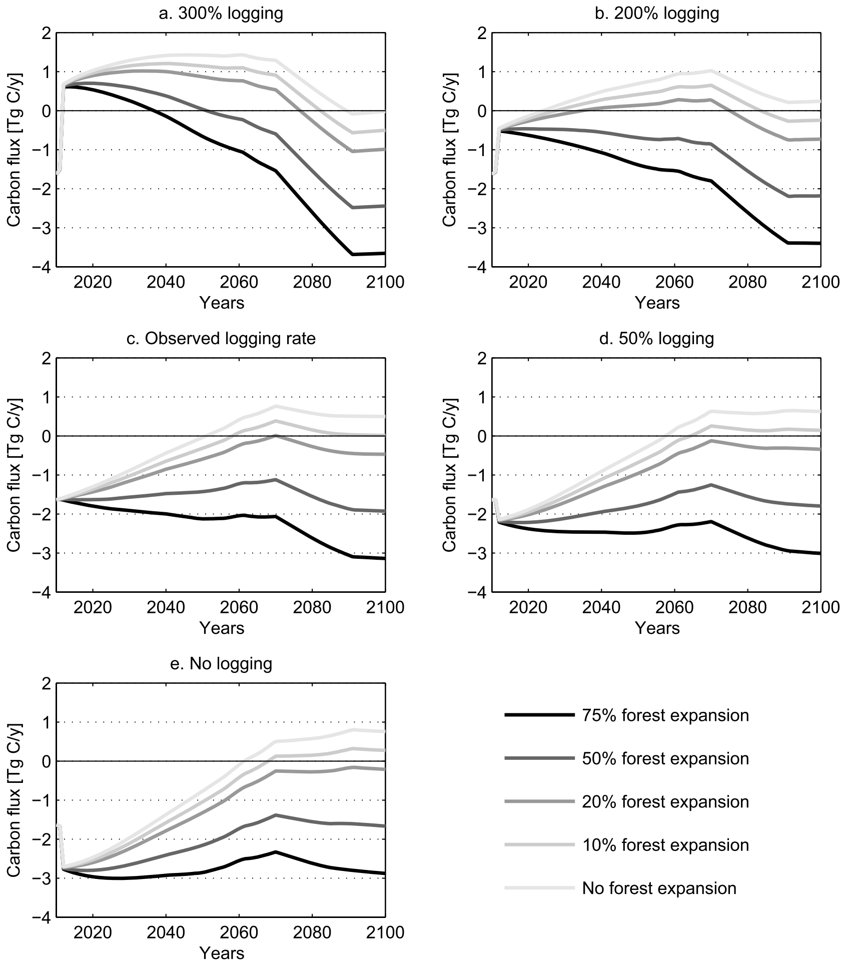

Figure 5. The net terrestrial carbon flux when running the model with 25 combinations of different logging and forest expansion rates. Each of the five plots represents a logging scenario. Figure 5(a) ('300% logging') shows the terrestrial carbon flux for a threefold increase of the current logging rate between 2011 and 2100, while figure 5(c) ('observed logging rate') shows the flux if the current rate is kept constant until 2100. The lines in each plot represent different rates of forest expansion on non-forested lands. Increased logging results in higher initial release but also higher sequestration at the end of the century. Higher rates of forest expansion rates result in dramatically increased carbon sequestration.

emissions resulting from logging during the socialist period. Despite increased forest harvesting rates in 2005–10 compared to 1990–2000, logging rates are considerably lower than those prior to 1989. Socialist-era logging was particularly intensive in the 1960s and 1970s. During that time, maximum utilization of natural resources was the main land use paradigm in many socialist countries, often leading to unsustainable resource use (Turnock 2002) (in the case of forest due to massive development of the woodworking industry). Although excessive logging resulted in high initial carbon emissions, regenerating forests on former logging sites also sequestered considerable amounts of carbon. As logging rates gradually decreased during the last years of socialism, Romania shifted from a terrestrial net carbon source to a net carbon sink. Considering the relatively long time of sustained growth (180 years) of regenerating forests on former logging sites, Romanian forests will continue to sequester carbon throughout the first half of the 21st century. This result highlights the long-lasting legacy of socialist-era forest management on today's carbon budgets (Main-Knorn *et al* 2009, Kuemmerle *et al* 2011).

Forest harvest in Romania dropped markedly after 1989 (figure 3) and this further accentuated the ongoing carbon sink. As elsewhere in Eastern Europe (Bergen *et al* 2008, Kuemmerle *et al* 2007), timber markets collapsed and prices for inputs and outputs were liberalized. In addition, the early post-socialist years were characterized by substantial tenure insecurity and harvesting of forests designated for restitution was sometimes stopped (Abrudan and Parnuta 2006). The immediate effect of decreasing forest harvests on the terrestrial carbon budget is mainly defined by the forest growth curve and the allocation of wood products to the carbon decay pools. In Romania's case, 31% of the carbon is released immediately, which explains the drop in terrestrial emissions after 1989. Lower harvesting rates since 1989 resulted both in foregone emissions and an increasing growing stock for Romania's forests, both increasing the magnitude of the carbon sink during the post-socialist period.

The current sink strength is furthermore notable considering that the extent of forestland remained nearly constant, both during socialism and in the post-socialist period. This is remarkable as much farmland was abandoned or set aside after the collapse of socialism. Quantitative data on the extent of farmland abandonment is scarce, but almost 3 million ha of farmland have been reported as being out of production as of 2009. Several reasons explain why only a small proportion of these lands have reverted to forest since 1989. First, much of these former farmlands may not be permanently abandoned or are still being used for occasional grazing. Second, abandoned farmland may be degraded (up to 400 000 ha of such degraded lands exist throughout Romania (Abrudan *et al* 2009)), thereby inhibiting spontaneous forest regeneration. Third, abandoned or set-aside land may occur far away from existing forests (e.g., in Romania's plains, where forest cover has been dramatically decreased historically), thus retarding succession to woody communities. Last, afforestation rates were very low in Romania until a systematic afforestation program was initiated in 2005 (Dutca 2011).

The steady decrease of forest cover before World War II and the relative stability thereafter (figure 2) also suggest that Romania has not experienced a forest transition, in contrast to many neighboring countries (Kuemmerle *et al* 2011, Kozak *et al* 2007, Mather 2001). Forest transition theory describes the reversal of deforestation associated with industrialization and urbanization (Mather 1992). In Romania, forest cover appears to have declined in several phases, most markedly after 1918 when about 1.3 million ha of forest land were given to World War I soldiers with the obligation to farm these lands (triggering a staggering carbon release of up to 19 Tg C during the 1920s, figure 4). Although speculative, one interpretation of the missing forest transition pattern is that much of the currently unused farmlands will eventually return to forests, especially those areas that are marginal for farming.

Comparing different scenarios of future logging and forest expansion highlights the variety of plausible carbon flux futures. Even with zero future logging, the current sink strength is projected to decrease over the 21st century. The reason is that carbon storage due to regenerating forests on areas logged during socialism will decrease, while more than half of the wood harvested during that time is still oxidizing because it became long-lived wood products (53% of all wood). With the restitution process not fully finished and forest institutions still in transition, either drastically increasing or declining logging rates are plausible. Our scenarios reveal that even under current logging rates, Romania's carbon sink will only last until about 2050 after which it will convert into a small source for the rest of the century. This shift would occur substantially earlier if logging rates would rise further (e.g. in 2025 for twice the current logging rate, figure 5(b)).

The regrowth of forest on former farmland could help offset terrestrial emissions from logging and maintain or even strengthen the current sink throughout the 21st century even if logging rates increase (figure 5). How much of the currently unused farmland will be returned into production remains highly uncertain. Our scenarios highlight the vast carbon sequestration potential on these abandoned farmland, similar to other post-socialist countries (Vuichard *et al* 2008, Kuemmerle *et al* 2011). Because spontaneous forest development is unlikely for many degraded areas, reforestation and afforestation of abandoned farmland could be an attractive land use in light of incentives provided by carbon markets (Kuemmerle *et al* 2011). Romania has recently established the ambitious goal of expanding forestland in the coming decades by about 2 million hectares. This is close to a forest expansion scenario of 75% of all currently abandoned farmland, suggesting that such a policy would result in a large carbon sink of about 3 Tg y^{-1} by the end of this century (even when further increasing forest harvesting). The population of Romania has been decreasing steadily since 1990, with an annual decrease of 90 000 people on average (World Bank 2010). If this trend continues, it is likely to result in increasing rates of farmland abandonment.

A sensitivity analysis of the carbon book-keeping model aiming at investigating the effect of errors in the estimated model parameters was not performed. However, many of the values of the model parameters in this study were also used in Kuemmerle *et al* (2011) in which a rigorous sensitivity analysis was performed. Further sensitivity analysis was performed by Houghton (2005).

5. Conclusions

Our study revealed a significant effect of forest restitution on Romania's terrestrial carbon budget and emphasized the significant legacy of socialist land use and forest harvesting on today's carbon budget. The current carbon sink in the terrestrial ecosystems of Romania is a substantial fraction of the country's anthropogenic emissions, and future forest expansion could substantially increase the current sink strength even under increased logging scenarios. Romania harbors some of Europe's last relatively undisturbed forest ecosystems, and substantial concerns have been expressed about unsustainable forest use triggered by the forest restitution process (Ioras *et al* 2009, Ioja *et al* 2010, Knorn *et al* 2011). While the carbon effects of logging were comparatively small in our study, we urge policy makers and land use planners to fully account for the trade-offs and synergies between economic returns from forestry, provision of ecosystem services (e.g., flood retention, soil stability), and biodiversity conservation.

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