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Projected changes in mineral soil carbon of European forests, 1990–2100

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Smith, P., Smith, J., Wattenbach, M., Meyer, J., Lindner, M., Zaehle, S., Hiederer, R., Jones, R. J. A., Montanarella, L., Rounsevell, M., Reginster, I. and Kankaanpää, S. 2006. **Projected changes in mineral soil carbon of European forests, 1990–2100**. Can. J. Soil Sci. **86**: xxx–xxx. Forests are a major land use in Europe, and European forest soils contain about the same amount of carbon as is found in tree biomass. Changes in the size of the forest soil carbon pool could have significant impacts on the European carbon budget. We present the first assessment of future changes in European forest soil organic carbon (SOC) stocks using a dedicated process-based SOC model and state-of-the-art databases of driving variables. Soil carbon change was calculated for Europe using the Rothamsted Carbon model using climate data from four climate models, forced by four Intergovernmental Panel on Climate Change (IPCC) emissions scenarios (SRES). Changes in litter input to the soil due to forest management, projected changes in net primary production (NPP), forest age-class structure, and changes in forest area were taken into account. Results are presented for mineral soil only. Under some climate scenarios carbon in forest soils will increase slightly (0.1 to 4.6 Pg) in Europe over the 21st Century, whilst for one scenario, forest SOC stocks are predicted to decrease by 0.3 Pg. Different trends are seen in different regions. Climate change will tend to speed decomposition, whereas increases in litter input due to increasing NPP and changing age-class structure will slow the loss of SOC. Increases in forest area could further enhance the total soil carbon stock of European forests. Whilst climate change will be a key driver of change in forest soil carbon, changes in age-class structure and land-use change are estimated to have greater effects.

Key words: soil organic carbon, Europe, climate change, forest management, land-use change, Rothamsted Carbon model, EFISCEN model, LPJ model

Smith, P., Smith, J., Wattenbach, M., Meyer, J., Lindner, M., Zaehle, S., Hiederer, R., Jones, R. J. A., Montanarella, L., Rounsevell, M., Reginster, I. et Kankaanpää, S. 2006. **Évolution prévue des stocks de carbone dans le sol minéral des forêts européennes de 1990 à 2100**. Can. J. Soil Sci. **86**: xxx–xxx.. Les terres boisées abondent en Europe et le sol forestier européen renferme à peu près la même quantité de carbone que la biomasse des arbres. Une modification du réservoir de carbone que représente le sol forestier aurait des répercussions sensibles sur le bilan du carbone européen. Les auteurs présentent une première estimation des changements que les stocks de carbone organique du sol (COS) des forêts européennes pourraient connaître dans l'avenir. Ils ont pour cela recouru à un modèle du COS reposant sur un processus dédié et à des bases de données ultra perfectionnées de variables déterminantes. L'évolution des stocks de COS en Europe a été analysée au moyen du modèle du carbone de Rothamsted, qui utilise les données climatologiques de quatre modèles climatiques alimentés selon les quatre scénarios du GIEC sur les émissions (*in* SRES). Les auteurs ont aussi pris en compte le changement des apports de résidus végétaux attribuable à l'aménagement forestier, les variations prévues de la production primaire nette, la pyramide des forêts par classe d'âge et l'évolution de la superficie des terres boisées. Les résultats ne portent que sur le sol minéral. Selon certains scénarios climatiques, l'Europe assistera à une légère hausse (de 0,1 à 4,6 Pg) du volume de carbone dans les sols forestiers au cours du XXI^e siècle, cependant un scénario prévoit une baisse de 0,3 Pg des stocks. Les tendances varient avec la région. Le changement climatique aura tendance à accélérer la décomposition, mais des apports plus importants de résidus végétaux résultant d'une hausse de la production primaire nette et de l'évolution de la pyramide de classes d'âge ralentiront les pertes de COS. Un agrandissement de la superficie des forêts pourrait accroître encore plus les réserves globales de carbone du sol dans les forêts européennes. Même si le changement climatique constituera l'un des moteurs principaux de l'évolution du carbone dans les sols forestiers, la modification de la pyramide de classes d'âge et les nouvelles vocations des terres devraient avoir un impact encore plus important à ce titre.

Mots clés: Carbone organique du sol, Europe, changement climatique, aménagement forestier, nouvelles vocations des terres, modèle du carbone de Rothamsted, modèle EFISCEN, modèle LPJ

Abbreviations: **GCM**, general circulation model; **IPCC**, Intergovernmental Panel on Climate Change; **NPP**, net primary production; **SOC**, soil organic carbon; **SRES**, Special Report on Emissions Scenarios

Forests are a major land use in Europe, occupying around 173.5 Mha in the EU25 plus Norway and Switzerland (Eurostat 2003). European forest soils contain about the same amount as carbon (C) as is found in tree biomass (Karjalainen et al. 2003), and usually contain more C than equivalent soils under cropland, and often more than those under grassland (Guo and Gifford 2002). Changes in the size of the forest soil C pool could have significant impacts on the European C budget (Janssens et al. 2003). Further, with forest C sinks playing an important role in the Kyoto process, both under article 3.3 for afforestation/reforestation/deforestation (ARD) activities, and article 3.4 for forest management activities, estimates of changes in forest soil C stocks over the next century are of critical importance. Previous assessments of European forest C stocks (including soils) have been conducted by Narbuurs et al. (2003) for 1950 to 1999, and also for the future using (a) a modified version of the yearly-time-step ForClim-D model, which includes the litter layer (Liski et al. 2002) for the EU15 (1990–2040) and, (b) the five-yearly-time-step EFISCEN model (Karjalainen et al. 2003) for 27 European countries (1990–2050). In this paper, we present the first assessment of European (EU25 plus Norway and Switzerland) of future changes in forest SOC stocks using a dedicated process-based SOC model and state-of-the-art databases of soil, climate change, land-use change and projected changes in litter input.

MATERIALS AND METHODS

The Rothamsted Carbon Model

The Rothamsted Carbon Model (RothC; Coleman and Jenkinson 1996) is one of the most widely used SOC models (e.g., Post et al. 1982; Jenkinson et al. 1991; McGill 1996) and has been evaluated in a wide variety of ecosystems including croplands, grasslands and forests (e.g., Coleman et al. 1997; Smith et al. 1997a). It has been used to make regional and global scale predictions in a variety of studies (Post et al. 1982; Wang and Polglase 1995; Falloon et al. 1998b; Tate et al. 2000). The model was adapted to run with large spatial datasets and to use potential evapotranspiration in place of open pan evaporation. The adaptations are described further in section “Running the Model”.

Data Sets

The Geographic Window

The geographic window, within which the study was performed, is a 10′ by 10′ (minutes of longitude and latitude) grid for Europe covering the area: longitude 10.4958 E to 31.3376 W; latitude 34.0497 N to 71.0831 N used within the ATEAM project (Advanced Terrestrial Ecosystem Assessment and Modelling; EU-funded contract no. EVK2-2000-00075). For all model runs, data were prepared on this grid (hereafter referred to as the ATEAM grid). The total number of land grid cells within the window is 31143.

Climate Data, 1900 to 2100

Monthly temperature and precipitation for each 10’ by 10’ cell were taken from the climate data sets provided to the ATEAM project by the University of East Anglia, Climate Research Unit (Mitchell et al. 2004). Monthly values were provided for 1900 to 2000 based on interpolated observed data and for 2000 to 2100 using outputs from four different global climate models (general circulation models; GCMs) forced by four IPCC CO_2 emissions scenarios reported in the Special Report on Emissions Scenarios (SRES; Nakićenović et al. 2000). The GCMs for which outputs were provided were HadCM3, CSIRO2, PCM and CGCM2 (Mitchell et al. 2004). The four climate scenarios examined (based on the emission scenarios) were A1FI (“world markets-fossil fuel intensive”), A2 (“provincial enterprise”), B1 (“global sustainability”), and B2 (“local stewardship”; Nakićenović et al. 2000; Parry 2000; Smith and Powlson 2003). Potential evapotranspiration for each 10’ by 10’ cell was calculated from monthly temperature and cloudiness of the ATEAM climate data sets described above according to Prentice et al. (1993), as in Sitch et al. (2003). Climate data were available for all 31143 grid cells.

Soil Data

Mean SOC stocks in Mg C ha^{-1} to 30-cm depth (calculated from percentage C content and bulk density), and the percentage clay content in that layer, were derived for each 10’ by 10’ grid cell, from the European Soils Bureau 1 km^2 soils database (Jones et al. 2003, 2004). The total number of grid cells for which both SOC and percentage clay content could be calculated was 21976. Since RothC has not been parameterised for, and is not recommended for use on, organic soils (Coleman and Jenkinson 1996), cells with starting soil C values of 200 Mg C ha^{-1} or above were excluded (equivalent to about 5–7% C for a bulk densities 1 to 1.2 g cm^{-3}; a similar cut-off for organic soils, based on the soil organic matter map of Europe, was used by Smith et al. (1997b), leaving 16719 grid cells on mineral soils.

Litter Input Data

Forest litter inputs to the soil (above- and below-ground) for each 10’ by 10’ cell for 2000–2100 were calculated using the EFISCEN model (Karjalainen et al. 2002, Nabuurs et al. 2001) based on projections from national scale forest inventory data in Europe and changes in NPP calculated by the LPJ model (Sitch et al. 2003) for each cell. Litter data were used to adjust the annual C input to the soil as described in section “Running the Model” below. Forest inventory data were not available for all countries represented within the geographic window; data were available for 20 000 grid cells.

Land Use Data

For each grid cell, the proportion of land under cropland, grassland, forest, urban and other (e.g., open water and bare ground) were taken from the PELCOM database (Mücher et al. 2000) to derive the 2000 baseline land use data set. Future land use change scenarios were constructed according to Ewert et al. (2004), Kankaanpää and Carter (2004), Reginster and Rounsevell (2004) and Rounsevell et al. (2004) for 2020, 2050 and 2080. Compared with the baseline data, the future scenarios also included liquid, non-woody and woody bioenergy crops as well as a “surplus”

Table 1. The proportion of C assumed to be added in plant material each month

Month	1	2	3	4	5	6	7	8	9	10	11	12
Proportion of plant addition	0.025	0.025	0.025	0.025	0.05	0.05	0.05	0.05	0.20	0.20	0.20	0.10

class to represent land with no socio-economic purpose. The scenarios were available only for the EU15 countries, Norway and Switzerland, which corresponds to 15 036 grid cells. Land-use data were used as described in section "Running the Model" below.

Running the Model

Simulation Procedure

The initial C content of the soil organic matter pools and the annual plant addition to the soil were obtained by running the RothC model to equilibrium under constant environmental conditions (Coleman and Jenkinson 1996). The constant climatic conditions were taken to be the average of climate data from 1900 to 1930. RothC is known to be relatively insensitive to the distribution of C inputs through the year; the proportions of plant material added to the soil in each month were set to describe the pattern of inputs for a typical European forest as given in Table 1.

Initially, the total plant input was obtained by summing these proportions; this was not intended to represent the actual plant addition, but provided the first point in the initialisation, indicating how the annual plant addition should subsequently be adjusted. After the first equilibrium run, the annual plant addition, P, was adjusted to give the measured soil C content given in the soils database, using Eq. 1

$$P = Pi \times \frac{C_{meas} - IOM}{C_{sim} - IOM}. \tag{1}$$

where P_i is the initial total plant addition (the sum of the proportions given in table 1), C_{meas} is the measured soil C given in the soils database, C_{sim} is the simulated soil C after the 10 000 yr run, and IOM is the C content of the inert organic matter fraction in the soil (all in Mg C ha^{-1}). The size of the IOM fraction was set according to the equation given by Falloon et al. (1998a) shown in Eq. 2

$$IOM = 0.049 \times C_{meas}{}^{1.139}. \tag{2}$$

The adjusted annual plant addition was then redistributed through the months as in Table 1, and the equilibrium run was repeated. This iteration was continued until the measured and the simulated C contents of the soil were within 0.00001 Mg C ha^{-1}.

Having determined the plant additions and C contents of the soil organic matter pools, the simulations were continued from 1900 to 2000 using the measured climate and simulated NPP data described above. Predicted climate, NPP, litter and land use data were used to run the simulations between 2000 and 2100. Results are reported for 1990 to 2100, since litter data are available only for this period.

Changes in Litter Input to the Soil

Litter inputs to the soil as simulated by the EFISCEN model were used to adjust plant additions (P) between 2000 and 2100, as shown in Eq. 3,

$$P_t = P_{t-1} \times \frac{L_t}{L_{t-1}}. \tag{3}$$

where L_t is the litter input in year t, and L_{t-1} is the litter input in the previous year (all in Mg C ha^{-1}).

Changes in Land Use

The model was run to the year 2100 for each land use type (arable, grassland and forest) assuming no land use change. The C contents of the soil organic matter pools were stored for each land use in the last month of the years for which land use data were provided. The land use data were used to determine changes in land use occurring during 30-yr time slices from 2000 to 2100 (land use data were given for 2020, 2050 and 2080). The changes in land use necessary for replicating the observed patterns were obtained by assuming the amount of land changed is given by the proportioned decrease from each type of land use, as shown in Eqs. 4 to 7.

$$\Delta LU_{(ARA \to FOR)} = I_{FOR} \times \frac{D_{ARA}}{D_{ARA} + D_{GRA}} \tag{4}$$

$$\Delta LU_{(GRA \to FOR)} = I_{FOR} \times \frac{D_{GRA}}{D_{ARA} + D_{GRA}} \tag{5}$$

$$\Delta LU_{(FOR \to GRA)} = I_{GRA} \times \frac{D_{FOR}}{D_{ARA} + D_{FOR}} \tag{6}$$

$$\Delta LU_{(FOR \to ARA)} = I_{ARA} \times \frac{D_{FOR}}{D_{GRA} + D_{FOR}} \tag{7}$$

where $\Delta LU_{(LU1 \to LU2)}$ is the amount of land changed from land use 1 to land use 2, I_{LU1} is the increase in land use 1, and D_{LU1} is the decrease in land use 1 (all in hectares); $_{ARA}$ indicating arable, $_{GRA}$ indicating grassland, and $_{FOR}$ indicating forest land use. This assumption greatly reduces the number of calculations needed, and is reasonable for forest, where land use change tends to be a long-term process. The land use change occurring in each year was obtained by linear interpolation between the calculated land use changes in 1990, 2020, 2050 and 2080. The simulation was then run forward, imposing land use changes from 2080, 2050, 2020 and 1990, using the stored soil organic C values for unchanged land uses to seed the simulations. The results in each year were summed in proportion to the percentage land use change of that type occur-

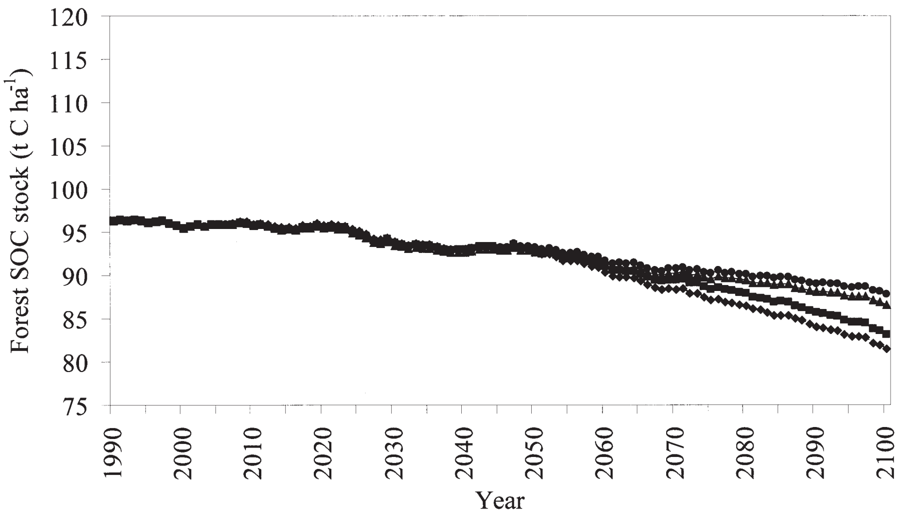

Fig. 1. Mean European forest SOC stocks (t C ha^{-1}), 1990–2100, under four climate scenarios as implemented by the HadCM3 climate model, when considering only direct climate impacts upon SOC. The four climate scenarios are shown as: triangles = B2, circles = B1, squares = A2, diamonds = A1FI.

ring in each grid cell, and divided by the total forest area of the cell to give results in Mg C ha^{-1}.

RESULTS

Climate Impacts on European Forest Soil Carbon

Increasing temperatures will speed decomposition and will tend to increase the loss of soil C in the future. If climate impacts on soil C are considered in isolation, forest C stocks were projected to fall by a mean across Europe of between 8.6 and 15 Mg C ha^{-1} across all emission scenarios with the HadCM3 model. This is equivalent to a fall of between 9 and 15.5% of the 1990 mean European forest SOC stocks (Fig. 1).

The A1FI scenario was projected to have the greatest effect on forest SOC stocks because it produces the largest temperature change. The B1 scenario showed the least decline in SOC. There is also considerable variation among climate models. When comparing the four climate models forced with the same emission scenario (A2), the variation between models is greater (Fig. 2) than the variation among emission scenarios when implemented in the same climate model (Fig. 1).

There are regional variations in the impact of climate, which can be seen in Fig. 6 for an example emission scenario (A2) and climate model (HadCM3) run.

Incorporating Changes in Litter Input

Using national forest inventories and NPP changes calculated by the LPJ model as input, the EFISCEN model projected forest resource development over the 21st century. Current harvest levels are significantly below the increments (UN-ECE/ FAO 2000) and together with an unbalanced age-class structure this led to increased litter inputs to the soil over the 21st Century. Increases were projected to be most rapid until about 2050, after which they are projected to gradually level off. Figure 3 shows the percentage increase in litter inputs (compared with 1990) for each climate scenario implemented by the HadCM3 climate model.

When included, these increased litter inputs resulted in a projected increase in European forest SOC stocks. Figure 4 shows the impact of including litter changes (due to management plus NPP, changes in NPP alone, and changes in management alone) compared with the climate-only run of the model, for an example climate model (HadCM3) and emission scenario (A2). Change in NPP accounts for about 28% of the increased litter input with 72% accounted for by forest management/age class structure change (Fig. 4).

The variation among climate models is similar to that reported for climate-only runs (not shown). The difference between emission scenarios shows a similar pattern to that reported for climate-only runs with the A1FI scenario having the most adverse impact on forest SOC and B1 having the least adverse affect. Our projections suggest that all scenarios will lead to an increase in mean forest SOC until about 2050 (increases from 98 Mg C ha^{-1} to around 101–102 Mg C ha^{-1} in 2050) after which the scenarios diverge. By 2100, the model predicted that SOC values will have dropped to below 2001 values for A1FI (94 Mg C ha^{-1}) and A2 (96 Mg C ha^{-1}) scenarios, whilst B1 and B2 scenarios will result in an overall increase over the century with values in 2100 of 101 and 100 Mg C ha^{-1} respectively (Fig. 5).

These per-hectare values correspond to a loss in forest SOC stock for EU25 plus Norway and Switzerland of 0.7 and 0.4 Pg (4.3 and 2.2%) for A1FI and A2 respectively, and increases of 0.46 and 0.27 Pg (2.7 and 1.5%) for B1 and B2 respectively (Fig. 6b). The effect of including changes in litter input (due to changes in age class structure and NPP) to climate-only runs is shown in Fig. 6 for a single emission scenario (A2) and climate model (HadCM3) run.

The regional pattern shows that climate warming has the greatest impact in the colder regions (Fig. 6a). Increased lit-

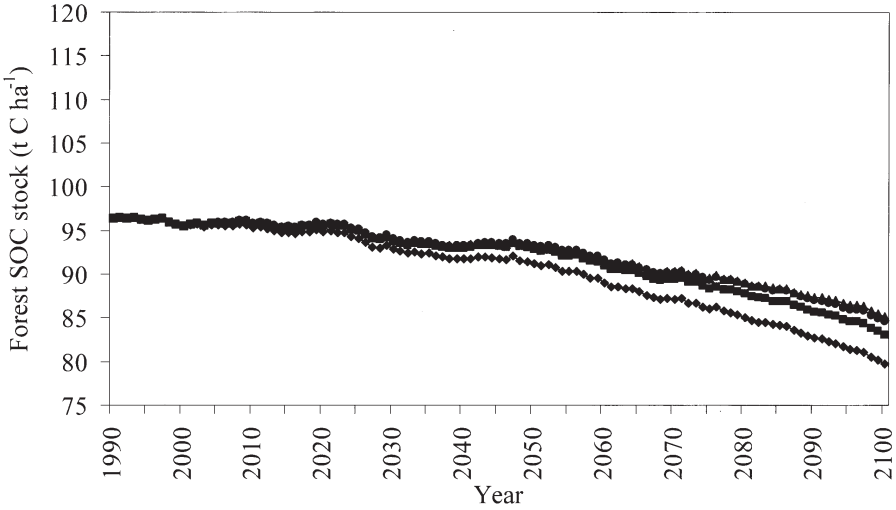

Fig. 2. Mean European forest SOC stocks (t C ha^{-1}), 1990–2100, under the A2 climate scenario as implemented by four climate models, when considering only direct climate impacts upon SOC. The four climate models are shown as: triangles = PCM, circles = CGCM2, squares = HadCM3, diamonds = CSIRO2.

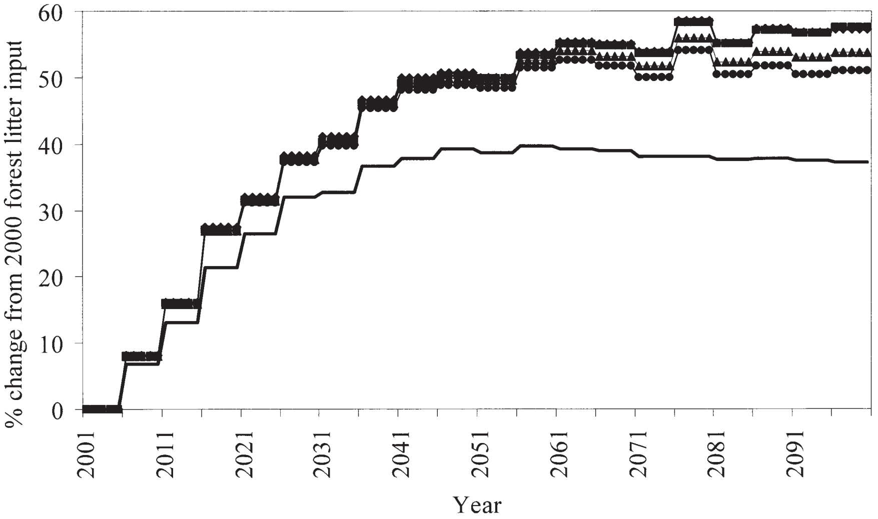

Fig. 3. Litter input changes (% of 2000 litter inputs) over 21st Century showing the difference between climate scenarios as implemented by the HadCM3 model. Triangles = B2, circles = B1, squares = A2, diamonds = A1FI. For comparison, the change in litter input due to age-class structure changes alone (thick solid line – no symbols) is shown.

ter inputs counteract this effect most effectively in the north and west, where NPP increases are the greatest, but towards the south and east, where NPP increases less, soil C losses continue (Fig. 6b).

The Impact of Land-Use Change on European Forest SOC Stocks

The forest area for the EU25 plus Norway and Switzerland is 173.5 Mha (Eurostat 2003). Extrapolating our results to this area, mineral soils under European forests in 1990 are estimated to contain around 17.1 Pg C to a depth of 30 cm (Fig. 7). Forest area is projected to change over the next 100 yr for all scenarios, but is most pronounced in the B1 and B2 scenarios. Consequently, the B1 and B2 scenarios showed the greatest increases in total SOC stock (3.3 and 4.6 Pg, respectively, equivalent to increases of 19 and 27%), whilst A1FI gained a small amount of SOC (0.1 Pg; 1%) and A2 lost a small amount of SOC (0.3 Pg; 2%: Fig. 7a). The overall loss of SOC in the A2 scenario was driven by land use change in which forest area is projected to increase until about 2050, after which it declines rapidly. The influence of land-use change can be seen by comparing parts (a) and (b) of Fig. 7. Increase in the forest area was projected to increase the forest SOC stock of EU15 by 4.1 Pg for the B2 scenario, 3 Pg for B1, 0.1 Pg for A2 and 0.8 Pg for A1FI, relative to forest areas being held at 1990 levels (Fig. 7b).

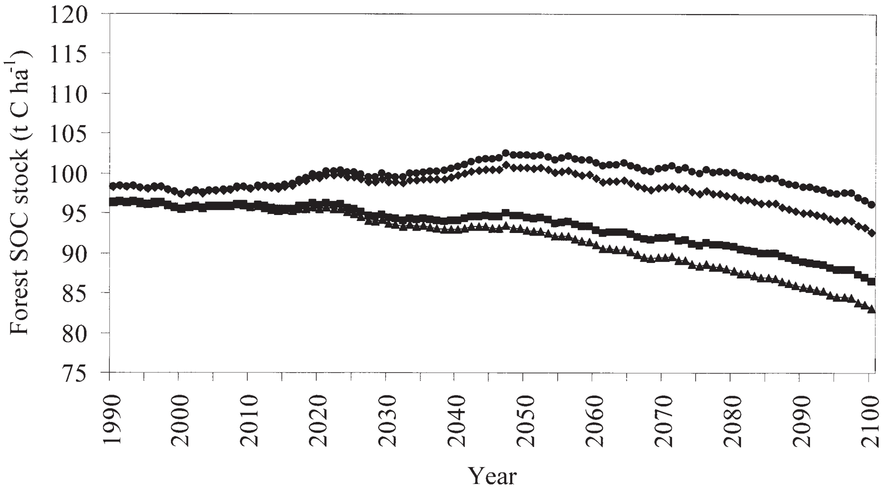

Fig. 4. Comparison of mean forest SOC stock for runs with (i) litter changes from management and changes in NPP included (circles), (ii) litter changes from management included but effects of NPP excluded (diamonds), climate and NPP considered without litter changes due to management (squares), and for climate impacts only, excluding all effects on litter from management or changes in NPP (triangles), for an example climate model (HadCM3) and emissions scenario (A2). The small difference (1.8 Mg C ha^{-1}) between the lines in 1990 is due to (i) different number of grid cells used according to missing data and (ii) divergence during the 20th century.

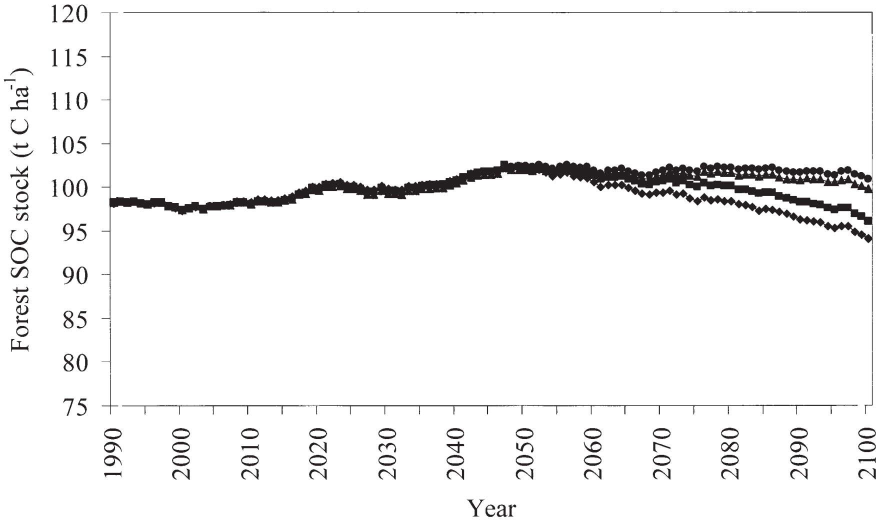

Fig. 5. Mean European forest SOC stocks (t C ha^{-1}), 1990–2100, under four climate scenarios as implemented by the HadCM3 climate model, when considering direct climate impacts upon SOC and the effects of increased litter inputs in to the soil. The four climate scenarios are shown as: triangles = B2, circles = B1, squares = A2, diamonds = A1FI

DISCUSSION

Interactions among Global Change Drivers

Increasing temperatures will speed decomposition, so direct climate impacts on European forest soils will tend to decrease SOC stocks. This effect is greatly reduced, however, by increasing C inputs to the soil due to enhanced NPP (resulting from a combination of climate change and increased atmospheric CO_2 concentration; accounting for about 28% of the increased litter input) and the discrepancy between forest increment and felling.

Increasing litter inputs cause increases in SOC until about 2050 when they level/decline, and when the climate-mediated speeding of decomposition becomes dominant. Under some climate scenarios, C in forest soils will increase slightly in Europe over the 21st Century (increases of 0.1, 3.3 and 4.6 Pg for A1FI, B1 and B2, respectively), whilst for the A2 scenario, forest SOC stocks are predicted to decrease by 0.3 Pg. The corresponding per-hectare increases in forest SOC (between –4.3% and +2.7%) are lower than the increases of 6–8% in SOC predicted by Karjalainen et al. (2003) using the IS92a emission scenario and two forest management scenarios, Business as Usual and Multifunctional Forest Management for the EU25 plus Norway and Switzerland, but their estimates of soil C increase include only C that originates from trees. This means that the relative increase in SOC compared with the

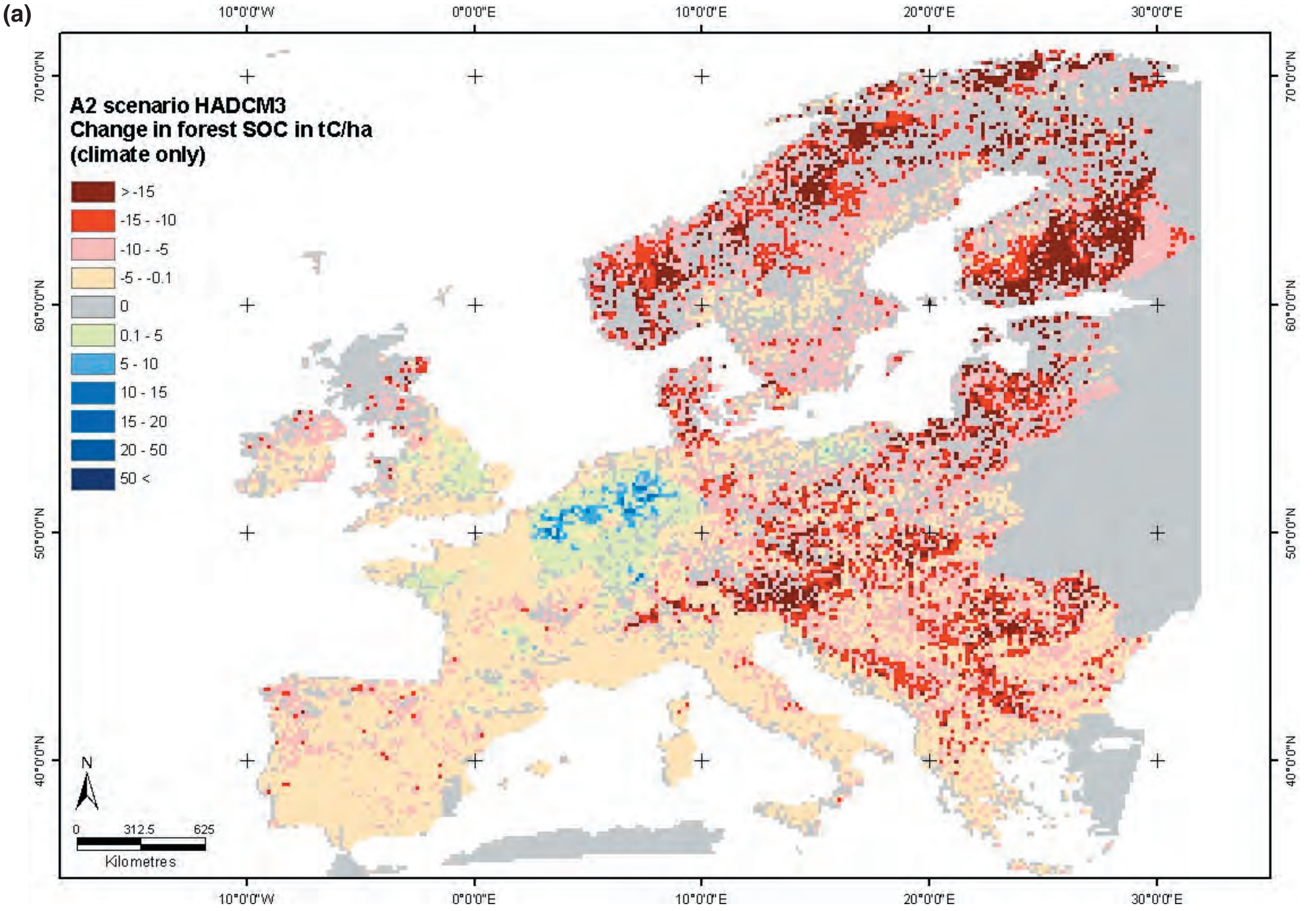

Fig. 6. Maps showing the difference in mean SOC stocks between 2080 and 1990 for climate change only (a), and climate-plus-litter input change (b), and regional differences in SOC stocks, for a single climate scenario (A2)/climate model (HadCM3) run.

total SOC actually present will be overestimated. The absolute Mg C ha^{-1} increases are similar. Increases of about 40% in SOC stock (uncertainty reported to be –60 to +34% of estimated stock) were estimated for forest SOC in the EU15 plus Norway and Switzerland by Liski et al. (2002) using a modified version of the yearly-timestep ForClim-D model. Our estimates are far lower. One possible reason for the apparent discrepancy is that the estimates of Liski et al. (2002) include the litter layer whilst ours do not. Other possible reasons for differences include the use of an older demand scenario (Pajuoja 1995) in the Liski et al. (2002) study, compared with the SRES demand scenarios derived from the IMAGE 2.0 model, used here to drive EFISCEN.

Land-use change over the next century is projected to increase forest areas with the effect most pronounced in the B1 and B2 scenarios, and with the A2 scenario showing an increase in forest area up to 2050 with a decline thereafter. Where forest area increases, this further increases the total C stock of European forest soils. Forest areas increase at the expense of cropland and grassland leading to a corresponding decrease in SOC in cropland and grassland. SOC stocks tend to be higher under forest than cropland (and possibly grassland; Guo and Gifford 2002), yielding a net gain in SOC due to land-use change. Nevertheless, accounting for increases in forest SOC due to increases in forest area in isolation from other land use changes can overemphasise the gains in SOC to be made from afforestation.

Policy Implications of Direct and Indirect Effects on Soil Carbon

Increases in forest SOC due to increased NPP are an indirect human-induced effect (IPCC 2003) and are not eligible as a sink under the Kyoto process. However, SOC stock increases due to increased forest area will be eligible as sinks under article 3.3 as afforestation/reforestation/deforestation (ARD) activities. Active forest management changes to enhance SOC stocks post-1990 could be eligible under Kyoto Article 3.4 as forest management. We did not consider management changes such as increasing rotation lengths in our management scenarios, which are expected to have mainly positive effects on the C balance (Liski et al. 2001; Harmon and Marks 2002; Kaipainen et al 2004). The main factor contributing to the increasing litter fall is the discrepancy between increments and fellings in European

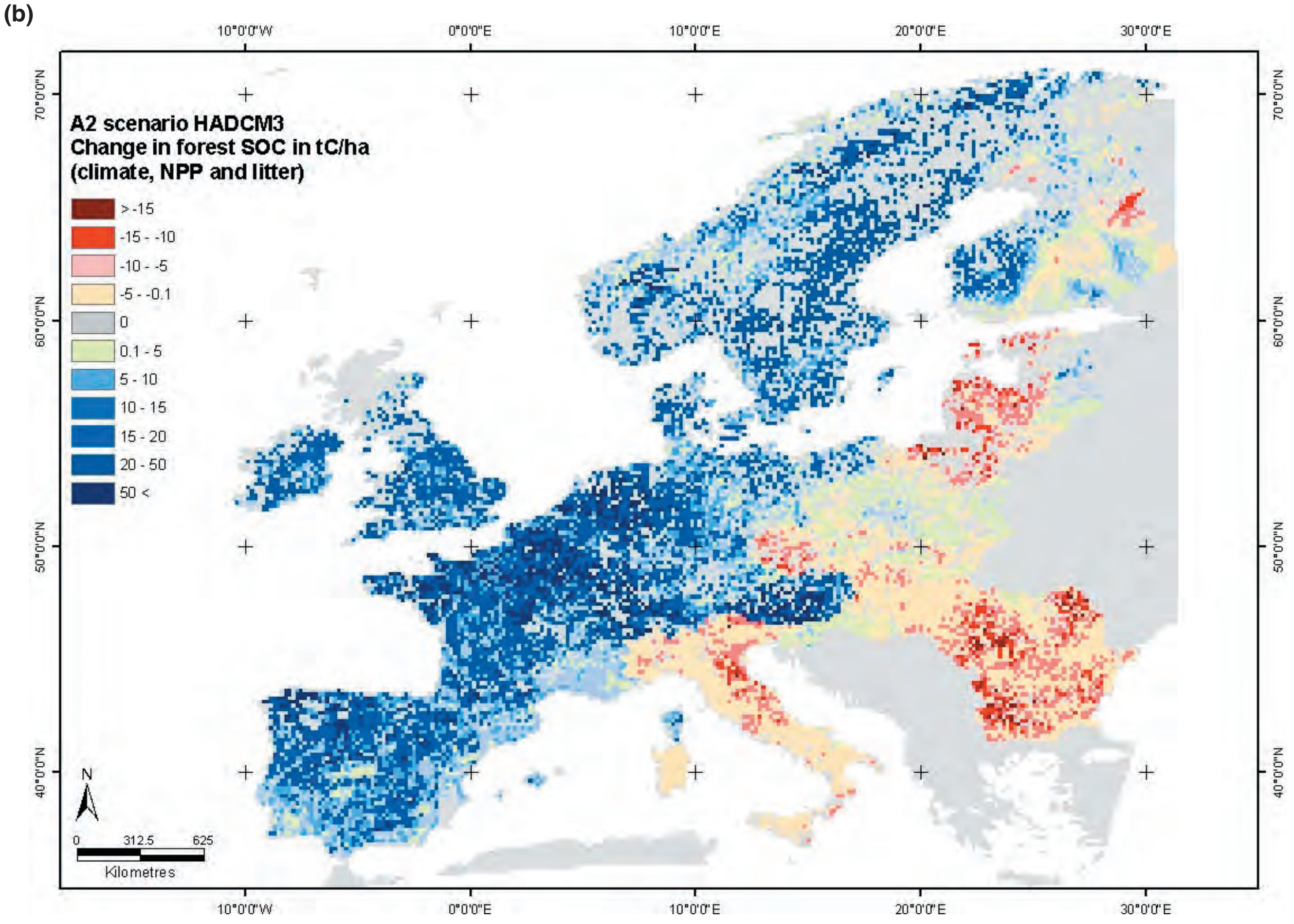

Fig. 6. Continued.

forests (UN-ECE/FAO 2000), which is partly caused by enhanced growth rates (cf. Spiecker et al 1996). As the higher increment rates are mainly due to nitrogen deposition (Karjalainen and Schuck 2005), they have to be considered as an indirectly human-induced factor.

Factoring out human-induced increases in forest SOC stock since 1990 from indirect effects and natural effects will be difficult (IPCC 2003), but studies such as this help to show the potential contribution from various sources. In this study, for example, in the A2 scenario (as implemented by HadCM3), direct impacts of climate change on the soil would cause a loss in SOC of 13 Mg C ha^{-1}, which is reduced to a loss of 2 Mg C ha^{-1} if changes in litter input are considered. Around 28% of the improvement of the SOC stock due to increased litter input results from enhanced NPP (as a result of climate- and CO_2-induced increases in NPP), and about 72% due to differences between the annual increment and felling.

Sources of Uncertainty

Sources of uncertainty include the variation between climate models, that NPP estimates by LPJ are not nitrogen limited meaning that the CO_2 response may be overestimated, and that litter fall data in EFISCEN are derived from biomass expansion factors, which have a high uncertainty. The land-use scenarios are also uncertain, but serve to give a measure of the potential contribution of land-use change in the future. Soil C stocks varied by less than 1.5 Mg C ha^{-1} between the end of the period for which meteorological data were used for initialisation, i.e., 1930, and 1990 for all runs, showing that the model was not subject to drift or instability following initialisation. By initialising the model in, and running the model from 1900, we further minimise any potential initialisation effects. The results presented here are for mineral soils only and do not include changes in the forest floor/litter layer. The litter layer may also accumulate C under the scenarios considered. Highly organic soils are also excluded from this study yet, given the large stocks of C held within them, could contribute significantly to the overall soil C balance of European forests. A remaining challenge is to accurately simulate the response of organic soils to future environmental change.

CONCLUSIONS

This is the first European assessment of future changes in forest mineral soil organic C stocks using a dedicated

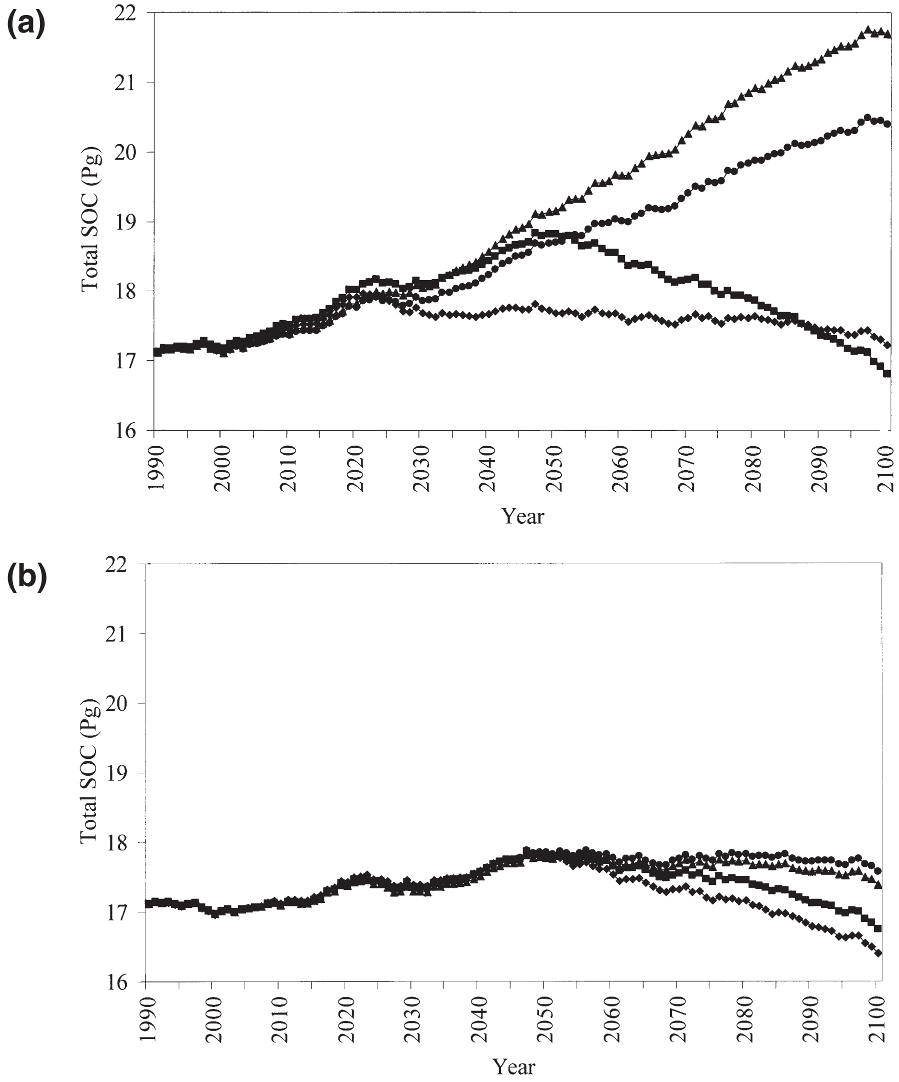

Fig. 7. Total SOC stock of mineral forest soils in the EU25 plus Norway and Switzerland, 1990–2100, accounting for direct climate change impacts on SOC, NPP increases due to climate change, and increased litter inputs due to changed age-class structure, with and without land-use change; including land-use change (a), and no land use change (land use as for 1990; (b). The four climate scenarios as implemented by HadCM3 are shown as: triangles = B2, circles = B1, squares = A2, diamonds = A1FI.

process-based SOC model and detailed databases of soils, climate and land use. Whilst climate change was found to be an important driver of change in forest soil C over the 21st century, projected forest management and land-use change will have greater effects, leading to only small losses or increasing European forest SOC stocks.

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