Global Change Biology

Global Change Biology (2010) **16**, 1451–1469, doi: 10.1111/j.1365-2486.2010.02215.x

REVIEW

The European carbon balance. Part 4: integration of carbon and other trace-gas fluxes

E. D. SCHULZE*, P. CIAIS†, S. LUYSSAERT†, M. SCHRUMPF*, I. A. JANSSENS‡, B. THIRUCHITTAMPALAM§, J. THELOKE§, M. SAURAT¶, S. BRINGEZU¶, J. LELIEVELD‖, A. LOHILA**, C. REBMANN††, M. JUNG*, D. BASTVIKEN‡‡, G. ABRIL§§, G. GRASSI¶¶, A. LEIP¶¶, A. FREIBAUER‖‖, W. KUTSCH‖‖, A. DON‖‖, J. NIESCHULZE*, A. BÖRNER*, J. H. GASH***, ††† and A. J. DOLMAN†††

*Max-Planck Institute for Biogeochemistry, PO Box 10 01 64, 07701 Jena, Germany, †Lab. des Sciences du Climat et de l'Environment, CEA CNRS UVSQ, Gif-sur-Yvette, France, ‡Department of Biology, University of Antwerp, Antwerp, Belgium, §Institut für Energiewirtschaft und Rationelle Energieanwendung, University Stuttgart, Stuttgart, Germany, ¶Wuppertal Institut, Wuppertal, Germany, ‖Max Planck Institut für Chemie, Mainz, Germany, **Finish Meteorological Institute, Helsinki, Finland, ††Helmholtz Centre for Environmental Research, UFZ, Leipzig, Germany, ‡‡Dept. of Thematic Studies – Water and Environmental Studies, Linköping University, Linköping, Sweden, §§Laboratoire EPOC, CNRS, University of Bordeaux, Bordeaux, France, ¶¶Joint Research Centre, European Commission, Ispra, Italy, ‖‖von Thuenen Institut, Department for Agricultural Climate Research, Braunschweig, Germany, ***Centre for Ecology and Hydrology, Wallingford, UK, †††VU University, Amsterdam, The Netherlands

Abstract

Overviewing the European carbon (C), greenhouse gas (GHG), and non-GHG fluxes, gross primary productivity (GPP) is about 9.3 Pg yr^{-1}, and fossil fuel imports are 1.6 Pg yr^{-1}. GPP is about 1.25% of solar radiation, containing about 360×10^{18} J energy – five times the energy content of annual fossil fuel use. Net primary production (NPP) is 50%, terrestrial net biome productivity, NBP, 3%, and the net GHG balance, NGB, 0.3% of GPP. Human harvest uses 20% of NPP or 10% of GPP, or alternatively 1‰ of solar radiation after accounting for the inherent cost of agriculture and forestry, for production of pesticides and fertilizer, the return of organic fertilizer, and for the C equivalent cost of GHG emissions. C equivalents are defined on a global warming potential with a 100-year time horizon. The equivalent of about 2.4% of the mineral fertilizer input is emitted as N_2O. Agricultural emissions to the atmosphere are about 40% of total methane, 60% of total NO-N, 70% of total N_2O-N, and 95% of total NH_3-N emissions of Europe. European soils are a net C sink (114 Tg yr^{-1}), but considering the emissions of GHGs, soils are a source of about 26 Tg CO_2 C-equivalent yr^{-1}. Forest, grassland and sediment C sinks are offset by GHG emissions from croplands, peatlands and inland waters. Non-GHGs (NH_3, NO*x*) interact significantly with the GHG and the C cycle through ammonium nitrate aerosols and dry deposition. Wet deposition of nitrogen (N) supports about 50% of forest timber growth. Land use change is regionally important. The absolute flux values total about 50 Tg C yr^{-1}. Nevertheless, for the European trace-gas balance, land-use intensity is more important than land-use change. This study shows that emissions of GHGs and non-GHGs significantly distort the C cycle and eliminate apparent C sinks.

Keywords: agriculture, carbon cycle, CH_4, CO_2, Europe, forestry, greenhouse gases, land-use change, N_2O, NH_3, non-greenhouse gases, NO*x*, O_3

Received 8 February 2010 and accepted 3 March 2010

Introduction

The difference between carbon dioxide (CO_2) emissions from burning fossil fuels and land use, and the growth rate of atmospheric CO_2 suggests the existence of a terrestrial and oceanic carbon (C) sink. Globally, the terrestrial C sink has absorbed about 30% of anthropogenic emissions over the period 2000–2007 (Canadell *et al.*, 2007; LeQuéré *et al.*, 2009), showing that C sequestration by land vegetation is a major ecosystem service. If we had to create a sink of that magnitude by mitigation technologies, it would currently cost about 0.5 trillion US$ per year (Canadell & Raupach, 2008). The fact that the inter-hemispheric gradient of CO_2, δ^{13}C, and O_2 in the atmosphere is smaller than predicted from fossil fuel emissions alone (Tans *et al.*, 1990;

Correspondence: Ernst-Detlef Schulze, Max-Planck Institute for Biogeochemistry, PO Box 10 01 64, 07701 Jena, Germany. tel. + 49 3641 576100, e-mail: Detlef.Schulze@bgc-jena.mpg.de

Ciais *et al*., 1995; Keeling *et al*., 1996) suggests that a significant fraction of the global land sink must be north of the Equator. Using vertical profiles of atmospheric CO_2 concentrations as a constraint on atmospheric inversions, Stephens *et al*., (2007) inferred that the magnitude of the total northern land sink ranges between 0.9 and $2.1\,Pg\,C\,yr^{-1}$, which would be about 10–25% of the anthropogenic fossil fuel emissions in 2006 (Canadell *et al*., 2007). Assuming that this sink was evenly distributed across the land surface, the European continent would absorb about $-120\,Tg\,C\,yr^{-1}$, which is of the same magnitude as earlier estimates ($-135\,Tg\,C\,yr^{-1}$; Janssens *et al*., 2003). New estimates, combining atmospheric and land-based measurements indicate an even stronger C sink of about $-270\,Tg\,C\,yr^{-1}$ (Schulze *et al*., 2009); however, these estimates also suggest that this 'sink' is being balanced by emissions of other greenhouse gases (GHGs), contributing little to climate mitigation.

In this study, we summarize the most important greenhouse and nonGHG fluxes for geographic Europe as bordered in the east by the Ural mountains, the Caspian Sea, the Caucasus and the Black Sea. Some data refer to the EU-25, which is shorthand for the western European nations [excluding Switzerland, Norway, Rumania and Bulgaria and the west Balkans see Schulze *et al*. (2009)]. A summary of the data-sources is given in the Appendix S1.

The C cycle of Europe

The C cycle of Europe consists of two major components: (1) activities within terrestrial and aquatic ecosystems, and (2) industrial-, transport- and household-activities. The latter activity accounts for most of the fossil fuel burning. Since our focus is on the contribution of the land surface and of land use to the overall trace-gas fluxes of Europe, we will first discuss these land-use related fluxes on a per unit area basis and then expand to the continent. Point sources which may be underestimated by averaging per area are considered by comparing atmosphere-based data with land-based data (Schulze *et al*., 2009).

The C and GHG balance of different land-use types

When comparing all CarboEurope eddy-covariance sites across Europe (see Appendix S2), no statistically significant difference could be found between the annual gross primary productivity (GPP) per unit land area of forests, grasslands and croplands (Table 1). Only peatlands have a lower GPP. This came as a surprise because crops are fertilized and occasionally irrigated, and they are typically grown on better soils and under better climatic conditions than forests. Crops are also seeded cultivars, and under favourable conditions multiple crops may be grown each year. We therefore expected to see larger GPP in croplands than in forests and grasslands. However, most often crops have a shorter growing season than forests and grasslands (see Fig. 1). This figure shows that the available light and the length of the growing season are the limiting factors in central and northern Europe. Drought is an additional limitation mainly in southern Europe.

Forest is the only land-use type that stores C in aboveground biomass across Europe and these stocks have grown mainly because harvest has been lower than growth for the past few decades (Ciais *et al*., 2008a, b). Forest standing-stocks have nearly tripled during the past 50 years. Because this C is being sequestered in the ecosystems over decades to centuries it has been regarded as a component of the net biome productivity ($NBP_{biomass}$). However, this accumulation should not hide the fact that the C incorporated in forest biomass is vulnerable to natural disturbances such as fire or pests, and of course to harvest. Part of the capacity of European forests to sequester C results from an uneven age structure caused by large-scale clear cuttings during and after World War I and II and the subsequent replanting (Nabuurs *et al*., 2003; Böttcher *et al*., 2008), and from new plantations in the 1970s. Now, sixty to a hundred years later, these stands are reaching the time to be harvested. Thus, this sink component of NBP in biomass should not be regarded as permanent or secure. The magnitude of the forest sink depends on stand age (Luyssaert *et al*., 2008), atmospheric nitrogen (N)-deposition (Schulze & Ulrich, 1991; de Vries *et al*., 2009; Magnani *et al*., 2007; Reay *et al*., 2008) and forest management (de Vries *et al*., 2006; Ciais *et al*., 2008a, b).

C storage in soils is a key component of NBP. Comparing the European grassland analysis of Soussana *et al*. (2007) and the forest analysis of Luyssaert *et al*. (2010), it can be seen that grasslands sequester more C in soils than forests – likely due to a higher belowground C allocation and root turnover, and possibly to N fertilization. In addition, the vesicular–arbuscular mycorrhizae of grasses are specialized in mobilizing mineral ions, especially phosphorus (Smith & Read, 1997), but are less efficient in breaking down organic matter, than the ectomycorrhizae, which are associated with European tree species (Read, 1993). Moreover, vesicular–arbuscular mycorrhizae may exude components that stimulate the stabilization of organic matter through accelerated formation of soil aggregates (Rillig, 2004). A direct consequence of these mycorrhizal characteristics is that afforestation of grasslands may enhance decomposition of soil organic matter, rather than sequestering more C in the soil. Thuille & Schulze

Table 1 Carbon, water, heat and nitrogen fluxes in major land-cover types (C-flow: Schulze *et al.*, 2009; water vapour and sensible heat as estimated from eddy covariance and hydrological data: M. Jung, pers comm.; Nitrogen requirement: Schulze (2000); Aldous (2002)

	Flux unit	Forest	Grassland	Cropland	Peatland
Gross Primary Productivity, GPP	$g\,C\,m^{-2}\,yr^{-1}$	**−1107 ± 55**	**−1343 ± 269**	**−1120 ± 224**	**−690 ± 340**
Autotrophic respiration, R_a	$g\,C\,m^{-2}\,yr^{-1}$	589 ± 88	593 ± 297	570 ± 171	395 ± 190
Net Primary Productivity, NPP	$g\,C\,m^{-2}\,yr^{-1}$	**−518 ± 67**	**−750 ± 150**	**−550 ± 50**	**−295 ± 150**
Harvest	$g\,C\,m^{-2}\,yr^{-1}$	63 ± 11	217 ± 43	257 ± 23	91
Net Biome Productivity, $NBP_{Biomass}$	$g\,C\,m^{-2}\,yr^{-1}$	**−55**	**0**	**0**	**0**
Manure	$g\,C\,m^{-2}\,yr^{-1}$	0	−40	−26	0
Heterotrophic respiration, R_h	$g\,C\,m^{-2}\,yr^{-1}$	368 ± 107	508 ± 152	319 ± 89	172 ± 86
Disturbance	$g\,C\,m^{-2}\,yr^{-1}$	5 ± 1	1 ± 0.3	3 ± 2	6 ± 2
Dissolved carbon, DOC/DIC	$g\,C\,m^{-2}\,yr^{-1}$	7 ± 3	7 ± 3	7 ± 3	7 ± 3
Net Biome Productivity, NBP_{soil}	$g\,C\,m^{-2}\,yr^{-1}$	**−20 ± 12**	**−57 ± 34**	**± 10 ± 9**	**−19 ± 12**
Other greenhouse gases, GHGs	$g\,CO_2\text{-}C\,eq\,m^{-2}\,yr^{-1}$	1 ± 1	43 ± 14	30 ± 9	63 ± 30
Net Greenhouse gas Balance, NGB	$g\,CO_2\text{-}Ceq\,m^{-2}\,yr^{-1}$	**−19 ± 11**	**−14 ± 18**	**+ 40 ± 40**	**+ 44 ± 7**
Water vapour, ET	$MJ\,m^{-2}\,yr^{-1}$	873 ± 60	891 ± 101	1204 ± 64	744 ± 260
	$mm\,yr^{-1}$	353 ± 24	360 ± 41	487 ± 26	300 ± 105
Interception, $E_{wet\ surfaces}$	$mm\,yr^{-1}$	240 ± 40[1]	<1	<1	<1
Water use efficiency, ET/NPP	$g\,g^{-1}$	680	480	885	996
Sensible heat, H	$MJ\,m^{-2}\,yr^{-1}$	720 ± 45	1077 ± 105	634 ± 35	455 ± 80
Nitrogen requirement for NPP	$gN\,m^{-2}\,yr^{-1}$	9 ± 3	18 ± 3	18 ± 3	3 ± 1

The bold lines indicate the main units of the carbon cycle.

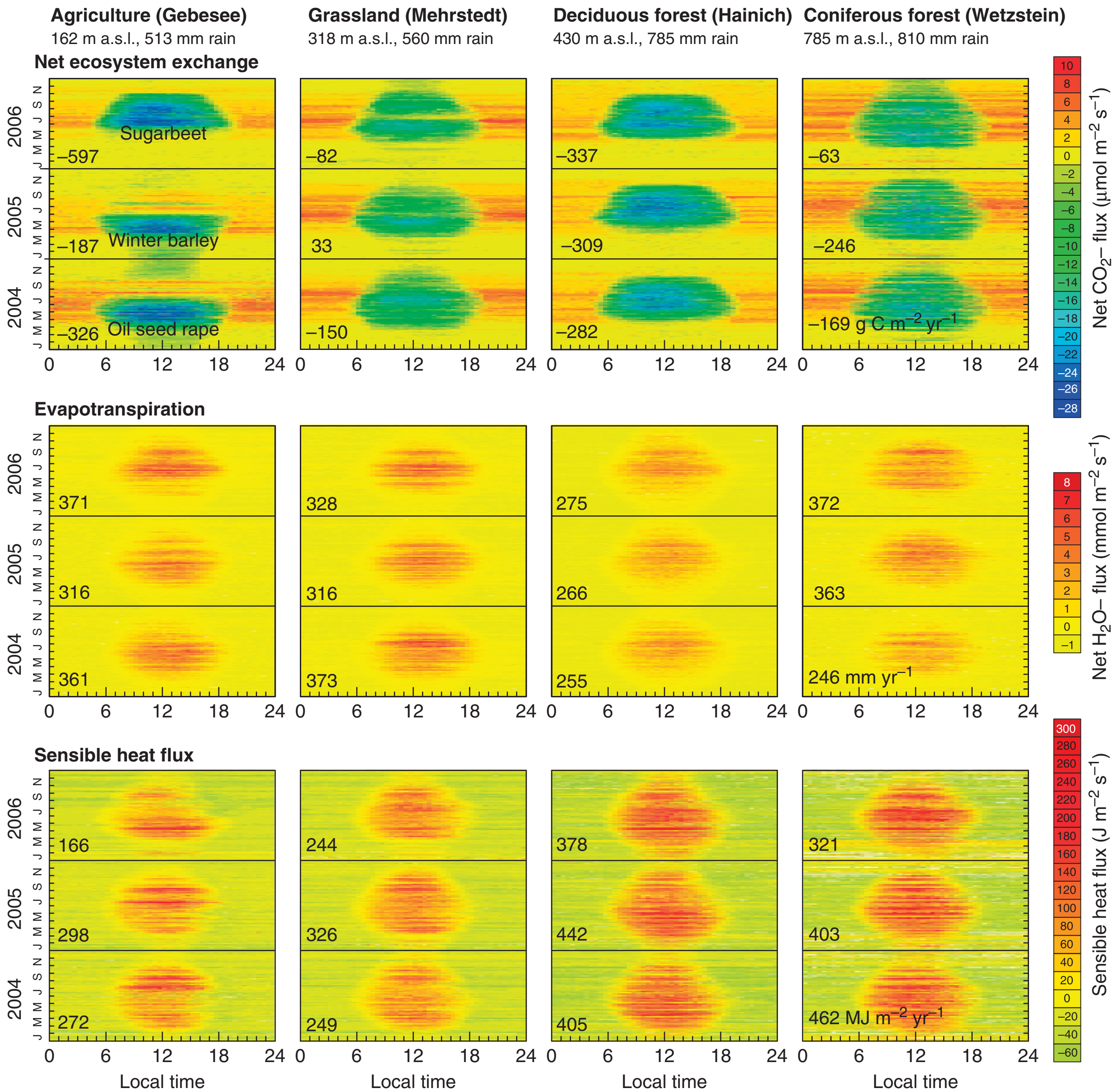


Fig. 1 Flux fingerprint of net ecosystem exchange, evaporation and sensible heat for cropland, grassland, deciduous forest and conifers in Thuringia, Germany for the year 2004–2006. Annual sums for Net Ecosystem Exchange are in $g\,C\,m^{-2}\,yr^{-1}$, for evaporation in mm, and for sensible heat in $MJ\,m^{-2}$.

(2005) found that soil C decreased following afforestation across central Europe; for 60 years following afforestation, the total C balance was found to be negative. After that time the C storage in tree biomass balanced the soil C losses, but at that age the trees are close to harvest. A similar trend appeared in a meta-analysis of land-use change (LUC) effects on soil C stocks (Guo & Gifford, 2002).

Cropland NBP, as assessed through a full crop cycle, is distinct from that in grasslands and forests in that, when averaged over the last decade, cropland soils appear to be a small C source to the atmosphere through management (Ciais *et al.*, 2010a). Per unit ground area, the net loss of C is of the same order of magnitude as the rate of soil C sequestration in forests. A verification of this flux through direct observation remains an important issue.

All agriculturally managed ecosystems (grasslands and croplands) emit other trace gases, mainly methane from grazing animals, nitric oxides (NO, NO*x*)

(Steinkamp *et al*., 2009), and nitrous oxide (N_2O). In this study we compare all GHGs based on their global warming potential over a 100 year time horizon according to IPCC (2007) by multiplying the fluxes of CH_4 by a factor of 25, N_2O a by a factor 289, and CO by a factor 1.9 (indirect warming through ozone), and taking the molar ratio of C/CO_2 into account. Accounting for their GHG emissions, croplands are a source of radiative forcing to the atmosphere. Also, GHG emissions partially offset the strength of the C sink of grasslands to the extent that their NGB is no longer higher than in forests, as was the case for NBP (Table 1). However, in contrast to croplands, grasslands do remain a net sink of radiative forcing. The GHG emissions from croplands increase NGB to about $40\,g\,m^{-2}\,yr^{-1}$, which more than balances the NGB-sink of grasslands and forest totalling about $33\,g\,m^{-2}\,yr^{-1}$. The absence of substantial CH_4 and N_2O emissions from forests differentiates them from agricultural ecosystems. However, tree plantations that produce biomass for energy production (*Populus, Salix*) will also emit NO and N_2O if they are fertilized (Schmid *et al*., 2006).

Table 1 includes the C flow through peatlands, which in this study are mainly bogs dominated by *Sphagnum*. Wetlands with grasses or sedges are included in the grassland sector and afforested bogs are included under forests. We must emphasize that the information on peatlands is less integrated than the information on forests, grasslands and croplands. Our data are based on a transect study in Finland (Alm *et al*., 2007; A Lohila personal communication) without weighting the results by the area of the different peatland types. Thus, the peatland data will need to be revisited in the future (Appendix S3). Peatland GPP, NPP and NBP are significantly lower than in the other land-use types, but they still may be overestimated. The uncertainty of these data is large due to the heterogeneity of peat management, which ranges from pristine bogs to commercial peat extraction. Depending on the height of the water table, substantial methane emissions may occur from peatlands. The CO_2-C equivalent CH_4 fluxes change the C sink (negative NBP) into a GHG source (positive NGB).

Ecosystems do not only exchange CO_2, but also need other elements, such as N for growth; they also exchange water vapour and heat with the atmosphere. Therefore, Table 1 also includes the specific fluxes of water vapour (or latent heat), LE and sensible heat, H, and N. Per unit area, croplands transpire/evaporate about 30% more water than forests and grasslands. However, this difference also includes the fact that crops are grown at lower elevation and in warmer climates than forests. The higher water use by crops is accompanied by lower dissipation of sensible heat into the atmosphere than by forests. Forests are coupled to the vapour pressure deficit of the atmosphere while short vegetation is coupled to net radiation (Jarvis & McNaughton, 1986; Schulze *et al*., 2002). The evaporation and sensible heat fluxes were estimated by upscaling eddy-covariance measurements (Baldocchi, 2003) based on the approach of Jung *et al*. (2009) using satellite and meteorological data. A first-order correction of the measurements was applied to ensure consistency with measured net radiation, which yields estimates consistent with the hydrological balance of catchments and largely eliminates the systematic underestimation of evaporation by the eddy-covariance technique (M. Jung *et al*. in preparation). Because of the frequent removal of nutrient-rich biomass during harvest, crops and grasslands require almost twice as much N as forests to maintain their growth. Considering the combined use of all resources (C, N, and water), forests are the least demanding land use with the lowest demand for N per unit of C assimilated into NBP and NGB. Pristine peatlands have an even higher N-use per unit of C sequestered than forests, but peatlands remain a GHG source due to their methane emissions.

The comparisons of the flux balances between land-use types presented in Table 1, which are European averages, implicitly include the variation related to where these land-use types exist. Forests are dominant in northern Europe, crops cover lower elevations, and grasslands dominate in southern and eastern Europe, and near the Atlantic coast. Thus, it is important to also compare these land-use types at regional scale under similar climatic conditions. Presenting daily and seasonal rates of net ecosystem exchange, NEE, via so-called 'fingerprints' of CO_2 and water vapour exchange makes specific differences between land-cover types more obvious than the European annual budgets. Figure 1a clearly shows the shorter growing season and the larger variation of active photosynthesis in crops than in forests and grasslands. Barley (2005) and oil seed rape (2004) have the shortest period of C uptake despite these crops being seeded in autumn, and grasslands show seasonal variability due to grazing. In contrast, conifers show the longest period of net C uptake. During warm winters temperate coniferous ecosystems may act as sinks throughout the year (Carrara *et al*., 2004; Dolman *et al*., 2008). In total, the NEE measurements reveal that the CO_2 sink capacity of forests, growing in the same region is about 10% higher than the sink capacity of grasslands and agriculture; this is the opposite to the European averages shown in Table 1 for NPP and NBP. It demonstrates the effects of geographic differences in the growing regions underlying the European comparisons.

The eddy-covariance technique also measures the latent heat or water vapour fluxes (Fig. 1b). Water vapour fluxes show less variation than the CO_2 fluxes, likely because the bare soil of arable fields also loses water vapour through evaporation from the soil. Evaporation is also constrained by the precipitation and the available soil moisture. Thus, differences between land-cover types are less obvious for evaporation. Within the same region, deciduous forests have about 20% lower water consumption than coniferous forests, which lose as much water as agricultural systems. Owing to differences in albedo and Bowen ratio the sensible heat flux is about 50–60% higher in deciduous and coniferous forests than in grasslands and croplands (Fig. 1c). In addition to the differences in NGB and the water fluxes, this difference of about 125 MJ m^{-2} yr^{-1} should be considered when assessing the effects of land use and LUC on climate.

Fossil fuel emissions per unit area

Regional differences of fossil fuel emissions across Europe (Ciais *et al.*, 2010b) indicate that the main region of fossil fuel burning stretches from the south of England to Italy, with highest emissions in the Benelux states and in north-western Germany (see also Fig. 5a). Russia and the Scandinavian countries are distinctly different from Western Europe due to their high proportion of energy generated as hydroelectricity in the north and due to lower energy consumption in the east. France is notably different from neighbouring countries due to the 80% of electricity that is generated by nuclear power, lowering fossil fuel emissions per unit land area by about one-third. The per capita emissions confirm the high emissions in central Europe (Schulze *et al.*, 2009). In total, and neglecting changes in bunker fuels, the fossil fuel emissions of continental Europe in the period of 2000–2004 average 1620 Tg C yr^{-1}, amounting to 162 g C m^{-2} yr^{-1} (Schulze *et al.*, 2009c; Ciais *et al.*, 2010b). Based on an energy mix for the EU-27 of 7.9% coal and lignite, 36.8% oil and 23.9% gas (and 31.3% nuclear power and renewable energies), the energy content of the 1620 Tg C yr^{-1} fossil fuel used is equivalent to 1.8 Gt of oil with 41.868 GJ t^{-1}. Thus, the fossil fuel use is equivalent to 75.4 10^{18} J yr^{-1} (http://epp.eurostat.ec.europa.eu/portal/page/portal/sdi/indicators/theme6, and http://www.sei.ie/reio.htm).

The C cycle of continental Europe

Conceptually, the cycle of plant photosynthesis, plant biomass production and decay of dead organic matter is disturbed by the injection of additional CO_2 through fossil fuel burning, and by the injection of additional trace gases into the atmosphere by land use and fossil fuel burning (Fig. 2). The effects of land use are diverse. Agriculture is responsible for methane emissions from animal husbandry and for N_2O and NH_3 emissions from fertilizers and manure (Schulze *et al.*, 2009). Combustion in vehicle engines produces not only CO_2 but also NO*x*, which is not a GHG in the strict sense (IPCC, 2007). Also agriculture contributes a major fraction of total NO production. NO*x* is not a GHG (IPCC, 2007) but it interacts with oxygen in the atmosphere and is the main catalyst for tropospheric ozone production and removal (Lelieveld & Dentener, 2000; Ravishkanara *et al.*, 2009). Attribution studies of the radiative forcing of chemically reactive species showed that globally the NO*x* emissions have a cooling effect on climate because they indirectly remove CH_4 through increased abundance of OH radicals (Shindell *et al.*, 2005) and because they produce aerosols that cool the climate. NO*x* is indeed oxidized to nitrate-anions which react with ammonium producing ammonium-nitrate, the most abundant aerosol component across Europe. This reaction results in an additional cooling effect on climate. Polluted atmospheres with higher NO*x* content also show an increased conversion of SO_2 into sulphate aerosols, which again cool the climate (Shindell *et al.*, 2009). Recently, a positive radiative forcing trend of about 1.2 W m^{-2} yr^{-1} has been observed across Europe, attributed to solar brightening associated with the abatement of sulfate aerosol pollution (Wild *et al.*, 2009). Although the residual solar brightening effect of ammonium nitrate remained un-estimated the effect is likely to be smaller than the effect of sulphate (Haywood & Schulze, 2007).

Ammonium nitrate is washed out of the atmosphere as 'acid rain' (Schulze & Ulrich, 1991), but at the same time stimulates plant growth through N fertilization. Evidence is accumulating that in the long run plant growth can only benefit from increased CO_2 when sufficient N is available (Oren *et al.*, 2001). In N-limited regions, atmospheric wet deposition of ammonium nitrate, and dry deposition of NH_3 and NO*x* (Harrison *et al.*, 2000; Nösberger *et al.*, 2006; Reay *et al.*, 2008) could be a major source of plant-available N. We emphasize through Fig. 2 that the C cycle strongly interacts with the N cycle not only in producing additional trace gases, but also by affecting plant growth and retarding decomposition of soil organic matter (Janssens & Luyssaert, 2009). We further emphasize that the quantification of nonGHG fluxes, such as NO, NO*x* and ammonia, is essential if we are to understand changes in important greenhouse effect determinants, such as ozone and aerosols.

Based on this conceptual representation of the C cycle and its main drivers, we detailed an integrated flux balance of trace gases across the continent of Europe (Fig. 3, a deconvoluted version of Fig. 3 and the data-sources are presented in Appendices S1 and S4). This

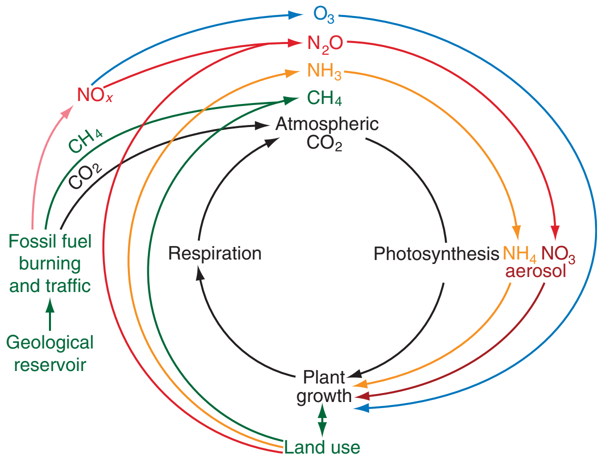
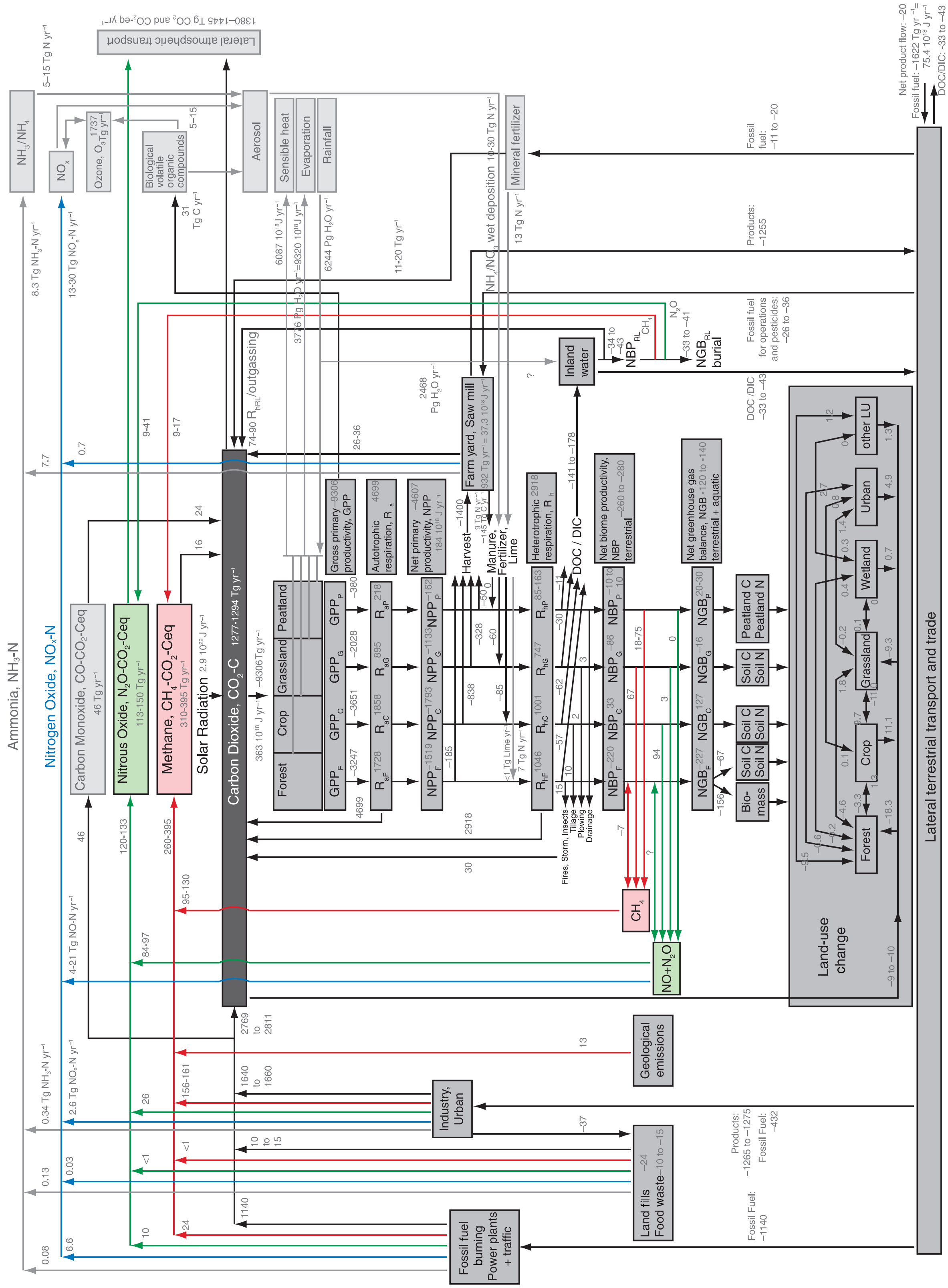


Fig. 2 General scheme of carbon–nitrogen interactions in the carbon cycle.

figure contains in its centre the C fluxes (black lines) of the main land-use types, i.e. forest, grassland, cropland and peatland as integrated across Europe. In addition to this natural C-cycle we have added the anthropogenic fluxes due to imports of wood and food products, the losses by disturbance e.g. by fire, and fossil fuel C emitted as CO_2 and CO to the atmosphere. Associated with the land biosphere fluxes and fossil fuel emissions are the fluxes of CH_4 (red lines) and N_2O (green lines). Additional trace gases are N oxides, NO*x*, (blue line) and ammonia, NH_3, (grey lines). These species have an indirect effect on climate through their role in atmospheric chemistry processes, particularly the abundance of OH (see above and Shindell *et al*., 2009). These gases, together with biological volatile organic compounds, BVOC, interact with OH radicals and thus impact the radiative forcing of ozone and aerosols (white lines). Figure 3 also shows the major water fluxes (rain, evaporation and run-off, assuming a constant groundwater-level) and the flux of sensible heat. Although combining all fluxes in Fig. 3 results in a fairly complex scheme, this is still a simplification that omits the feedbacks and controls. However, to our knowledge, this is the first time that all these fluxes have been assembled in one single scheme for one region. The fluxes have different units for C, N, water and energy. Molar units would simplify the scheme, but molar units are not established in this field of science. Whenever possible, fluxes were expressed as C or CO_2-C equivalents (IPCC, 2007). The present knowledge of the emissions and sinks of atmospheric trace gases indicates decreasing knowledge and thus increasing uncertainty of these fluxes from the inner core of the diagram, i.e. plant C cycle towards the outer envelope of nonGHGs (see 'Uncertainty of the C balances' of this study for the associated uncertainty analysis). The total photosynthetic carbon fixation (GPP) of Europe amounts to about 9.3 Pg C yr^{-1}. Based on an energy content of 15.65 kJ g^{-1} of glucose (Bresinsky *et al*., 2008) which is 39 J g^{-1} C, total GPP transfers about 360×10^{18} J yr^{-1}, which is 1.24% of shortwave solar radiation reaching Europe. About 50% of GPP is transformed into plant growth (net primary production, NPP). Biomass has an energy content of about 20 kJ g^{-1} dry weight (Larcher 1993, 40 kJ g^{-1} C). Thus, total NPP represents about 180×10^{18} J yr^{-1}, which is only 0.6% of shortwave solar radiation. About 30% of NPP enters the product chain as harvestable food, wood or fibre (1.4 Pg C yr^{-1}). But harvesting has its own 'cost'. Some of the harvestable biomass returns to the field as manure (about 150 Tg C yr^{-1}), and fossil fuel is needed to manage the field and for pesticide production (26–36 Tg C yr^{-1}). In addition fossil fuel is needed for fertilizer production (11–20 Tg C yr^{-1}; www.fertilizer.org/ifa, Dalgaard *et al*., 2001; Hülsbergen *et al*., 2001) and to produce mechanical force necessary for cultivation. It was estimated for the USA that the operational CO_2 emissions of land management should be doubled in order to obtain the total emissions by agriculture, not including non-CO_2 gases (Nelson *et al*., 2009). Agricultural land also contributes to the emission of N_2O and CH_4 from the land surface and from freshwater (in total about 165 Tg CO_2-C equivalent per year from croplands and grasslands, plus 40 Tg CO_2-C equivalent per year from surface waters). All these factors (manure, fossil fuel for operation, pesticides and fertilizer, CH_4 and N_2O emissions) add to a cost amounting to at least a sum of about 400 Tg CO_2-C equivalent per year. Our data on the cost factors in agriculture remain quite uncertain, and are most likely a low estimate. They do not include the energy requirements for heating greenhouses or for cooling cold-stores, to mention just a few unaccounted costs. Considering these costs, the net yield (about 1000 Tg CO_2-C equivalent per year) is only about 20% of NPP and about 10% of GPP. In terms of energy, the harvested net yield contains about 0.1% of solar radiation, which is a very low energy use efficiency when for example compared with solar cells (WBGU, 2004). This low efficiency does not account for the considerable N_2O emissions by bioenergy plantations (Schmid *et al*., 2006).

Disturbances consume, on average, only an additional 0.5% of NPP, but this may be a low estimate due to dispersed records and documentation (Schelhaas *et al*., 2003). The highest rates of damage take place in forests, and the lowest in peatlands. Total terrestrial net biome productivity (NBP, which accounts for heterotrophic respiration and disturbance losses) throughout Europe amounts to about 270 Tg yr^{-1} (Table 1), which is



about 3% of the photosynthetic C gain as net yield, and 0.3‰ of solar radiation, or one-third of that entering into the human product chain. Croplands are net CO_2 sources offsetting 10% of the forest and grassland NBP. Forest NBP contains the increment in woody biomass. At this moment we are unable to predict how NBP would quantitatively change with anthropogenic harvests, but, most likely, increased C extraction from ecosystems for human use will reduce NBP.

The definition of NBP requires a time scale, which must be long enough to average out inter-annual variability. Although not all data we analyse cover the same period of time, our NBP estimate corresponds broadly to the period 2000–2005. We are aware of decadal variability in C fluxes reflecting decadal variability in climate (e.g. Piao *et al*., 2009). Thus, our estimate of NBP is performed over a short period and is affected by climate variability, in particular with the presence of an extreme year like 2003 in the period. In particular, the North Atlantic Oscillation (NAO), which is strongly correlated with winter rainfall and precipitation patterns has been in a high phase since 1990, favouring warm and humid winters in northern Europe and lower winter precipitation in southern Europe. We can speculate that a high NAO is also systematically associated with an earlier onset of vegetation growth in spring (Menzel & Fabian, 1999; Maignan *et al*., 2008), and thus higher than average NBP.

Large amounts of CH_4 and N_2O are lost from croplands and grasslands, including housed animals (here the additional emissions and radiative forcing of NO*x* are ignored). Additional amounts of CH_4 and N_2O are emitted from inland waters (Seitzinger & Kroeze, 1998; Kroeze *et al*., 2005; Tranvik *et al*., 2009) based on lateral inputs from the land surface. The resulting NGB of the land surface appears as a sink of radiative forcing that represents (in CO_2 equivalents) 3‰ of the photosynthetic CO_2 fixation. This sink is established by forests, grasslands, and burial in sediments, while croplands and peatlands are C-equivalent sources to the atmosphere offsetting about 55% of the forest and grassland sink. Discarding the harvestable and thus vulnerable biomass sink of wood in forests, the only long-term storage of C is in soils and inland water sediments. Our C balance suggests the C sink of forest and grassland soils ($-83\,\mathrm{Tg\,yr^{-1}}$) is negated by losses in crops and wetlands ($+152\,\mathrm{Tg\,yr^{-1}}$). Thus, the terrestrial soils are a net C-equivalent source totalling $69\,\mathrm{Tg\,C\,yr^{-1}}$. Part of this loss is balanced by burial of C in sediments (-37 Tg CO_2-C equivalent per year). Nevertheless, European soils and sediments remain a net C-equivalent source of about 30 Tg CO_2-C equivalent per year. This demonstrates a substantial impact of humans on the C cycle of Europe. Considerable re-allocation of land and associated C pools occurs with LUC. These changes are estimated to have created only an additional small C sink of 9–10 $\mathrm{Tg\,yr^{-1}}$ across Europe over the past 20 years (see 'Regional distributions of GHG fluxes' on LUC, below). Forests and grasslands gain C in the process of LUC, but a loss of similar magnitude exists due to expansion of agriculture, settlements and infrastructure. Comparing this estimate with the C balance of soils and sediments, it is obvious that in Europe as a whole the effects of land-use intensity on the atmospheric composition are more important than effects of LUC.

Fossil fuels are used in power stations, in ground transportation, by industry (partly as substrate for products and partly as fuel) and households, and for agriculture (e.g. to produce fertilizers and pesticides, and for operations). The total fossil fuel emission of $1620\,\mathrm{Tg\,yr^{-1}}$ in Europe is slightly higher than the total C in harvested products of forestry and agriculture ($1400\,\mathrm{Tg\,yr^{-1}}$). This comparison can be made, because most of the harvested biomass has a mean life time of <2 years. For the EU-25 it has been estimated that the pool of wood products with mean life time exceeding 25 years grows by only $4\,\mathrm{Tg\,C\,yr^{-1}}$ (Nabuurs *et al*., 2003). However, in terms of energy, the fossil fuel use of $75\times10^{18}\,\mathrm{J\,yr^{-1}}$ is eight times larger than the energy content of harvested net yield (harvest minus fossil fuel

Fig. 3 A summary of greenhouse and nongreenhouse gas fluxes across Europe. Black: Carbon fluxes (Schulze *et al*., 2009; Tranvik *et al*., 2009); red: Methane fluxes (Bastviken *et al*., 2004; Schulze *et al*., 2009), **green**: N_2O fluxes (Seitzinger & Kroeze, 1998; Schulze *et al*., 2009; NAMEA data base Wuppertal Institute); blue: NOx fluxes (IER-Stuttgart database, NAMEA data base Wuppertal Institute, Eurostat Air Emissions Accounts), grey: CO fluxes (Lelieveld *et al*., 2002), NH_3 fluxes (IER-Stuttgart database, NAMEA data base Wuppertal Institute), Ozone flux (Lelieveld *et al*., 2002), water fluxes (M. Jung, personal Communication), and input of mineral fertilizer (http://www.fertilizer.org/ifa). Solar radiation: CE-IP ECMWF data base. The fluxes have different units for carbon, nitrogen and water. Molar units would simplify the scheme, but molar units are not established even in the science community. The boxes at the top of the scheme indicate the total net flux of CO_2, CH_4, and N_2O as a range which originates from the atmosphere-based assessments (Schulze *et al*., 2009), and the land-based assessment (this study). The atmosphere-based estimate is the larger number for CO_2 and CH_4 and the smaller number for N_2O. CO, NO*x* and NH_3 are land-based estimates only. The present knowledge of the emissions and sinks of atmospheric trace gases indicate a decreasing knowledge of these fluxes from the inner core of the plant carbon cycle towards the outer envelope of nonGHGs. The background picture is from J. Bruegel the elder (1568–1625): Forested Landscape, Landesmuseum Hannover, Germany. The sources of the data for individual fluxes are listed in the supplement. The uncertainties are depicted in Fig. 4.

and GHG cost) and about half of the energy content in NPP.

In the overall balance of Fig. 3, for the main trace gases CO_2, CH_4 and N_2O, the range of values represents the atmosphere-based estimates of Schulze *et al*. (2009) and the land-based estimates of this study. It is interesting to note that the atmosphere-based estimates tend to be higher than the land-based estimates for CO_2 and CH_4 but not for N_2O. It is possible that the area-based estimates of surface emissions underestimate point sources, such as high chimneys of power-stations which would emit mainly CO_2. The N_2O flux originates mainly from surface areas. Although, the CO_2 emitted by fossil fuel burning originates from fossil fuel inventories (Ciais *et al*., 2010b), the emissions of CO_2 might be underestimated. At this moment there is no access to the measured emission of point sources, and the combination of atmosphere- and land-based estimates is the only way to approach the flux-mix from land surfaces and point sources.

Carbon monoxide, CO, is a by-product of fossil fuel burning. CO is a relatively short-lived greenhouse-gas and ozone precursor, which is eventually oxidized into CO_2. The oxidation of CO consumes OH radicals, which increases the lifetime of CH_4. Therefore, anthropogenic CO emissions have a net warming effect through its effect on CH_4 and O_3. Human activities and fossil fuel burning also emit significant amounts of CH_4. CH_4 emission from urban areas and industry is about the same as from agriculture. The CH_4 losses from power plants and traffic are small.

Three important nonGHGs are emitted in the process of burning fossil fuel. These are NO and NOx from vehicle transport, energy production, industrial processes and agriculture (Steinkamp *et al*., 2009) and NH_3 mainly from agriculture. NO is converted into NO_2 (together with NOx), which photochemically interacts with volatile organic compounds in the formation of ozone and increases OH (Lelieveld & Dentener, 2000; Vestreng *et al*., 2004; Jöckel *et al*., 2006). The ozone flux shown in Fig. 3 is the gross flux, which does not include ozone losses, because both processes nearly balance on large scales in the anthropogenically influenced, as well as the pristine, atmosphere. NOx oxidizes into NO_3^- and combines with NH_4^+ from NH_3 forming ammonium nitrate aerosols, which in turn are washed out from the atmosphere by wet deposition of nitrogen (Schulze & Ulrich, 1991). Dry deposition of NOx and NH_3 through stomatal uptake, and of ammonium and nitrate through uptake by plant surfaces have not been included in this study, but may be two to seven times higher than wet deposition (Harrison *et al*., 2000; M. Sutton personal communication). A full quantification of dry deposition (aerosol deposition and gas uptake) was not possible in this study. Wet deposition, originating from NH_3 and NOx emissions plus fertilizer input total at least $33\,Tg\,yr^{-1}$. This input can be compared with the total N emissions of N_2O-N from agriculture and freshwaters (Seitzinger & Kroeze, 1998), in total about $0.34\,Tg\,N\,yr^{-1}$. Thus, about 2.4% of the N input of mineral fertilizer (or 1.8% of organic and mineral fertilizer) is emitted as N_2O, which is close to the estimate of 2.5% by Davidson (2009). Based on total N inputs from mineral and organic fertilizers ($22\,Tg\,N\,yr^{-1}$ based on inventories and $18.5\,Tg\,yr^{-1}$ based on the fertilizer data base, see Fig. 5f) plus the atmospheric input ($15\,Tg\,N\,yr^{-1}$) N_2O-N production is only 0.7% of total N input. However, since fertilizer is not applied evenly, we think that the emission factor based on fertilizer addition only is the appropriate estimate. Even though the total N_2O-N flux appears to be small per unit of added N, due to its global warming potential, the CO_2-C equivalent flux of N_2O is seven to eight times larger per unit of N input. Basically the short-lived N contained in fertilizer is converted into a long-lived GHG at a rate of seven to eight.

Human N inputs are a major disturbance of the C cycle. $13\,Tg\,N\,yr^{-1}$ are added as mineral fertilizer, $9\,Tg\,N\,yr^{-1}$ through manure application and animal droppings, and $10–30\,Tg\,N\,yr^{-1}$ through wet deposition. The addition of compost and sewage residues is not included. Also dry deposition of N remains an additional un-quantified source. How to quantify the effects of the atmospheric N input on growth is still under discussion. de Vries *et al*. (2006) suggested that the C pool changes in European forests result mainly from forest management. In contrast, Magnani *et al*. (2007) described wet deposition as the major determinant of the CO_2 uptake over entire forest rotation cycles. Although an intense debate arose about the exact magnitude of the N-induced C sink in forests (e.g. de Vries *et al*., 2008; Sutton *et al*., 2008; Janssens & Luyssaert, 2009), the fact is that N is a major cause of variation in the net annual productivity, NEP, of forests. In a recent analysis of soil and wood C changes in nearly 400 intensively monitored European forests, de Vries *et al*. (2009) reported that N deposition typically stimulated forest ecosystem C sequestration by $20–40\,gC\,g^{-1}N$ deposited, with lower efficiency of C sequestration at higher N deposition rates. According to Fig. 3, $20\,Tg\,N\,yr^{-1}$ wet deposition would result in 400–800 Tg of added growth across all land-use types; 30% of which would be covered by forests. Thus, $200\,Tg\,yr^{-1}$ N induced growth can be compared with forest NBP and the harvest ($405\,Tg\,yr^{-1}$), which implies that at least 50% of forest growth are caused by wet deposition.

Human activities also create an additional C sink by dumping materials. The values in Fig 3 represent the actual losses from dumping irrespective of the age of the material. Food waste (Hall *et al*., 2009) may represent as much C as dumping of C-containing products (1% of total agricultural yield). While food waste would decompose rapidly, mainly into CO_2, their products would remain in the ground as a sink. In Europe, the associated losses of other trace gases appear to be small (see also Bogner & Matthews, 2003).

The entire C cycle is closely linked to the hydrological cycle. Water availability is essential for plant production: the dry, hot year of 2003 showed a 20% reduction in grain yields (Ciais *et al*., 2005). Moreover microbes need water to decompose soil C (Davidson & Janssens, 2006). Therefore, we have included the main components of the water cycle into Fig. 3. Based on river outflow, about 40% of the rainfall return to rivers via groundwater discharge and surface runoff. This river discharge contains a considerable amount of dissolved C. This C is processed, entrained or buried in inland waters and partly discharged into the coastal margins, where it interacts with the marine C cycle. The remaining 60% of the water returns as water vapour to the atmosphere. Our ratio between river discharge and evapotranspiration confirms regional water balances (see Schulze *et al*., 2002). The energy dissipation associated with the evaporation is about 50% higher than the energy content of the sensible heat flow (H/LE is 0.65). Although large-scale agricultural irrigation does not currently take place in Europe, possible future irrigation of crops for biodiesel would perturb the water cycle (Service, 2009).

Uncertainty of the C balances

The accuracy of regional C balances (i.e. closeness to its actual (unknown) value) and their components can be assessed by estimating the same quantities using independent data. Luyssaert *et al*. (2010) and Ciais *et al*. (2010a, b) used field observations, remote sensing and ecosystem model simulations as largely independent approaches to estimate NPP and other components of ecosystem C flows in forests, grasslands and croplands. For example, up-scaled terrestrial observations and model-based approaches agree on the mean NPP of forests to within 25%. Similarly, Schulze *et al*. (2009) compiled the European C balance based on atmospheric GHG concentration measurements on the one hand and land-based C stocks and fluxes on the other. Based on atmospheric measurements a terrestrial C sink of $-120\,\mathrm{Tg\,C\,yr^{-1}}$ was estimated for the EU-25 whereas the land-based approach estimated a sink of $-102\,\mathrm{Tg\,C\,yr^{-1}}$ (Schulze *et al*. 2009). Again, convergence of the outcomes of independent approaches suggests increased confidence in the mean estimate of the component. For the moment, the various data streams can only be verified by applying at least two approaches (i.e. top-down and bottom-up as by Schulze *et al*. (2009) or by a rigorous consistency check, as by Luyssaert *et al*. (2009). Although using independent estimates is a powerful tool to increase our confidence, it cannot assist us in quantifying the precision (i.e. the degree to which repeated measurements under unchanged conditions show the same result) of individual component fluxes. In this study, uncertainty was used as the composite of accuracy and precision.

Precision of individual components are needed to quantify the importance of individual processes, their interactions and statistical significance. Large but imprecise component fluxes are typically the prime target when it comes to reducing the overall uncertainty of the estimate. Heterotrophic respiration, for example, is a key flux in determining soil C sequestration in croplands. Partly due to the lack of spatially representative and reliable heterotrophic respiration estimates, models (i.e. $-8.3 \pm 13\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$) and soil inventories ($13 \pm 33\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$) are both inconclusive whether croplands are a C sink or a C source (Ciais *et al*., 2010a). Reducing the uncertainty of the heterotrophic respiration flux would help to establish whether European croplands are a small sink or a small source.

The uncertainty of an individual component should be quantified by subjecting the measurements to rigorous uncertainty propagation (i.e. accuracy of the measurements, representativeness of the samples, spatial and temporal resolution of the sample design, etc.) and all subsequent data processing (i.e. uncertainty of the relationships used for up or down-scaling, etc.). Typically, only few of the possible sources of uncertainty are quantified; this was certainly the case for the uncertainties reported by Luyssaert *et al*. (2010) and Ciais *et al*. (2010a, b). In most cases none of the components of uncertainty have been estimated and spatial, seasonal or interannual variability is often (wrongly) used as a proxy for the total uncertainty. Consequently, methods that report a low uncertainty are not necessarily more reliable than methods with a high uncertainty, and it is possible that the latter simply reflects a more complete uncertainty estimate.

When independent estimates, each with their own uncertainty, are available for the same flux quantity, propagating uncertainties becomes even more complicated. Forest inventories, for example, use a model to estimate heterotrophic respiration. Although the modelled flux is highly uncertain, owing to the high number of sampling plots (10^5) its spatial up-scaling is quite certain. On the other hand, site-level heterotrophic measurements are more reliable than the modelled flux, but are available on just 100 sites resulting in an

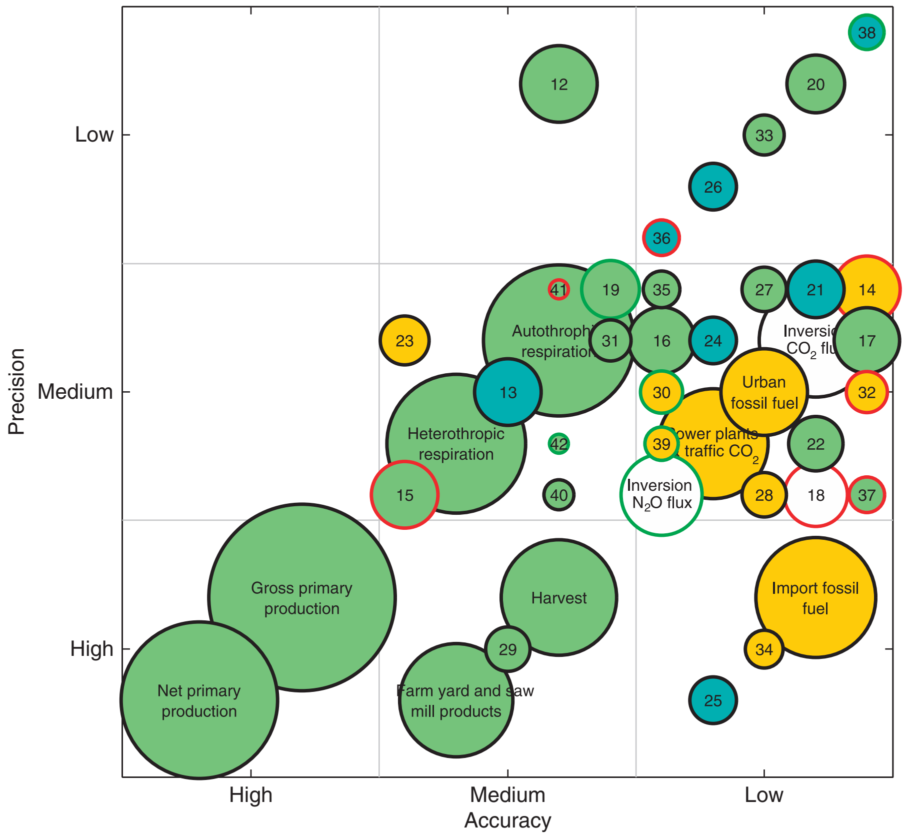


Fig. 4 Flux magnitude for a 100-year horizon (surface of the bubble; Tg C y^{-1}) as a function of current accuracy and precision of the component flux. Given that a balance is most sensitive to its largest components, ideally these large components should have a high accuracy and precision and appear in the lower left corner of the graph. Substantial improvements in the European carbon balance are expected by either increasing the accuracy by confirming the present magnitude with an independent estimate of the component flux, increasing the precision by rigours measurements and representative sampling networks or both. Edge colour of the bubble shows the flux species where black denotes carbon, red methane and green nitrous oxide fluxes. Bubbles with a green, blue, orange and white face colour show respectively terrestrial, aquatic, anthropogenic and inversion fluxes. 12, Terrestrial net biome production; 13, Dissolved (in)organic carbon; 14, Urban emissions CH_4; 15, Terrestrial CH_4; 16, Forest biomass; 17, Carbon in manure; 18, Change in atmospheric CH_4; 19, Terrestrial N_2O; 20, Terrestrial net greenhouse gas (GHG) balance; 21, Aquatic outgassing; 22, Forest soils; 23, Fossil Fuel CO; 24, Aquatic net biome production; 25, Export of dissolved (in)organic carbon; 26, Aquatic net GHG balance; 27, Biological volatile organic compounds; 28, Farm yard fossil fuel; 29, Disturbance; 30, Urban emissions N_2O; 31, Land fills CO_2; 32, Power plants and traffic CH_4; 33, Import products; 34, Fertilizer fossil fuel; 35, Respiration from food waste; 36, Aquatic CH_4; 37, Geological CH4; 38, Aquatic N_2O; 39, Power plants and traffic N_2O, 40 Land use change; 41, Land fills CH_4; 42, Land fills N_2O.

uncertain up-scaling. How should the uncertainty of these independent data streams be weighted? Data assimilation tools could prove to be a useful tool to address this issue, if the errors are known.

Finally, components and their uncertainties are compiled in a single balance sheet. Given the lack of information, due to the shortcomings mentioned above, such compilations rely on assumptions i.e. uncertainties of different estimates are independent, the sampling networks are representative, and the uncertainties follow a predefined distribution (i.e. normal or uniform). The impact of these assumptions on our estimate of the European C sink and subsequent statistical analyses remains to be determined. Future work should pay more attention to consistent and rigorous analysis of the uncertainty of the component fluxes that make up the GHG balance under study.

The flux magnitude is plotted in Fig. 4 as a function of accuracy and precision, these are the two metrics that determine the uncertainty of flux components and eventually the reliability of the C balance (see also Appendix S5). Given that a balance is most sensitive to its largest components, ideally these large components should have a high accuracy and precision, and appear in the lower left corner of the graph. Substantial improvements in the European C balance are expected by either increasing the accuracy by confirming the present magnitude with independent estimates of the component fluxes (i.e. import of fossil fuel, harvest, farmyard and sawmill products, and dissolved organic and inorganic C), or by increasing the precision by rigorous measurements and representative sampling networks for assessing the components of autotrophic and heterotrophic respiration, and terrestrial trace gas fluxes of CH_4 and N_2O, as well as the anthropogenic fluxes of urban and industrial activities.

The role of soils

The importance of soils for the C balance of European ecosystems is generally accepted (Bellamy *et al*., 2005; Don *et al*., 2008). Nevertheless, our knowledge about quantitative changes in soil organic carbon (SOC) over time is still very limited. The sequestration of soil C (NBP_{soil}) is presently predicted mostly from top-down modelling of NBP and observations of C exchange between the atmosphere and the biosphere. In future it will be important to confirm and constrain these predictions with direct measurements of soil C changes (von Lützow *et al*., 2006; Schrumpf *et al*., 2008). Field-based measurements of soil C changes are scarce and hampered by the inherently high small-scale spatial heterogeneity of SOC stocks. Owing to the long observation period necessary for observing changes in soil C against a very high background of C in soils, it is expected that it may take decades to verify soil C changes (Smith, 2004; Meersmans *et al*., 2009). In addition, the C store in soils is sensitive to changes in vegetation cover, harvest of biomass residues in croplands and forests, and to all kinds of mechanical soil disturbances such as ploughing (Schrumpf *et al*., 2008). However, irrespective of these inherent difficulties another 'tier' of top-down predictions and bottom-up verifications is needed to reduce the uncertainty of soil C changes.

Regional assessments of SOC changes suffer from various shortcomings usually as a result of their relying on soil surveys originally not designed for the purpose of assessing SOC stock changes. Often only concentrations of organic C were directly determined in the field. Average bulk densities and stone contents, were derived from pedotransfer functions (Sleutel *et al*., 2003; Bellamy *et al*., 2005; Hopkins *et al*., 2009). Also changes in methodologies and instrumentation take place over the very long period of observation. This increases the uncertainty of the results. Conversion factors for new methods are often not generally applicable (Lettens *et al*., 2007). Furthermore, most studies of the past focused on the upper 5–30 cm of the mineral soil. Results were expanded to 1 m using soil models. Meanwhile several studies showed that SOC changes are not simply restricted to topsoil layers (e.g. Don *et al*., 2008). For grassland soils in Flanders, Meersmans *et al*. (2009) calculated small SOC losses for the upper 30 cm of the mineral soil, but gains of 14 g C m^{-2} yr^{-1} when 0–100 cm was considered. Changes in management such as shifts from organic to mineral fertilizer, changing the tillage regime or forest regrowth following harvest can cause SOC changes in topsoils as well as in deeper soil layers (Gál *et al*., 2007; Diochon *et al*., 2009). SOC losses in topsoils may be balanced by gains in subsoils, which are overlooked when only topsoils are analysed or modelled. This range of possible limitations makes the use of past soil studies problematic when aiming at the detection of a change in SOC.

The CarboEurope project chose a different approach; rather than regional surveys (Schrumpf *et al*., 2008) many samples were taken at individual sites to measure the small scale variability, which could override time-dependent changes. A total of 100 soil cores were taken at each of three cropland sites, three grassland sites, three deciduous forests, and three coniferous forests. The resampling of these sites is still ongoing, and so the NBP of soil was not directly measured by CarboEurope. However, first resampling data are available from the Hainich site, a beech forest reserve, which has been protected for the past 60 years, and which was resampled after 5 years; a short period considering soil processes. For this site, Mund & Schulze (2006) analysed a transect study across age classes in that region and reported 20–50 g C m^{-2} yr^{-1} soil C accumulation. However, this estimate was not statistically significant. Kutsch *et al*. (2010) used CO_2 fluxes and tree growth studies to deduce a sequestration rate of 1–35 g C m^{-2} yr^{-1}. A soil survey (M. Schrumpf, unpublished data) taking 100 repeated samples after 5 years, showed a significant C accumulation of 26–50 g C m^{-2} yr^{-1}. Thus, we are confident, that this particular forest accumulates C in soils, even in the short term. We speculate that the soil C sink will be found to be lower in other land uses and with different soil textures and more active management, but data to test this hypothesis are not yet available.

Regional distributions of GHG fluxes

The distribution of GHG fluxes obtained from inverse models (total CO_2 and CH_4 fluxes) and from emission inventories (fossil fuel CO_2, agricultural N_2O, NOx, NH_3) shows large regional variation (Fig. 5). Fossil fuel emissions are centred in mid-Europe with highest values in a region between the south of England and north Italy (see Schulze *et al*., 2009). The fossil fuel consumption is much lower in eastern than in western Europe. Highway traffic emerges as a main source (see Fig. 5b). The additional main input into the ecosystem is the input of organic and mineral fertilizer (Fig. 5f). It shows

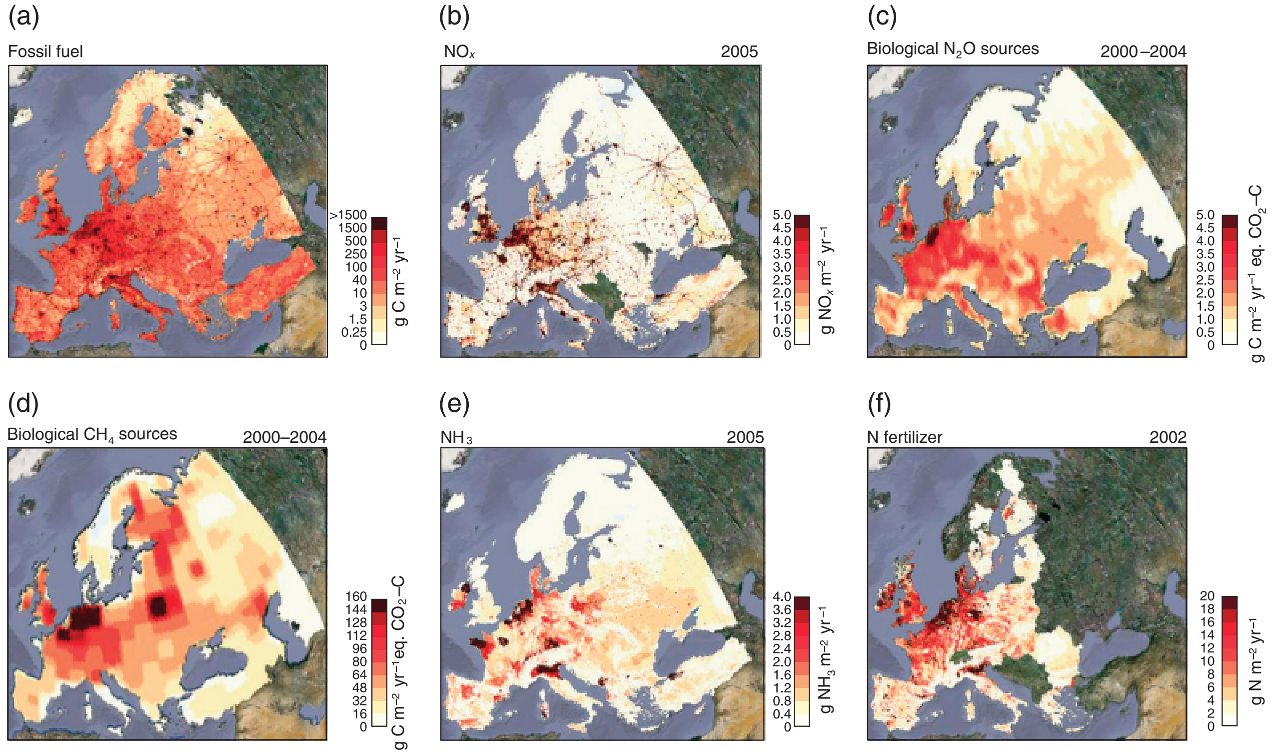


Fig. 5 Regional distribution of trace gas fluxes across Europe based. (a) fossil fuel (Schulze *et al.*, 2009), (b) NO*x* (IER data base, Stuttgart), (c) Biological N_2O-sources (Schulze *et al.*, 2009), (d) Biological CH_4 sources (Schulze *et al.*, 2009), (e) Ammonia (IER data base, Stuttgart), (f) organic and inorganic fertilizer input (JRC-data base).

a maximum in the Benelux states, in northwestern and eastern Germany, and in north Italy, with high rates across the main cropping regions of Europe. The regional patterns of NH_3 and N_2O are very similar.

The N_2O emission map is based upon emission inventories scaled to match the atmospheric inversion mean flux of Hirsch *et al.* (2006) on atmospheric measurements and inverse modelling, the emission database for NO*x*, NH_3 and fossil fuel maps are based on national reports to the UNFCCC secretariat, and the NH_3 emission database are based on the work of Amann *et al.* (2008). The figures on fertilizer inputs are based on a separate database (Appendix S1). The assumption that the maps for fossil fuel, NH_3 and NO*x* emissions, and on fertilizer on the one side and the N_2O map on the other side are based on independent information, justifies an investigation into correlations between these fluxes and N_2O. In a pixel by pixel comparison of the maps (Fig. 5) NH_3 emissions correlate with total fertilizer input with an r^2 of 0.42. Manure application to soils is the dominant source of NH_3 and the second most important source of N_2O after mineral fertilizer application. Thus, N_2O fluxes correlate with NH_3 fluxes with an r^2 of 0.32. N_2O fluxes also correlate with fossil fuel consumption with an r^2 of 0.25 and with the NO*x* flux with an r^2 of 0.31 due to absorption and denitrification in soils. In a multiple regression, two variables, namely fossil fuel consumption and fertilizer application explain 58% of the variation of N_2O.

Quantifying the effects of LUC

LUC C balance of the EU 25

Assessing the C balance of LUCs at the European level is challenging. LUC usually represent relatively small and scattered events, not easily captured by official statistics or independent studies; but also the effects of LUC depend on how associated GHG emissions are considered i.e. for how much time the emissions are counted as being generated by the LUC, before being included in a new land-use category. The GHG inventories that countries submit annually to the United Nation Framework Convention on Climate Change (UNFCCC, http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/4771.php) are a valuable source of information on LUC. Although the accuracy and completeness of LUC estimates in GHG national inventories can still improve for many countries, the value of these inventories is that they condense a large amount of information from national statistics (which on LUC is often not easily accessible to the scientific community), and that an independent UN expert team reviews annually such estimates for their adherence to the IPCC methodological guidance (IPCC, 2003). Following Guidance (IPCC, 2006), LUC in UNFCCC context is defined as any transition between six land uses: forest, cropland, grassland, wetland, settlements and other lands. By default, land remains in 'conversion status' in the UNFCCC statistics for 20 years (e.g. the sink of a 'cropland converted to forest' in 1984 is counted in the LUC flux till 2003), but different periods may also be used.

According to the information contained in the 2009 GHG inventory reports, the total area reported under 'LUC' categories in EU-25 was about 380 000 km^2 for the year 1990 and 352 000 km^2 for the year 2007, i.e. slightly decreasing over time (Table 2). When considering the time land remains in the conversion status (20 years for most countries), approximate values of LUC annual rates may be estimated (Table 2, average for the period 2003–2007). About 17 800 km^2 undergo a LUC every year within EU-25, representing a small fraction (0.41%) of the total area. Additionally, it is estimated that about 4300 km^2 are annually converted to forest in the European part of the Russian Federation, Belarus and Ukraine. The gross fluxes from LUC at European level are summarized in Fig. 3. The C balance associated with LUC is a net sink of 1.5 $Tg\,C\,yr^{-1}$ for EU-25 and reaches 9.6 $Tg\,C\,yr^{-1}$ when data from European Russia, Belarus and Ukraine are also considered (a sink of 9.0 $Tg\,C\,yr^{-1}$ due to conversion to forest and a source of 0.9 $Tg\,C\,yr^{-1}$ due to deforestation reported in European Russia). These numbers include average emissions during 2003–2007 due to LUC that occurred up to 20 years before, depending on the methods used by each country.

The small net sink from LUC at the European level masks large fluxes of opposite signs between different land-use types. For instance, at EU-25 level one can see that the largest single LUC-induced gross area change is the conversion of croplands to pasture (5000 $km^2\,yr^{-1}$), which sequestered 11 $Tg\,C\,yr^{-1}$ C. But this transition is offset elsewhere by about 4400 $km^2\,yr^{-1}$ of grasslands being ploughed for crop cultivation, which causes a net loss of C to the atmosphere of nearly 10 $Tg\,C\,yr^{-1}$. At the European level, the largest single flux occurs in lands converted to forests (a sink of 18.3 $Tg\,C\,yr^{-1}$). Part of this sink is balanced by C loss by deforestation (7.3 $Tg\,C\,yr^{-1}$). If the absolute values of all LUC are summed up, it results in a total flux of 50 $Tg\,C\,yr^{-1}$ induced by LUC at the European level. As many countries do not yet report all LUC to UNFCCC, this estimate is likely to be an underestimate. The analysis

Table 2 Areas of land-use change in Europe (EU-25) as reported to the UNFCCC (kha yr^{-1}; elaborated data)

Average 2003–2007	Conversions from forest	Conversions from cropland	Conversions form grassland	Conversions from wetlands	Conversions from Settlements	Conversions from Otherlands	Total 'to'
Conversions to forest		96	179	19	18	86	398
Conversions to cropland	13		445	1	15	16	490
Conversions to grassland	37	500		3	21	39	600
Conversions to wetlands	2	3	11		2	8	26
Conversions to settlement	24	65	81	2		19	192
Conversions to other land uses	15	10	46	7	1		80
Total 'from'	91	673	762	32	57	168	1784

indicates that despite the net C balance of all LUCs being small, and despite the fact that the LUC areas are usually very small compared with total area, regionally the LUC can be very important, corresponding to a very high NBP of positive or negative sign.

When interpreting the data on LUC in Table 2 and Fig. 3 it is important to note that differences may occur among countries in terms of: (i) completeness of reporting (while most countries report conversions to forests and many report conversions from/to cropland and grasslands, conversions from other land uses are reported less frequently); (ii) reported time series (e.g. most countries use the 20 year default transition period, but some countries have data only since1990); (iv) coverage of C pools (e.g. many countries do not report fluxes from forest soils); (iii) land use definition (e.g. some lands may be classified either under cropland or grassland, depending on the country's definitions); (v) methods to estimate C stock changes (in some case the spatiotemporal variability of soil C and biomass is explicitly considered, but in other cases only default IPCC emission rates are used). Moreover, some basic data are unknown, such as for instance, the fate of C in settlements. When buildings are constructed, whether soil C buried under concrete isolated from the atmosphere, or decomposed by microbes and quickly lost to the atmosphere, will change the sign of the C balance of new settlements. At face value, gardens are productive and fertilized lands, which are overlooked by most GHG national inventories. We speculate that gardens may be a significant C sink given the total urban and peri-urban area, which is about 7% of total land area, on the other hand gardens are also intensively managed, which might compensate the inputs. Despite these limits, the data from countries' GHG inventories are presently the best data available for LUC-induced C flux estimates.

Obviously, net LUC has no major effect on the trace gas cycle of Europe. Land-use intensity and the associated emissions from fertilizer application and meat production are more important than LUC.

Where does the excess C dioxide and N_2O go?

Figure 3 shows an export of CO_2 and N_2O out of the European domain, and the question emerges: Where do these reactive and nonreactive trace gases go, and what area outside Europe would be needed to assimilate this surplus? This would be the trace-gas footprint of Europe. In addition, there is a footprint for the import of feeding stocks grown outside Europe (e.g. soya), which has not been considered here.

N_2O and CO_2 are the main trace gases being exported to other regions of the globe. In total, Europe exports $0.4\,\mathrm{Tg\,N_2O\text{-}N\,yr^{-1}}$. Assuming an uptake in forest equivalent to Europe of about $2\,\mathrm{g\,N_2O\text{-}CO_2\text{-}C\text{-}eq\,m^{-2}\,yr^{-1}}$, the Siberian forests extending over $12.80 \times 10^{12}\,\mathrm{m^2}$ (Shvidenko & Nilsson, 1994) would assimilate only an equivalent of about 20% of this excess. The rest would be mixed across the globe, or enter into the stratosphere. The estimate of the land-surface N_2O sink is likely to be a high estimate.

The excess CO_2 of $1294\,\mathrm{Tg\,C\,yr^{-1}}$ produced by Europe could be absorbed by oceans or land ecosystems in other regions, or add to the atmospheric increase in CO_2. According to Canadell *et al*. (2007) we may assume that about 25% enters into the oceans, and 45% remains in the atmosphere. Thirty percent or $465\,\mathrm{Tg\,yr^{-1}}$ is expected to be absorbed by terrestrial ecosystems globally. We may take Siberia as one region that absorbs an excess of CO_2. Shvidenko & Nilsson (2002) estimate a C sequestration rate for Siberian forest of $210\,\mathrm{Tg\,C\,yr^{-1}}$ and an additional $50\,\mathrm{Tg\,C\,yr^{-1}}$ may enter into soils (A. Shvideno and S. Nilsson, unpublished data). Thus, the Siberian forests sequester an amount of C being equivalent to 83% of the excess European CO_2.

Conclusions

The C cycle shows a significant distortion from human impacts. In Europe 30% of the C flow is being extracted as harvest, which reduces the amount that could be stored in soils. The C balance of soils (excluding the C storage in forest biomass) still results in a minor C sink. However, studying only the C cycle is not sufficient, if a mitigation of the global warming potential is anticipated. Not only GHGs, but also nonGHGs interact, mostly offsetting the apparent terrestrial sink. Although CO_2 from fossil fuel burning remains the most important GHG added into the atmosphere by human activity, CH_4, N_2O and CO contribute almost 40% to the total European global warming potential, and about 50% of the nonCO_2-GHG input originates from agriculture. Including the GHG emissions, and summing up the NBG of soils in forests, grasslands, croplands and peatlands, the European soils are a net source.

The human impact on the C cycle is significant and occurs everywhere. Harvest exceeds NBP by threefold, which means that more C is extracted from the natural C cycle than is remaining in soils. Total harvest takes about 30% of NPP, but 10% of this fraction is the hidden cost of production. On the other hand, growth of vegetation is stimulated by atmospheric N deposition. Fifty percent of forest NBP and harvest could be due to the anthropogenic input of atmospheric N. Human activities convert short-lived resources (e.g. fertilizer) into long-lived gases (e.g. N_2O).

Europe creates an excess of N_2O and CO_2, which is reassimilated on other continents, in the ocean or remains in the atmosphere. For the excess CO_2 a land surface of at least twice the size of Siberia would be needed to compensate European emissions and ensure no net contribution to the global C balance (no climate mitigation). Obviously, Europe has a long way to go to reach a climate–neutral C balance.

What are the implications of these findings for climate change mitigation? Reducing fossil fuel burning still remains the prime target for climate mitigation. However, given the large emissions from croplands and grasslands, including housed livestock, and the still increasing intensity of land use, a strong effort will also be needed from agriculture. Thus, additional measures must be taken, to restrict fertilizer use according to site conditions and the types of crops, reduce the organic and mineral fertilizer input in hot-spot areas and reduce animal farming. We would not distinguish between ruminants and nonruminants, because each group has its own detrimental emissions. We would also not distinguish between organic and mineral fertilizer, because both produce similar effects. However, the choices between using the biosphere as C sink, for production of food, fibre, construction material and for bioenergy remain competing options of land use and mitigation. Obviously there is no general solution to the problem of defining the conditions and assumptions under which a certain option is to be recommended and regional conditions are important.

To improve the observation of the European C balance, a network of atmospheric and eddy flux stations together with a more comprehensive soil sampling scheme should be maintained. Only then we will be able to assess trends of change. A science driven Integrated Carbon (GHG) Observation System (ICOS) for Europe should be the basis for future research and observations.

At this moment a significant trend of greenhouse and nonGHG emission cannot be established from this study, but this study could be a benchmark against which to improve the science of the data base, and to measure the anticipated mitigation policies for the period up until 2020.

Acknowledgements

We are truly grateful for the funding of the CarboEurope-IP (Project No. GOGC-CT-2003n505572) by the EU. The EU funding supplemented national funding from different nations. EDS was supported by the Max-Planck Gesellschaft as Emeritus. SL received funding from the Centre of Excellence (ECO, University of Antwerpen-Methusalem) Markus Reichstein provided the solar radiation data. Jon Cole and Paul del Giorgio provided valuable input regarding aquatic carbon cycling. We acknowledge the very constructive comments by the referees.

Author Contributions: EDS wrote the manuscript and coordinated the CarboEurope project, GG, AF and PC: LUC analysis; SL: uncertainty analysis; MS and IJ: soils; BT, TJ, MS, SB: CH_4, NOx, NH_3, CH_4 fluxes; JL: CO, VOC, O_3-fluxes, AL and AF: peat, CR, AD and WK: regional fingerprints; MJ: ET and H, DB and GA: inland waters; AL: Fertilizer input; JN and AB: Statistics and maps; JG editorial, and AJD: regional assessments

References

Aldous AR (2002) Nitrogen transportation *Sphagnum* mosses. Effects of atmospheric nitrogen deposition. *New Phytologist*, **156**, 241–253.

Alm J, Shurpali NJ, Minkkinen K *et al*. (2007) Emission factors and their uncertainties for the exchange of CO_2, CH_4 and N_2O in Finish managed peatlands. *Boreal Environment Research*, **12**, 191–209.

Amann M, Bertok I, Cofala J *et al*. (2008) NEC Scenario Analysis Report 6 National Emission ceilings for 2020 based on 2008 Climate and Energy package. International Institute for Applied Systems Analysis (IIASA). Available at: http://www.iiasa.ac.at/rains/gains-online.html?sb=9 (accessed 2008).

Baldocchi DD (2003) Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. *Global Change Biology*, **9**, 479–492.

Bastviken D, Cole J, Pace M, Tranvik L (2004) Methane emissions from lakes. Dependence of lake characteristics, two regional assessments, and a global estimate. *Global Biogeochemical Cycles*, **18**, GB4009, doi: 10.1029/2004GB002238.

Bellamy PH, Loveland PJ, Bradley RI, Lark RM, Kirk GJD (2005) Carbon losses from all soils across England and Wales 1978–2003. *Nature*, **437**, 245–248.

Bogner J, Matthews E (2003) Global methane emissions from landfills: new methodology and annual estimates 1980–1996. *Global Biogeochemical Cycles*, **17**, 1065.

Böttcher H, Kurz W, Freibauer A (2008) Accounting of forest carbon sinks and sources under a future climate protocol - factoring out past disturbance and management effects on age-class structure. *Environmental Science and Policy*, **11**, 669–686.

Bresinsky A, Körner Ch, Kadereit JW, Neuhaus G, Sonnewald U (2008) *Straßburger: Lehrbuch der Botanik*. Spektrum Verlag, Berlin.

Canadell JG, LeQueré C, Raupach MR *et al*. (2007) Contributions to accelerating CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences USA*, **104**, 18866–18870.

Canadell JG, Raupach MR (2008) Managing forests for climate mitigation. *Science*, **320**, 1456–1457.

Carrara A, Janssens IA, Curiel Yuste J, Ceulemans R (2004) Seasonal changes in photosynthesis, respiration and NEE of a mixed temperate forest. *Agricultural and Forest Meteorology*, **126**, 15–31.

Ciais P, Borges AV, Abril G, Meybeck M, Folberth G, Hauglustaine D, Janssens IA (2008a) The impact of lateral carbon fluxes on the European carbon balance. *Biogeoscience*, **5**, 1259–1271.

Ciais P, Paris JD, Marland G *et al*. (2010b) The European carbon balance. Part 1: fossil fuel emissions. *Global Change Biology*, **16**, 1395–1408.

Ciais P, Reichstein M, Viovy N *et al*. (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, **437**, 529–533.

Ciais P, Schelhaas MJ, Zaehle S *et al*. (2008b) Carbon accumulation in European forests. *Nature Geoscience*, **1**, 425–429.

Ciais P, Tans PP, Trolier M, White JW, Francey RJ (1995) A large northern-hemisphere terrestrial sink indicated by the $^{13}C/^{12}C$ ratio of atmospheric CO_2. *Science*, **269**, 1098–1102.

Ciais P, Watterbach M, Vuichard N *et al*. (2010a) The European carbon balance. Part 2: croplands. *Global Change Biology*, **16**, 1409–1428.

Dalgaard T, Halberg N, Porter JR (2001) A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. *Agriculture Ecosystems and Environment*, **87**, 51–65.

Davidson EA (2009) The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience*, **2**, 659–662.

Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, **440**, 165–173.

de Vries W, Reinds GJ, Gundersen P, Sterba H (2006) The impact of nitrogen deposition on carbon sequestration in European forests and forest soils. *Global Change Biology*, **12**, 1151–1173.

de Vries W, Solberg S, Dobbertin M *et al*. (2008) Ecologically implausible carbon response. *Nature*, **451**, E1–E3.

de Vries W, Solberg S, Dobbertin M *et al*. (2009) The impact of nitrogen deposition on carbon sequestration by European forests and heathlands. *Forest Ecology and Management*, **258**, 1814–1823.

Diochon A, Kellman L, Beltrami H (2009) Looking deeper: an investigation of soil carbon losses following harvesting from a managed northeastern red spruce (*Picea rubens* Sarg.) forest chronosequence. *Forest Ecology and Management*, **257**, 413–420.

Dolman AJ, Freibauer A, Valentini R (2008) *The Continental Scale Greenhouse Gas Balance of Europe*. *Ecological Studies*, **Vol. 203**. Springer Verlag, Heidelberg.

Don A, Scholten T, Schulze ED (2008) Conversion of croplands into grasslands: implications for soil organic-carbon stocks in two soils with different texture. *Journal of Plant Nutrition and Soil Science*, **172**, 53–62.

Gál A, Vyn TJ, Michéli E, Kladivko EJ, McFee WW (2007) Soil carbon and nitrogen accumulation with long-term no-till versus moldboard plowing overestimated with tilled-zone sampling depths. *Soil & Tillage Research*, **96**, 42–51.

Guo LB, Gifford RM (2002) Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, **8**, 345–360.

Hall KD, Guo J, Dore M, Chow CC (2009) The progressive increase of food waste in America and its environmental impact. *PLoS One*, **4**, e7940.

Harrison AF, Schulze ED, Gebauer G, Bruckner G (2000) Canopy uptake and utilization of atmospheric pollutant nitrogen. *Ecological Studies*, **142**, 171–188.

Haywood J, Schulze M (2007) Causes of the reduction in uncertainty in the anthropogenic radiative forcing of climate between IPCC (2001) and IPCC (2007). *Geophysical Research Letters*, **34**, L20701, doi: 10.1029/2007GL030749.

Hirsch AI, Michalak AM, Bruhwiler LM, Peters W, Dlugokencky EJ, Tans PP (2006) Inverse modeling estimates of the global nitrous oxide surface flux from 1998–2001. *Global Biogeochemical Cycles*, **20**, GB1008, doi: 10.1029/2004GB002443.

Hopkins DW, Waite IS, McNicol JW, Poulton PR, Macdonald AJ, O'Donnell AG (2009) Soil organic carbon contents in long-term experimental grassland plots in the UK (Palace Leas and Park Grass) have not changed consistently in recent decades. *Global Change Biology*, **15**, 1739–1754.

Hülsbergen KJ, Feil B, Biermann S, Rathke GW, Kalk WD, Diepenbrock W (2001) A method of energy balancing in crop production and its application in a long-term fertilizer trial. *Agric. Ecosystem and Environment*, **86**, 303–321.

IPCC (2003) *Good Practice Guidance on LULUCF*. Intergovernmental Panel of Climate Change Publication, Cambridge University Press, Cambridge.

IPCC (2006) *Revised IPCC Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel of Climate Change Publication. Campridge University Press, Cambridge.

IPCC (2007) *IPCC Climate Change: The Physical Science Basis* (eds Solomon S *et al*.), Cambridge University Press, Cambridge.

Janssens IA, Freibauer A, Ciais P *et al*. (2003) Europe's terrestrial biosphere absorbs 7 to 12% of the European anthropogenic CO_2 emissions. *Science*, **300**, 1538–1542.

Janssens IA, Luyssaert S (2009) Nitrogen's carbon bonus. *Nature Geoscience*, **2**, 318–319.

Jarvis PG, McNaughton KG (1986) Stomatal control of transpiration: scaling from leaf to region. *Advances in Ecological Research*, **15**, 1–15.

Jöckel P, Tost H, Pozzer A *et al*. (2006) The atmospheric chemistry general circulation model ECHAM5/MESSy: consistent simulation of ozone from the surface to the mesosphere. *Atmospheric Chemistry and Physics*, **6**, 5067–5104.

Jung M, Reichstein M, Bondeau A (2009) Towards global empirical upscaling of Fluxnet eddy covariance observations: validation of a model tree ensemble approach using a biosphere model. *Biogeosciences*, **6**, 2001–2013.

Keeling RF, Piper SC, Heimann M (1996) Global and hemispheric CO_2 sinks deduced from changes in atmospheric O_2 concentrations. *Nature*, **381**, 218–221.

Kroeze C, Dumont E, Seitzinger SP (2005) New estimates of global emissions of N_2O from rivers and estuaries. *Journal of Integrative Environmental Sciences*, **2**, 159–165.

Kutsch WL, Persson T, Schrumpf M, Moyano FE, Mund M, Andersson S, Schulze ED (2010) Heterotrophic soil respiration and soil carbon dynamics in the decidous Hainich forest obtained by three approaches. *Biogeochemistry*, 0–17, doi: 10.1007/s10533-010-9414-9.

Larcher W (1993) *Ökophysiologie der Pflanzen*. Ulmer Verlag, Stuttgart.

Lelieveld J, Berresheim H, Borrmann S *et al*. (2002) Global air pollution crossroads over the Mediterranean. *Science*, **298**, 794–799.

Lelieveld J, Dentener F (2000) What controls tropospheric ozone? *Journal of Geophysical Research*, **105**, 3531–3551.

LeQuéré C, Raupach MR, Canadell JG *et al*. (2009) Trends in the sources and sinks of carbon dioxide. *Nature Geoscience*, **2**, 831–836.

Lettens S, De Vos B, Quataert P, van Wesemael B, Muys B, van Orshoven J (2007) Variable carbon recovery of Walkley-Black analysis and implications for national soil organic carbon accounting. *European Journal of Soil Science*, **58**, 1244–1253.

Luyssaert S, Ciais P, Piao SL *et al*. (2010) The European carbon balance. Part 3: forests. *Global Change Biology*, **16**, 1429–1450.

Luyssaert S, Reichstein M, Schulze ED *et al*. (2009) Towards a consistency cross-check of eddy covariance flux-based and biometric estimates of ecosystem carbon balance. *Global Biogeochemical Cycles*, **23**; GB3009, doi: 10.1029/2008GB003377.

Luyssaert S, Schulze ED, Boerner A *et al*. (2008) Old-growth forests as global carbon sink. *Nature*, **455**, 213–215, doi: 10.1038/nature 07276.

Magnani F, Mencuccini M, Borghetti M *et al*. (2007) The human footprint in the carbon cycle of temperate and boreal forests. *Nature*, **447**, 849–851.

Maignan F, Bréon FM, Vermote E, Ciais P, Viovy N (2008) Mild winter and spring 2007 over Western Europe led to a widespread early vegetation onset. *Geophysical Research Letters*, **35** L02404, doi: 10.1029/2007GL032472.

Meersmans J, Van Wesemael B, De Ridder F, Dotti MF, De Bats S, Van Molle M (2009) Changes in organic carbon distribution with depth in agricultural soils in northern Belgium, 1960–2006. *Global Change Biology*, **15**, 2739–2750.

Menzel A, Fabian P (1999) Growing season extended in Europe. *Nature*, **397**, 659.

Mund M, Schulze E-D (2006) Impacts of forest management on the carbon budget of European beech (*Fagus sylvatica*) forests. *Allgemeine Forst- und Jagd-Zeitung*, **177**, 47–63.

Nabuurs GJ, Schelhaas MJ, Mohrens GMJ, Field CB (2003) Temporal evolution of the European forest sector carbon sink from 1950 to 1999. *Global Change Biology*, **9**, 152–162.

Nelson RG, Hellwinckel CM, Brandt CC, West TO, Ugarte DG de la Torre, Marland G (2009) Energy use and carbon dioxide emissions from cropland production in the United States, 1990–2004. *Journal of Environmental Quality*, **38**, 418–425.

Nösberger J, Long SP, Norby RJ, Stitt M, Hendrey GR, Blum H (2006) *Managed Ecosystems and CO_2*. *Ecological Studies*, **Vol. 187**. Springer Verlag, Heidelberg.

Oren R, Ellsworth DS, Johnson KH *et al*. (2001) Soil fertility limits carbon sequestration by forest ecosystems in a CO_2-enriched atmosphere. *Nature*, **411**, 469–470.

Piao S, Friedlingstein P, Ciais P, Peylin P, Zhu B, Reichstein M (2009) Footprint of temperature changes in the temperate and boreal forests carbon balance. *Geophysical Research Letters*, **36** L07404, doi: 10.1029/2009GL037381.

Ravishkanara AR, Daniel JS, Portmann RW (2009) Nitrous oxide (N_2O): the DOMINANT ozone-depleting substance emitted in the 21st century. *Science*, **326**, 123–125.

Read DJ (1993) Plant-microbe mutualism and community structure. *Ecological Studies*, **99**, 181–210.

Reay DS, Dentener F, Smith P, Grace J, Feely RA (2008) Global nitrogen deposition and carbon sinks. *Nature Geoscience*, **1**, 430–437.

Rillig MC (2004) Arbuscular mycorrhizae and terrestrial ecosystem processes. *Ecological Letters*, **7**, 740–754.

Schelhaas MJ, Nabuurs GJ, Schuck A (2003) Natural disturbances in the European forests in the 19th and 20th centuries. *Global Change Biology*, **9**, 1620–1633.

Schmid E, Balkovic J, Moltchanova E, Skalsky R, Poltarska K, Müller B, Bojnovsky R (2006) *Biophysical process modeling for EU 25: concenpt, data, methods, and results*. Report IIASA, Luxenburg, 76 pp, doi: 10.1029/2009GL037381.

Schrumpf M, Schumacher J, Schöning I, Schulze ED (2008) Monitoring carbon stock changes in European soils: process understanding and sampling strategies. In: *The Continental-Scale Greenhouse Gas Balance of Europe* (eds Dolman AJ, Freibauer A, Valentini R), Springer, New York.

Schulze ED (2000) Carbon and nitrogen cycling in European forest ecosystems. *Ecological Studies*, 500pp.

Schulze ED, Beck E, Müller-Hohenstein K (2002) *Plant Ecology*. Springer Verlag, Heidelberg.

Schulze ED, Luyssaert S, Ciais P *et al*. (2009) Importance f methane and nitrous oxide for Europe's terrestrial greenhouse gas balance. *Nature Geoscience*, **2**, 842–850.

Schulze ED, Ulrich B (1991) Acid Rain – a large-scale, unwanted experiment in forest ecosystems. *SCOPE*, **45**, 89–106.

Seitzinger SP, Kroeze C (1998) Global distribution of nitrous oxide production and N-inputs in freshwater and coastal marine ecosystems. *Global Biogeochemical Cycles*, **12**, 93–113.

Service RF (2009) Another biofuels drawback: the demand for irrigation. *Science*, **326**, 516–517.

Shindell DT, Faluvegi G, Bell N, Schmidt GA (2005) An emissions-based view of climate forcing by methane and tropospheric ozone. *Geophysical Research Letters*, **32**, L04803, doi: 10.1029/2004GL021900.

Shindell DT, Faluvegi G, Koch DM, Schmidt GA, Unger N, Bauer SE (2009) Improved attribution of climate forcing emissions. *Science*, **326**, 716–718.

Shvidenko A, Nilsson S (1994) What do we know about the Siberian forests? *Ambio*, **23**, 396–404.

Shvidenko A, Nilsson S (2002) Dynamics of Russian forests and the carbon budget in 1961–1998: an assessment based on long-term forest inventory data. *Climatic Change*, **55**, 5–37.

Sleutel S, De Neve S, Hofman G *et al*. (2003) Carbon stock changes and carbon sequestration potential of Flemish cropland soils. *Global Change Biology*, **9**, 1193–1203.

Smith P (2004) How long before a change in soil organic carbon can be detected? *Global Change Biology*, **10**, 1878–1883.

Smith SE, Read DJ (1997) *Mycorrhizal Symbiosis*. Academic Press, San Diego.

Soussana JF, Fuhrer J, Jones M, VanAmstel A (2007) The greenhouse gas balance of grasslands in Europe. *Agric Ecosystems and Environment*, **121**, 1–4.

Sutton MA (2008) Uncertainties in the relationship between atmospheric nitrogen deposition and forest carbon sequestration. *Global Change Biology*, **14**, 2057–2063.

Steinkamp J, Ganzeveld LN, Wilcke W, Lawrence MG (2009) Influence of modeled soil biogenic NO emissions on related trace gases and the atmospheric oxidizing efficiency. *Atmospheric Chemistry and Physics*, **9**, 2663–3677.

Stephens BB, Gurney KR, Tans PP *et al*. (2007) Weak northern and strong tropical land carbon uptake from vertical profiles of atmospheric CO_2. *Science*, **316**, 1732–1735.

Sutton MA, Simpson D, Levy P, Smith RI, Reis S, vanOijen M, de Vries W (2008) Uncertainties in the relationship between atmospheric nitrogen deposition and forest carbon sequestration. *Global Change Biology*, **14**, 2057–2063.

Tans PP, Fung IY, Takahashi T (1990) Observational constraints on the global atmospheric CO_2 budget. *Science*, **247**, 1431–1438.

Thuille A, Schulze E-D (2005) Carbon dynamics in successional and afforested spruce stands in Thuringia and in the Alps. *Global Change Biology*, **12**, 325–342, doi: 10.1111/j.1365-2486.2005.01078.x.

Tranvik L, Downing JA, Cotner JB *et al*. (2009) Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and Oceanography*, **54**, 2298–2314.

Vestreng V, Breivik K, Adams M, Wagner A, Goodwin J, Rozovykaya O, Pacyna JM (2004) *Inventory review, emission data reported to CLRTAP and under NEC Directive, EMEP/EEA Joint Review Report*. EMEP/MSC-W Note 1/2004.

von Lützow M, Kogel-Knabner I, Ekschmitt K, Matzner E, Guggenberger G, Marschner B, Flessa H (2006) Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions - a review. *European Journal of Soil Science*, **57**, 426–445.

WBGU (2004) *World in Transition: Towards SUSTAINABLE Energy Systems. German Advisory Council on Global Change*. Earthscan, London.

Wild M, Trüssel B, Ohmura A, Long CN, König-Langlo G, Dutton EG, Tsvetkov A (2009) Global dimming and brightening: an update beyond 2000. *Journal of Geophysical Research*, **114**, D00D13, doi: 10.1029/2008JD011382.

Supporting Information

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

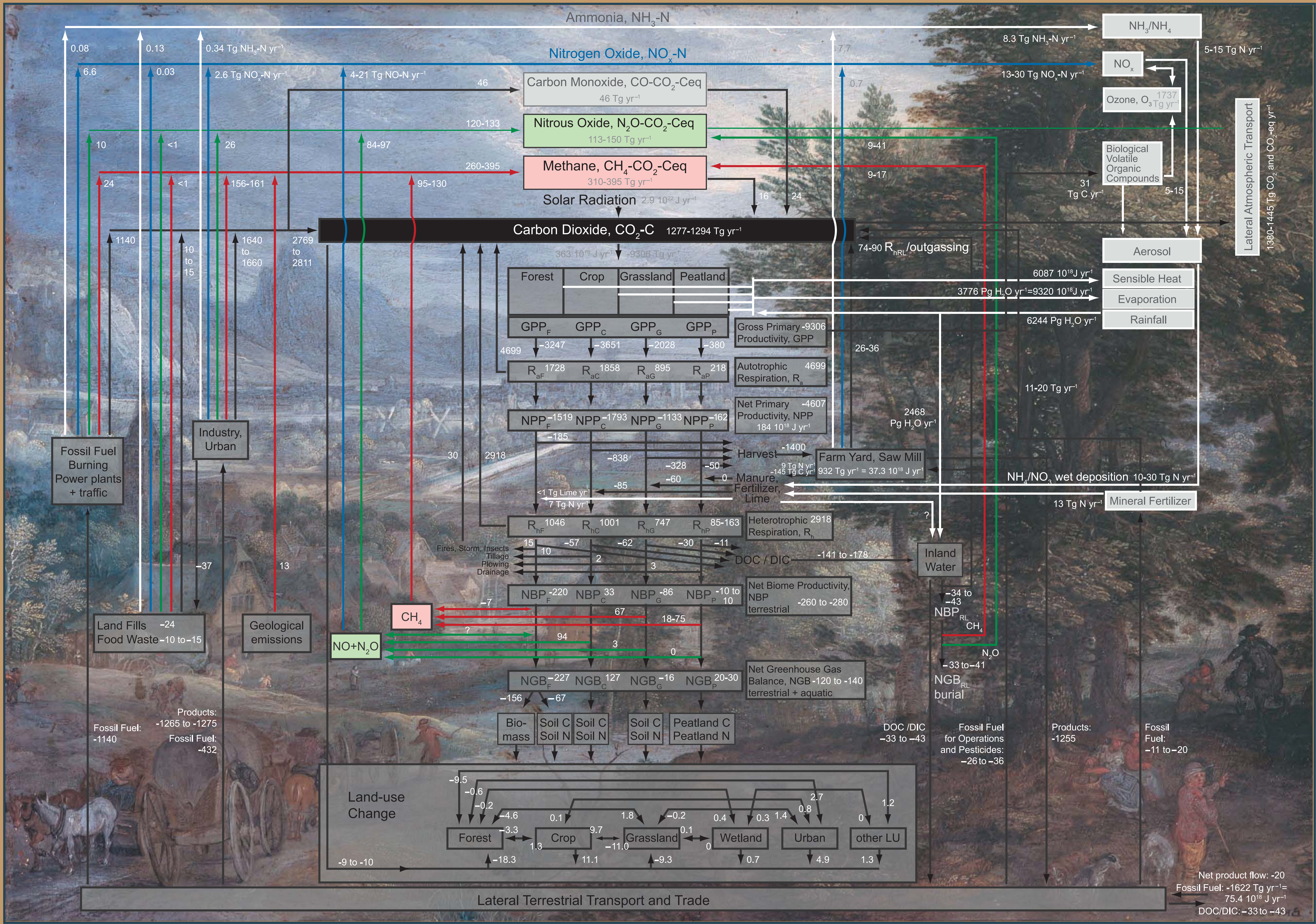
Appendix S1. Data sources.
Appendix S2. Network stations.
Appendix S3. Extended peat data.
Appendix S4. Flux component maps of Fig. 3.
Appendix S5. Data source of uncertainty analysis.

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

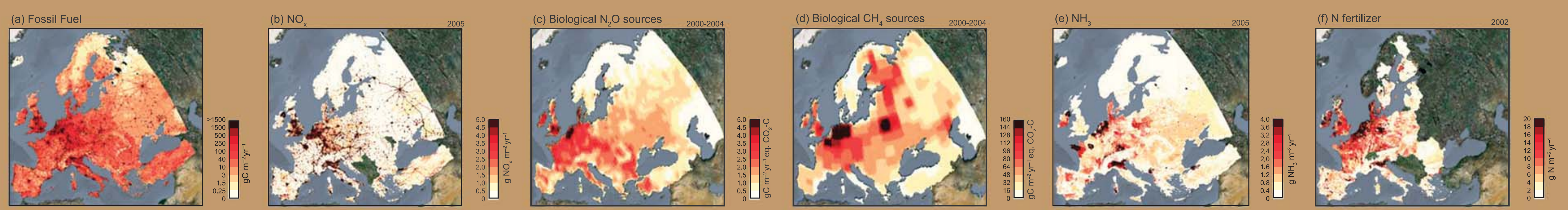
THE TRACE GAS BALANCE OF EUROPE

E.D. Schulze, P. Ciais, S. Luyssaert, M. Schrumpf, I.A. Janssens, B. Thiruchittampalam, J. Theloke, M. Saurat, S. Bringezu, J. Lelieveld, A. Lohila, C. Rebmann, M. Jung, D. Bastviken, G. Abril, G. Grassi, A. Leip, A. Freibauer, W. Kutsch, A. Don, J. Nieschulze, A. Börner, J. Gash, A.J. Dolman

The European carbon balance. Part 4: Integration of carbon and other trace-gas fluxes. Global Change Biology 2010, 1451–1469



Background picture: J. Brueghel the Elder (1568 to 1625): Forested Landscape. Landesmuseum Hannover, Germany



Black: Carbon fluxes (Schulze *et al.* 2009; Tranvik *et al.* 2009); **red:** Methane fluxes (Schulze *et al.* 2009, Bastviken *et al.* 2004), **green:** N_2O fluxes (Schulze *et al.* 2009, Seitzinger and Kroeze, 1998; NAMEA data base Wuppertal Institute); **blue:** NO_x fluxes (IER-Stuttgart database, NAMEA data base Wuppertal Institute, Eurostat Air Emissions Accounts), **grey:** CO fluxes (Lelieveld 2000), NH_3 fluxes (IER-Stuttgart database, NAMEA data base Wuppertal Institute), Ozone flux (Lelieveld 2002), water fluxes (M. Jung, pers. comm.), and input of mineral fertilizer (www.fertilizer.org/ifa). Solar radiation: CE-IP ECMWF data base. The fluxes have different units for carbon, nitrogen and water. Molar units would simplify the scheme, but molar units are not established even in the science community. The boxes at the top of the scheme indicate the total net flux of CO_2, CH_4, and N_2O as a range which originates from the atmosphere-based assessments (Schulze *et al.*, 2009), and the land-based assessment (this study). The atmosphere-based estimate is the larger number for CO_2 and CH_4 and the smaller number for N_2O. CO, NO_x and NH_3 are land-based estimates only.The present knowledge of the emissions and sinks of atmospheric trace gases indicate a decreasing knowledge of these fluxes from the inner core of the plant carbon cycle towards the outer envelope of non-greenhouse gases.