Biogeosciences Discussions, 1, 167–193, 2004
www.biogeosciences.net/bgd/1/167/
SRef-ID: 1810-6285/bgd/2004-1-167

Biogeosciences Discussions

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The carbon budget of terrestrial ecosystems at country-scale – a European case study

I. A. Janssens[1], A. Freibauer[2], B. Schlamadinger[3], R. Ceulemans[1], P. Ciais[4], A. J. Dolman[5], M. Heimann[2], G.-J. Nabuurs[6, 7], P. Smith[8], R. Valentini[9], and E.-D. Schulze[2]

[1]Department of Biology, Universiteit Antwerpen, B-2610, Wilrijk, Belgium
[2]Max-Planck-Institute for Biogeochemistry, 07701 Jena, Germany
[3]Joanneum Research, A-8010, Graz, Austria
[4]Laboratoire des Sciences du Climat et de l'Environnement, 91191, Gif sur Yvette, France
[5]Department of Geo-Environmental Sciences, Free University Amsterdam, 1081 HV Amsterdam, The Netherlands
[6]Alterra Green World Research, 6700 AC, Wageningen, The Netherlands
[7]European Forest Institute, 80100, Joensuu, Finland
[8]School of biological Sciences, University of Aberdeen, Aberdeen AB24 3FX, UK
[9]Department of Forest Science and Environment, University of Tuscia, 01100, Viterbo, Italy

Received: 21 June 2004 – Accepted: 12 July 2004 – Published: 22 July 2004

Correspondence to: I. A. Janssens (ivan.janssens@ua.ac.be)

Abstract

We summed estimates of the carbon balance of forests, grasslands, arable lands and peatlands to obtain country-specific estimates of the terrestrial carbon balance during the 1990s. Forests and grasslands were sinking carbon consistently, whereas arable soils were carbon sources in all European countries. Hence, countries dominated by arable lands tended to be losing carbon from their terrestrial ecosystems, whereas forest-dominated countries tended to be sinking carbon. In countries where peatlands are still being drained or extracted, net carbon balances were much lower than expected from land use.

Net terrestrial carbon fluxes were typically small relative to fossil fuel-related carbon emissions. Only where fossil fluxes were small and net terrestrial fluxes were large did terrestrial carbon fluxes matter (ranged between uptake of 70% of fossil fluxes and increase of emissions with 25%). Nonetheless, at the European scale, the small net balance is composed of two very large but opposing fluxes: uptake by forests and grasslands and losses from arable lands and peatlands. Thus, relatively minor changes in either or both of these large component fluxes could strongly affect the net total, indicating that mitigation schemes should not be discarded a priori.

In the absence of carbon-oriented land management, the current net carbon balance is bound to decline soon. Protecting it will require actions at three levels. Firstly, maintaining the current sink activity of forests. Secondly, altered agricultural management practices to turn arable soils into carbon sinks. Lastly, because carbon is lost more rapidly than sequestered, the current large reservoirs (wetlands and old forests) need extra protection.

1. Introduction

The accumulation of CO_2 in the atmosphere proceeds at a much slower rate than expected from the burning of fossil fuels and the deforestation on land (IPCC, 2001). Part

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of the reason for this is the current net uptake of carbon (C) by the terrestrial biosphere, which originates from the combination of an increased photosynthesis and vegetation rebound in the northern hemisphere (IPCC, 2001; Nabuurs, 2004). Thus, there is evidence for a large (1–2 Pg C a^{-1}) terrestrial C sink and the mechanisms via which this occurs are identified, albeit that their relative importance still remain unclear. There is also clear evidence that a major part of the terrestrial C sink is situated in the northern hemisphere (Ciais et al., 1995; IPCC, 2001). Research teams in Europe and the US have applied a dual constraint approach – a combination of atmospheric-based techniques and land-based methods – to assess the continental-scale terrestrial C budgets of Europe and contiguous America. For contiguous America, the terrestrial C sink during the 1980's was estimated at 0.3–0.6 Pg C a^{-1} (Pacala et al., 2001), while for Europe the terrestrial C sink during the 1990's is believed to amount to 0.1–0.2 Pg C a^{-1} (Janssens et al., 2003). However, international programs such as the Global Terrestrial Carbon Observation network (http://www.fao.org/GTOS/tcoABT.html) aim to improve the spatial resolution to the sub-continental scale and further reduce the substantial uncertainty of these estimates. While the spatial resolution of the atmospheric approach is currently constrained by the limited number of atmospheric monitoring stations, the land-based methods have a much larger spatial resolution and also provide information about the contributions of different ecosystem-types.

Hence, the first objective of this study is to apply a land-based approach to provide estimates of the terrestrial C balance for individual European countries and highlight which factors are determinant for the national balance. Because terrestrial C sequestration substantially mitigates global warming, at least in the short term, information about which ecosystems or which management practices foster C uptake and which reduce C sequestration has become an important issue for policy makers. Now that alternatives for post-Kyoto regimes are being discussed, policy makers are eager to know what certain regimes may imply for their specific country. Therefore, the second objective of this study is to explore the full terrestrial C balance of the separate European countries with a view to elucidate which ecosystems dominate the terrestrial C balance within the individual European countries and thus identify where gains can be made in enhancing the terrestrial C uptake from- or reducing the net C losses to the atmosphere.

2. Materials and methods

We estimated the country-specific C balances by adding up changes in the C reservoirs in forests, grasslands, arable soils and peatlands. Other ecosystems, such as urban areas and parks, or inland water bodies were not included because of lack of information. Nonetheless, the four ecosystem types included in this study covered about 85% of the surface area, so our results are likely to be representative.

2.1. Forest fluxes

We used the forest productivity estimates reported in TBFRA (2000) and combined these with modeled changes in soil C content (Liski et al., 2002) to obtain forest net biome productivity. We refer to these two publications for detailed description of the applied methodologies. Such inventory-based estimates have the advantage that they integrate measured stem growth data over thousands of sites and thus account for harvest and disturbances. Inventories also give proper weight to all areas and vegetation types in terms of stem growth, as for Europe, the results are based on over 420 000 study plots. However, these models are based only on estimates of stem volume increment. All other C stock changes (total biomass- and wood products stock change, litter and dead wood stock changes, and changes in soil carbon stocks) are usually simulated through the use of a combination of dynamic bookkeeping models with process-based models.

Estimates of carbon stock changes in the wood product pools were not included because we did not have access to estimates for each of the countries, and also because these C sinks are small in comparison to the stock changes within the forests.

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2.2. Agricultural fluxes

Agricultural (arable soils and grasslands) C fluxes were assumed to be limited to soil C stock changes. For countries within the European Union (EU-15), C stock changes were calculated by multiplying country-specific C sequestration rates estimated by the CESAR model (Vleeshouwers and Verhagen, 2002) with the mean surface area reported by Mucher (2000) and http://www.fao.org/waicent/portal/statistics_en.asp, and assumed that the biomass carbon pool remains constant and that harvested products are respired within the same year. For the arable soils, we did not use the mean output by the model, because this tended to overestimate the C fluxes in comparison with four other national scale estimates (Table 1). Instead we used the value halfway between the mean estimate and the highest (lowest losses) estimate. For grassland soils we used the mean output.

To estimate fluxes in non-EU-15 countries, the following assumptions were made: sequestration rates in Macedonia and Albania = Greece; Switzerland = Austria; Norway = Sweden; Baltic states = Finland; Denmark = The Netherlands; Yugoslavia = mean of Italy and Greece; Czech Republik, Slovakia and Poland = Germany; all other eastern European countries = mean of EU-15.

2.3. Peatland fluxes

National estimates of the C budget of the peat sector were obtained by summing up C stock changes in undisturbed peatlands, in drained peatlands, and in peatlands where peat is being extracted.

Carbon sequestration in undisturbed peatlands was estimated by multiplying remaining areas of undisturbed peatlands (Armentano and Menges, 1986; Botch et al., 1995; Lappalainen, 1996) with biome-specific C sequestration rates (between 20–50 $g\,C\,m^{-2}\,a^{-1}$; Armentano and Menges, 1986; Armentano and Verhoeven, 1990; Botch et al., 1995).

Estimates of areas drained to create cropland, pastures and forest were derived from

Armentano and Verhoeven (1990) and Lappalainen (1996). Combined with biome-specific C losses following drainage (56–281 g C m^{-2} a^{-1} for forest and pasture, 205–1125 g C m^{-2} a^{-1} for cropland; Armentano and Verhoeven 1990), this gives an estimate of total C losses from drained peatlands.

Carbon losses related to the use of peat in horticulture/agriculture, and as fuel were estimated as follows. Extraction data were derived from Lappalainen (1996). For those countries where peat extraction was reported in volumetric units, a bulk density of 0.14 g cm^{-3} was assumed (Botch et al., 1995). Where extraction was reported in tons, we assumed a water content of 40% and a carbon content of 0.565% (Botch et al., 1995).

3. Results and discussion

3.1. Forests

Forests are sinking C in almost all European countries (Fig. 1). The main reason for this is that annual production rates are larger than annual wood harvests (TBFRA, 2000). Forest productivity is very high in Europe because of the stimulative effects of increasing atmospheric CO_2, high nitrogen deposition and global warming (longer growing season), but mainly because European forests are relatively young and still in an exponential growth phase (TBFRA, 2000; Nabuurs et al., 2003).

On average, European forests annually sequester 124 g C m^{-2} a^{-1} from the atmosphere (coefficient of variance, C.V., among different countries = 0.62), of which about 70% in biomass and 30% in litter and soil (Liski et al., 2000, 2002; Nabuurs et al., 2001). As expected, countries with high forest cover tend to have a higher forest C sink per unit land area than countries with low forest cover, as is indicated by the statistically significant positive relationship between the forest C uptake per unit country area and the proportion of the land area taken in by forest (Fig. 1; $y=1.25x$; n=34; $p<0.001$). However, there is still considerable variability in this relationship ($R^2=0.29$).

For example, forest-dominated Scandinavian countries such as Finland and Sweden (Fi and Sw in Fig. 1) have a much smaller C stock change in their forests (normalized per unit land area) than central-European forest-dominated countries such as Slovakia, Slovenia and Austria (Sk, Sl and Au in Fig. 1).

In addition to the obvious effect of differences in forest cover, there are a number of other factors that explain differences in the forest C balance between countries. Firstly, most European forests are production forests. Hence, the forest C balance is primarily determined by the harvest ratio, i.e. the proportion of the annual wood increment that is annually harvested. Thus, the substantial differences in the harvest ratio among countries (TBFRA, 2000) contribute to the low R^2 in Fig. 1.

Secondly, inventory-based models rely heavily on so-called biomass expansion factors (BEF). These BEF's are used to convert stem volume to entire-tree biomass, and vary with species, climate and tree age. Therefore, BEF's are expected to vary among countries. However, forest inventory studies such as TBFRA (2000) use BEF estimates supplied by the individual countries and these reported BEF's vary much more than can be explained by natural factors. Thus, part of the observed variation in forest C balance among countries is related to the use of strongly differing BEF's.

A third and main reason for the differences in forest C balance are the regional differences in tree growth. Figure 2 shows the forest productivity in the European countries and it is clear that in northern and southern countries trees grow slower than in temperate central European countries. There are multiple reasons why tree growth differs regionally. Northern forests may grow slow because the growing season is short and because nutrient cycling is retarded. Southern forests may produce less because drought often occurs during the period with optimal light conditions, when potential photosynthesis rates are highest. In addition, the temperate countries with faster tree growth tend to have higher nitrogen deposition loads (http://europa.eu.int/comm/environment/water/water-nitrates/report407parta.pdf). Lastly, it cannot be excluded that part of the regional variation in tree growth may also be related to different management practices.

3.2. Arable soils

Croplands and grasslands represent important ecosystems in Europe, but there are only few large-scale inventory data that can be used to estimate changes in C stocks and thus validate the output of the CESAR model. Arable soils are losing C in all European countries (Fig. 3). The modeled European-wide mean change in soil C was a loss of 70 g C m^{-2} a^{-1} (C.V. among countries = 0.43) and there was a tight negative relationship between the C stock change per unit country area and the proportion of the land area taken in by arable land (Fig. 3; $y=0.68x$; n=34; p<0.0001; $R^2=0.66$).

To our knowledge, only two large-scale (national) and long-term inventories of organic matter in agricultural soils have been published. In the study by Sleutel et al. (2003), a repeated soil sampling of Belgian cropland soils (210 000 samples taken between 1989 and 1999) indicated a mean annual soil C loss of 76 g C m^{-2} a^{-1}. This estimate was slightly higher than the predicted loss of 61 g C m^{-2} a^{-1} from Belgian cropland soils (Fig. 3 and Table 1). For Austrian cropland soils, however, the mean C loss predicted by the model was 73 g C m^{-2} a^{-1}, which was much larger than the C losses measured in a repeated, large-scale inventory study (24 g C m^{-2} a^{-1}; Dersch and Boehm, 1997). Two other countries reported estimates of agricultural soil C changes (Table 1). For the UK, the output of the CESAR model was very close to the reported value (Milne et al., 2001), whereas for Finland the model estimate was much higher than the value reported to the UNFCCC (Finnish Ministery of the Environment, 2001).

Thus, for these four countries there is a reasonable agreement between modeled and measured or reported fluxes. However, in some cases the model overestimates and in others the model underestimates. The main reason for this is that the CESAR model was developed to predict the effects of management changes on soil C sequestration and not to predict baseline fluxes (Vleeshouwers and Verhagen, 2002). Hence, many of the assumptions and simplifications may not be valid for the prediction of the current situation.

These differences between predicted and observed soil C changes at the national level not only highlight the uncertainty in the predicted soil C losses and thus the need of a model specifically developed to predict the current changes in arable soil C, but also indicate the need for more repeated soil C inventories to help better constrain the modeled soil C losses. Such repeated inventories would also be useful for databases of regional carbon balance estimates based on soil properties, agricultural management practices, and land-use history.

Despite the difference in size, both model estimate and observations suggest a net loss of C from arable soils (Table 1). The model further indicates that arable soils are losing C consistently throughout Europe (Fig. 3). This net loss occurs because, in arable soils, harvest reduces C returns to the soil, while C losses may be enhanced due to agricultural practices such as tillage. Thus, land conversion from other land-uses to cropland is likely to lead to an overall decline in soil carbon. Because these losses can continue for a number of years, the current loss of C from cropland soils may be the legacy of conversion of land to cropland during the past 20–30 years, as is the case in the UK (Milne et al., 2001). However, in most European countries the major land use changes occurred much longer than 20–30 years ago and recent trends are more towards conversion of arable land to other land uses. Despite this, arable soils are losing C even in these countries where no new cropland has been created, as in the Belgian example discussed above (Sleutel et al., 2003). These measured soil C losses can therefore not be related to land use change, but are probably due to changes in management practice, such as a decrease in the application of organic manure to cropland (Sleutel et al., 2003). Another possible hypothesis that could explain why arable soils can lose C without net land use changes is rotation. If the conversion from cropland to grassland equals the conversion from grassland to cropland, national statistics will indicate no land use change while in reality there is. Under such conditions, arable soils can continue to lose C, and grasslands to gain C. Because national statistics only report net land use changes, this hypothesis could not be tested.

3.3. Grassland soils

In contrast to arable soils, grassland soils are predicted to be a net C sink in most European countries (Fig. 4). The overall mean C sink is 60 g m^{-2} a^{-1}, almost twice as high as the forest soil sink, but in many countries the uncertainty surrounding this estimate is larger than the sink itself (Vleeshouwers and Verhagen, 2002). As expected, countries with high grassland cover tend to have a higher grassland C sink than countries with low grassland cover, as is indicated by the statistically significant positive relationship between the grassland C uptake per unit country area and the proportion of the land area taken in by grassland (Fig. 4; y=2.9+0.46x; n=34; p<0.001). Similar to the forests, this relationship is not very tight (R^2=0.32), because the predicted grassland soil C balance ranges from a net loss of 50 g m^{-2} grassland a^{-1} to a net sink of 170 g m^{-2} grassland a^{-1} (C.V. among countries = 0.69). Thus, as with forests, differences in the grassland C balance among countries depend not only on the grassland area within each country, but also on regional differences in productivity and decomposition. Hence, most of the above-mentioned factors that explain the regional differences in forest productivity also explain the regional differences in grassland productivity.

Because both forests and grasslands are sinking C (with few exceptions), and arable soils are losing C, we expected countries dominated by forest and/or grassland to be sinking C, and countries dominated by arable land to be losing C. Such an overriding effect of land use on terrestrial C stock changes is indeed apparent in our data set (Fig. 5 top panel). In Fig. 5, we coined the term land use ratio as the ratio of the cropland area in a country over the sum of the forest and grassland areas. It is clear that as a country becomes cropland-dominated (high land use ratio), it is bound to lose C, whereas most countries with low land use ratio are absorbing C. However, Fig. 5a also indicates that Scandinavian and Baltic states (indicated by open circles) are below the mean trendline. Also most of the Mediterranean countries (indicated by asterix) are below the trendline. In contrast, the central European countries dominated by forest and/or grassland sequester much more than expected from their land use ratio. Thus,

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in addition to land use also geographic features explain the regional differences in terrestrial C stock changes.

Up to now we have ignored peatlands. Nonetheless, peatlands have a significant effect on the terrestrial C balance of those countries where they occur most.

3.4. Peatlands

Most undisturbed organic soil wetlands accumulate C at rates ranging between 0 and 80 g C m^{-2} a^{-1}, depending on age, climate and the type of wetland ecosystem (mires, fens, marshes,…; Armentano and Menges, 1986; Botch et al., 1995). Because of the relatively small area (Lappalainen, 1996) and predominantly slow accretion rates, undisturbed European peatlands constitute only a negligible C sink (0–6 g m^{-2} total land area a^{-1} compared to 60 in grasslands and 120 in forests).

However, large peatland areas have been and are being drained for pasture, cropland, and forestry purposes (Lappalainen, 1996; Armentano and Verhoeven, 1990). Drainage of organic soils enhances their aeration and the subsequent enhancement of decomposition results in significant soil C losses (Armentano and Verhoeven, 1990). Our estimate of the C loss from Europe's drained peatlands indicates that, despite a much smaller area, more C is lost due to drainage than is sequestered in undisturbed peatlands (0–47 g m^{-2} total land area a^{-1}). In a number of countries this situation is further exacerbated by the extraction of peat and use in horticulture, agriculture and in the energy sector (0–36 g m^{-2} total land area a^{-1}; Lappalainen, 1996).

Peat disturbance strongly confounds the regional pattern in terrestrial C stock changes (Fig. 5, open circles in bottom panel indicate countries with substantial wetland drainage and/or peat extraction). Thus, in addition to land use and geographical location, also peat disturbance contributes to the regional differences in the terrestrial C balance (Fig. 6).

3.5. Biospheric fluxes at the national scale

In most countries, the net terrestrial C balance estimate is thus very small. However, the reader should bear in mind that at the continental scale, most inverse atmospheric models estimate a 60% higher sink than the land-based approach in this study (Janssens et al., 2003). This discrepancy may suggest that we are missing C storage (e.g. in urban areas or in sediments of water bodies) or leaking C via another way (e.g. via rivers to oceans). The discrepancy could also be related to errors associated with the difficulties in measuring and modeling soil C dynamics and the need to use simplified models in such a complex landscape.

Nonetheless, Fig. 7 clearly shows that such small net uptake often conceals two large but opposing trends: C uptake by forests and grasslands versus C losses from arable soils (and in some countries from disturbed peatlands). The fact that the small net C balance is the result of a balance between large C sinks and large C sources has two important implications. Firstly, as discussed at great length before, since forestry-oriented countries are sinking C into their terrestrial ecosystems and agriculture-dominated countries tend to lose C, there is very large regional variability in the net biospheric C uptake among individual European countries. For example, in Slovenia and Sweden, terrestrial ecosystems sequester more than 50% of the C emitted to the atmosphere via fossil fuel consumption and cement manufacture (Fig. 7). In contrast, in cropland-dominated countries such as Moldova and Lithuania, and in countries with considerable extraction of peat deposits such as Ireland and Belarus, terrestrial C stocks decline at a rate equivalent to more than 25% of the nation's fossil fuel emissions. Thus, not only is there a large regional variability, but it is also clear that biospheric C sinks and sources are substantial in certain countries, even in a continent dominated by fossil fuel-derived C fluxes.

The second major implication of the balance between large sinks and large sources is that minor relative changes on either side of the balance could strongly affect the current small net C uptake by the European terrestrial biosphere. Hence, biospheric

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mitigation schemes should not a priori be discarded as an option to mitigate Europe's contribution to the rise in atmospheric CO_2 concentrations.

3.6. The sponge analogy

Functionally, the European biosphere is comparable with a sponge that is far from saturated. Some pores are currently filling up, while others are leaking C at a rate almost equal to that of the C being added, resulting in only minor changes in the total C content of the sponge. To fill up the sponge at a faster rate (enhance the net C sink), management policies should focus on three levels: a) ensure that pores that are currently filling up continue to fill up (managed forests and grasslands); b) reduce C losses from leaking pores (mitigation options for arable soils); and c) reduce the pressure on pores that are almost saturated (peat deposits and old forests).

3.6.1. Continue filling up...

During the 1990s European forests have reduced the increase in atmospheric CO_2 by absorbing no less than 20% of Europe's fossil C emissions (Janssens et al., 2003), almost the equivalent of all C emitted by the transport sector or the manufacturing industry (http://reports.eea.eu.int/environmental_assessment_report_2003_10/en). The current sink behavior of Europe's forest sector primarily originates from the uneven age structure, with a significant share of young forest stands. However, in the absence of protective or stimulative measures, the forest C sink will revert within a couple of decades as a result of the progressing tree age structure, and then more and more European countries will stop sinking C into their forests, potentially resulting in negative terrestrial C balances. If economic stimuli would change forest management towards shorter rotations, this process would even be accelerated. In contrast, C-oriented forest management practices such as selective rather than clear-cut harvesting, continuous-cover forestry, and setting aside part of the productive forests, all provide mechanisms via which the current sink strength of European forests can be sustained over much longer time periods. Of course, C-oriented forest management needs to focus not only on C storage in the forest itself, but on the full sectorial C balance. For instance, over-protection of forests could result in increased emissions from energy and wood-product using sectors (biomass fuels could be replaced by fossil fuels; construction wood could be replaced by steel, concrete, glass, etc.; Matthews, 1996).

Two articles in the Kyoto Protocol address crediting for certain forestry practices (http://unfccc.int/resource/docs/convkp/kpeng.pdf). Article 3.3 includes the carbon stock changes and other GHG emissions resulting from afforestation, reforestation and deforestation activities, that is, restricts itself to the conversion of non-forest lands into forests, and to permanent losses of forest lands. Article 3.4 accounts for carbon stock changes in existing managed forests up to a politically defined national cap that is only a fraction of the predicted total forest C sink. The rationale for restricting the C credits for forest management was that not all of the carbon uptake in forest management is due to direct human influence (as opposed to indirect or natural effects such as CO_2- or nitrogen fertilization, climate change) or to management actions undertaken since 1990 as stipulated in Article 3.4. Therefore, a discount factor of 85% was chosen as a means of factoring out indirect and natural effects and pre-1990 management actions. Another reason for capping the credits in Article 3.4 is that in the Kyoto negotiations emission reduction targets were agreed before the opportunities for meeting these targets with carbon sinks. Hence, there was a large potential for "windfall" credits in countries with large biospheric sinks, resulting in lower reductions of anthropogenic emissions of greenhouse gases than would have been the case if biospheric sinks were not included. If rules for inclusion of carbon sinks had been agreed before the emission limitation targets, the extent of sinks inclusion could have been factored in when setting the targets, and then there would not have been the need for an artificial cap on the C sink in forests. Because of the artificial cap and because the current forest C sink results from management practices that occurred long ago, the Kyoto Protocol does not give full credit to the sink in European forests and therefore does not provide incentives to protect or improve the current C sink.

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3.7. Reduce the leak...

At the pan-European scale, arable soils are losing C at a rate equivalent to 10% of the total fossil fuel emissions, although uncertainties remain large. In the absence of management changes, arable soils are bound to reach a new dynamic equilibrium at a lower C content and thus stop losing C within a couple of decades. However, considering that management changes turned arable soils in North-America into large C sinks (Pacala et al., 2001), it should also be possible to considerably reduce C losses from European arable soils even before the end of the first commitment period of the Kyoto protocol (2012), provided that stimulative measures are taken. Using biological, social and economical constraints, the realistic potential for reducing the current C losses by the year 2010 was estimated at 16–19 Mt a^{-1} for the EU-15 (Freibauer et al., 2003) and 46 Mt a^{-1} for continental Europe (Smith, 2004). This emission reduction potential estimate is smaller than the current C losses (estimated at 120 Mt a^{-1} for Europe excluding Russia), but uncertainty in both estimates is very large. Agriculture is Europe's largest emitter of N_2O and CH_4 (Freibauer, 2003), so mitigation should focus not only on C sequestration, but also on these other greenhouse gases.

In its current form, the Kyoto protocol does not contain any mechanism to credit past and present sustainable land management. Countries that have managed their land in a sustainable way and have small C losses are therefore not eligible for credits, whereas countries that have not managed land sustainably will have. Also, the Kyoto Protocol does allow credits for reductions in greenhouse gas emissions or enhancement of sinks due to agricultural management changes since 1990, but in the case of carbon, the reported gains need to be verifiable and only the net changes relative to the 1990 baseline are accepted. To date, estimating this net change based on trends in management remains challenging, limiting the capacity of the Kyoto Protocol to stimulate changes in agricultural practices to the reduction of N_2O and CH_4.

3.7.1. Protect existing large reservoirs

In addition to preserving the inflow – and reducing the outflow of C, there is also a need to protect existing large reservoirs. For example, European forests (Dixon et al., 1994) and peatlands (Armentano and Menges, 1986) are both estimated to contain 30–40 Pg C, and a 5% reduction of either of these C pools would equal the annual fossil fuel C emissions from the continent.

Because the rate of C losses from terrestrial ecosystems is an order of magnitude faster than that of C sequestration (Körner, 2003), an effective protection of the already existing carbon stocks therefore appears to be another important strategy. In its present form, the Kyoto protocol does not offer sufficient protection of large terrestrial C pools.

If Europe would manage to maintain its current forest and grassland sink and stop all C losses from arable soils and peat soils, the terrestrial C sponge would absorb 16% of the European C emissions from fossil fuel consumption, as opposed to the current 4.5% (this estimate is smaller than that cited above because it excludes Russia). Taking into account social and economical constraints, a more realistic potential for C sequestration during the first commitment period of the Kyoto Protocol is 9% (twice the current uptake). An additional uptake of almost 5% of the anthropogenic emissions would significantly slow the current increase in atmospheric CO_2. Furthermore, at the individual country level mitigation options could have even larger effects, turning most agriculture-dominated and peat-consuming countries into C-sinking regions. Furthermore, in addition to the climatic benefits of soaking up large amounts of C, also the water and nutrient household and biodiversity in terrestrial ecosystems would be positively affected by increasing soil C.

In the absence of management changes, the terrestrial C sink is bound to decline. National administrations are unlikely to change local land-use policies only for the sake of reducing the rise in atmospheric CO_2. To change current management practices, (economical) incentives should originate from international initiatives such as the Kyoto protocol. This calls for more flexibility and simplified treatment of the terrestrial sink in international negotiations in order to create the prospect of providing better incentives for C-oriented land management via international protocols.

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Acknowledgements. All authors are members of the CarboEurope-IP consortium, a project to understand and quantify the carbon balance of Europe (http://www.carboeurope.org/). CarboEurope-IP is supported by European Commission, Directorate-General Research, Sixth Framework Programme, Contract No. GOCE-CT-2003-505572.

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Table 1. Predicted versus reported soil carbon losses from arable soils for four European countries for which carbon losses have been reported.

Country	Reported flux	Model prediction	Reported flux	Model prediction	Reference
	(Tg C a-1)	(Tg C a-1)	g C m-2 a-1	g C m-2 a-1	
Finland	0.55	1.86			Finnish Ministry of Environment, 2001
UK	3.3	3.4			Milne et al., 2001
Austria			24	73	Dersch and Boehm, 1997
Belgium			76	61	Sleutel et al., 2003

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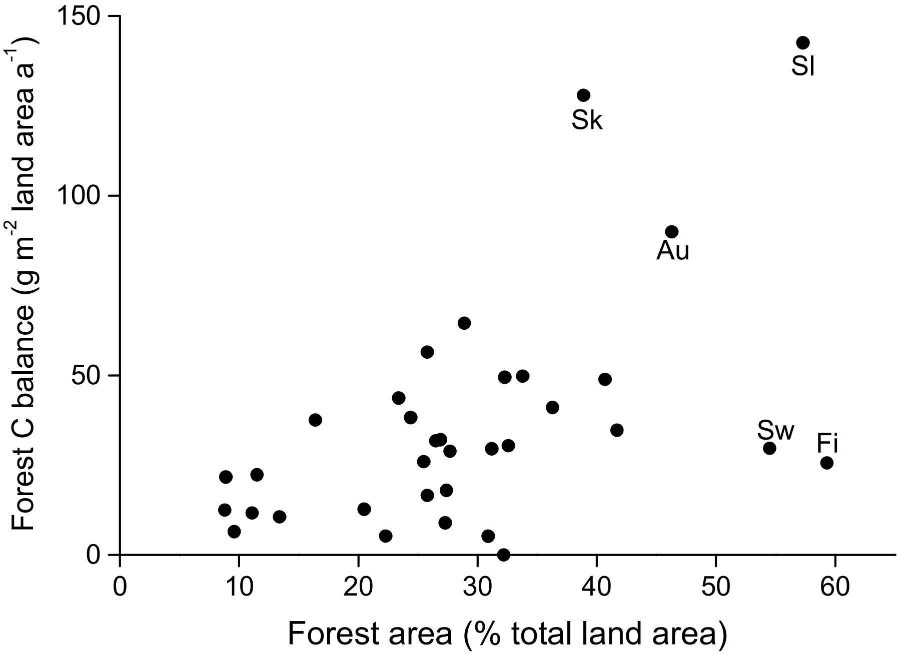

Fig. 1. Country-specific carbon balance of forest ecosystems expressed per unit total land area versus the percentage of land covered by forest (allows comparisons among countries of different sizes; positive indicates net sink; Sk = Slovakia, Sl = Slovenia, Au = Austria, Sw = Sweden, Fi = Finland).

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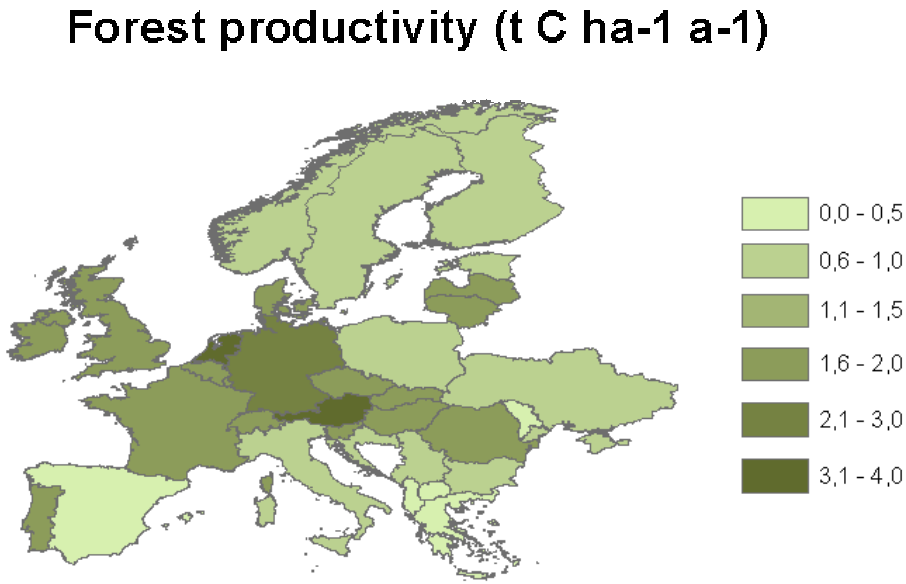

Fig. 2. Country-specific mean forest productivity estimates expressed per unit forest area ($t\,C\,ha^{-1}\,a^{-1}$).

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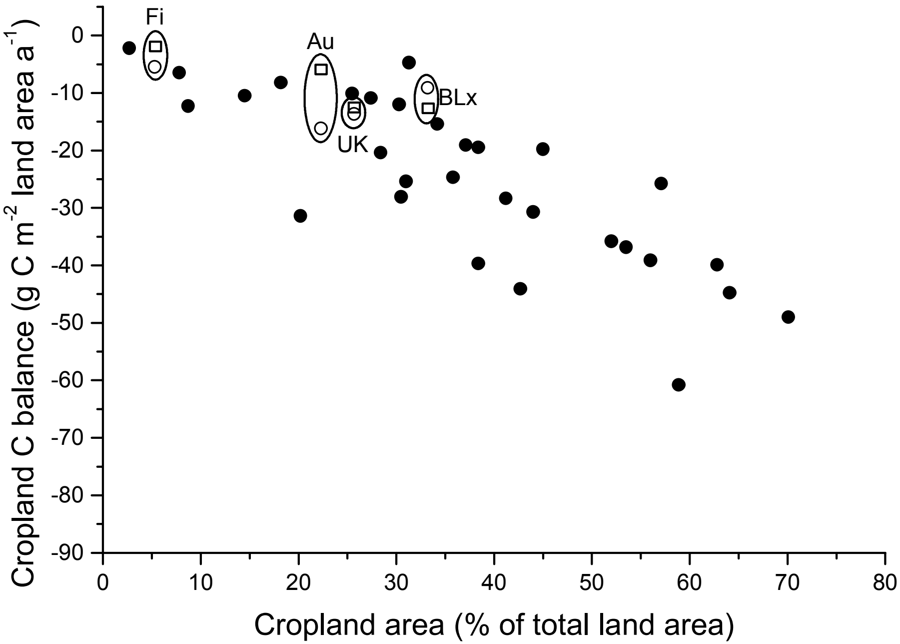

Fig. 3. Country-specific carbon balance of arable soils expressed per unit total land area versus the percentage of land covered by crops (allows comparisons among countries of different sizes; negative = net carbon loss). For four countries where validation was possible the independent estimates are also given, ∘ = modeled estimates, □ = independent published estimates (see also Table 1; Fi = Finland, Au = Austria, UK = United Kingdom, BLx = Belgium plus Luxembourg).

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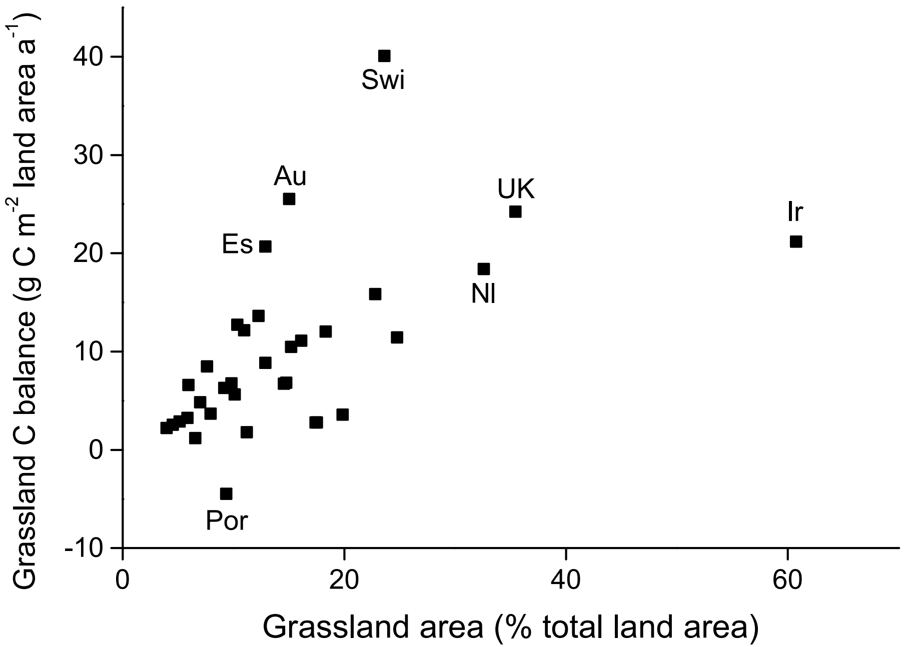

Fig. 4. Country-specific carbon balance of grassland ecosystems expressed per unit total land area versus the percentage of land covered by grass (allows comparisons among countries of different sizes; positive is net carbon gain; Por = Portugal, Es = Spain, Au = Austria, Swi = Switzerland, Nl = The Netherlands, UK = The United Kingdom, Ir = Ireland).

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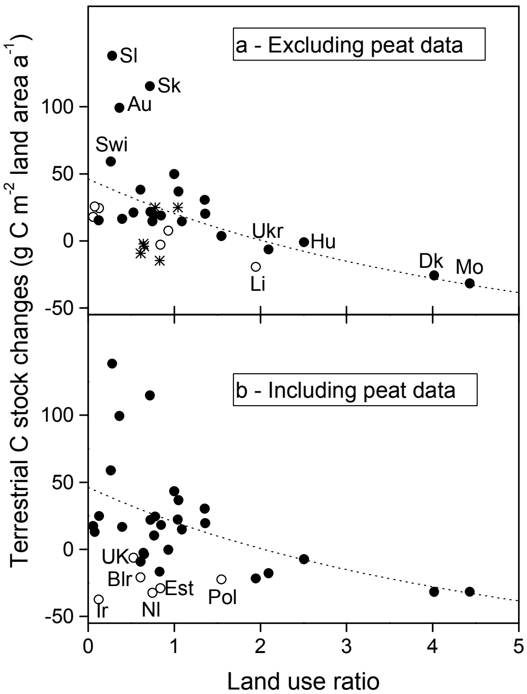

Fig. 5. Upper panel: country-specific carbon stock changes in terrestrial ecosystems (sum of forests, grassland and arable soils) expressed per unit total land area versus the land use ratio (= cropland area divided by sum of forest and grassland areas; * = Mediterranean countries, ∘ = Baltic and Scandinavian countries; Sl = Slovenia, Sk = Slovakia, Au = Austria, Swi = Switzerland, Ukr = Ukraine, Li = Lithuania, Hu = Hungary, Dk = Denmark, Mo = Moldova). Bottom panel: country-specific carbon stock changes in terrestrial ecosystems (sum of forests, grassland, arable soils and peatlands) expressed per unit total land area versus the land use ratio (= cropland area divided by sum of forest and grassland areas; ∘ = countries with substantial carbon losses from peatlands; Uk = United Kingdom, Blr = Belarus, Ir = Ireland, Nl = The Netherlands, Est = Estonia, Pol = Poland).

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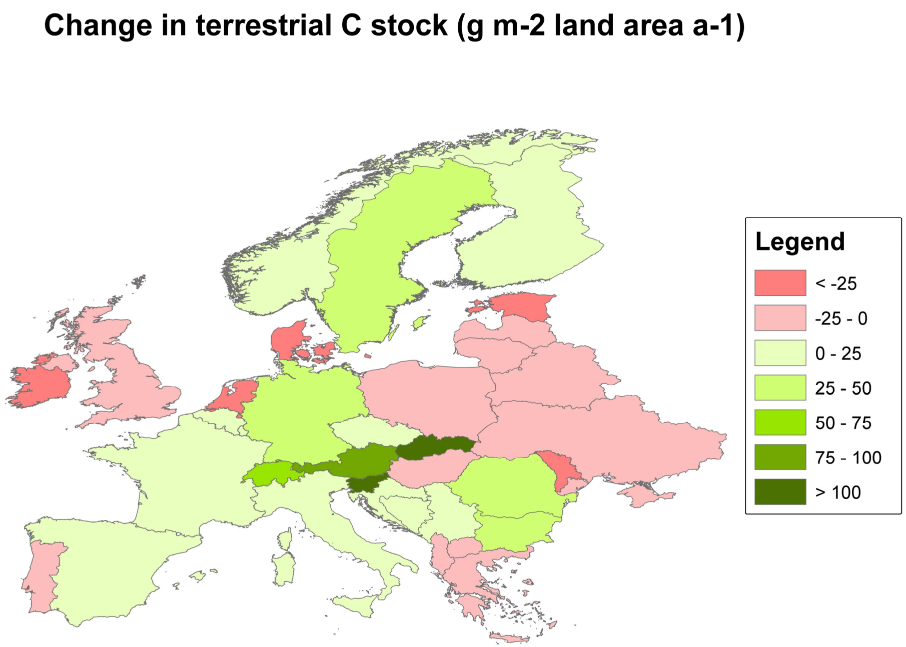

Fig. 6. Country-specific changes in terrestrial carbon stocks (sum of forests, grassland, arable soils and peatlands) expressed per unit total land area (g m^{-2} land area a^{-1}; allows comparisons among countries of different sizes). Negative values (red) indicate net losses, positive values (green) indicate net gains.

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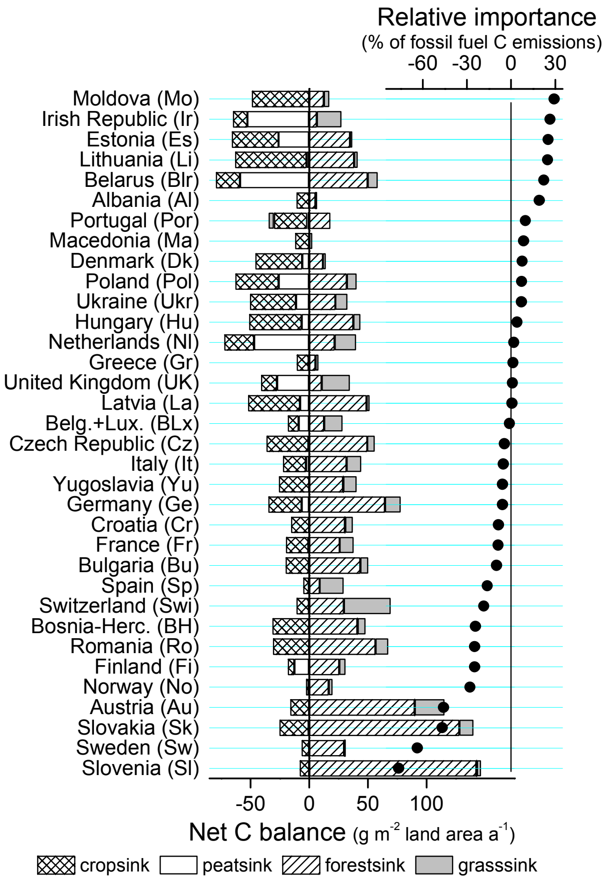

Fig. 7. National estimates of the carbon balance of the four main terrestrial ecosystems (negative is loss, positive is gain) and the importance of the total terrestrial carbon balance relative to the 1995 fossil fuel C emissions (negative is reduced emissions by uptake, positive is enhanced emissions by losses).

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