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

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The European Carbon and Greenhouse Gas Balance Revisited

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The European Carbon and Greenhouse Gas Balance Revisited

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REVIEW

The European Carbon and Greenhouse Gas Balance Revisited

Running title: Carbon and Greenhouse gas balance of Europe

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Key words: Carbon cycle, Greenhouse gases, non-greenhouse gases, CO_2, N_2O, CH_4, NH_3, NOx, O_3, Europe, agriculture, forestry, Land-use change

Abstract:

In an overview of the European carbon, greenhouse gas 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, which is five times as high as the energy content of the annual fossil fuel use (75 10^{18} J yr^{-1}). Net primary production, NPP, is 50%, terrestrial net biome productivity, NBP, is 3%, and the net greenhouse gas balance, NGB, is 0.3% of GPP. The net yield of human land use is 20% of NPP or 10% of GPP, or alternatively 1 ‰ of solar radiation after accounting for the inherent cost of agriculture and forestry for fossil fuel used during operations, for production of pesticides and fertilizer and for the carbon equivalent cost of GHG emissions. About 2.4% of the fertilizer input is converted into N_2O. Agricultural emissions are 50% of total methane and NO, 70% of total N_2O, and 95% of total NH_3 emissions. 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 sinks are offset by GHG emissions from croplands, peat-lands and inland waters. Non-GHGs (NH_3, NOx) interact significantly with the GHG and the carbon cycle through ammonium-nitrate aerosols and dry deposition. Wet deposition of nitrogen support about 50% of forest timber growth. Land use change is regionally important with large unidirectional fluxes totalling about 50 Tg C yr^{-1}. Nevertheless, for the European tracegas-balance, land-use intensity is more important than land-use change. Obviously, it is not sufficient to investigate the carbon cycle as an isolated entity, because associated emissions of GHGs and non-GHGs significantly distort the carbon cycle and compensate apparent carbon sinks.

1. 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 carbon sink has absorbed about 30% of anthropogenic emissions over the period 2000-2007 (Canadell *et al.* 2007; LeQuéré *et al.* 2009), showing that carbon 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, $\delta^{13}C$, and O_2 in the atmosphere is smaller than predicted from fossil fuel emissions alone (Tans *et al.* 1990; 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 in 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 to 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 carbon 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, leaving little or no net absorption.

In this study we summarize the fluxes of the most important greenhouse and non-greenhouse gas 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.* Supplement 2009).

2. The carbon cycle of Europe

The carbon cycle of Europe consists of two major components: (1) activities within terrestrial and aquatic ecosystems, and (2) industrial-, transport- and household-activities. These two account for most 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.

The carbon and greenhouse gas balance of different land-use types

When comparing all sites across Europe, 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 peat-lands 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 anticipated 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). Obviously the available light and the length of the growing season are the limiting factors.

Forest is the only land-use type that stores carbon 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.* 2008). Forest standing-stocks have nearly tripled during the past 50 years. Because this carbon is being sequestered in the ecosystems over decades to centuries it can be regarded as a component of the Net Biome Productivity ($NBP_{biomass}$). However, this accumulation should not hide the fact that the carbon incorporated in forest biomass is vulnerable to natural disturbances such as fire and insects, and of course to harvest. Part of the capacity of European forests to sequester carbon results from an 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-deposition (Schulze & Ulrich., 1991; Reay *et al.* 2008; Magnani *et al.* 2007; DeVries *et al.* 2009) and forest management (DeVries *et al.* 2006).

Carbon storage in soils is the most stable 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 carbon in soils than forests – likely due to a higher belowground carbon allocation and root turnover, and possibly to nitrogen fertilization. In addition, the vesicular-arbuscular mycorrhizae of grasses are specialized in mobilizing mineral ions, especially phosphorus (Smith & Read, 1988), 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 carbon in the soil. Thuille and Schulze (2005) found that soil carbon decreased following afforestation across central Europe; for 60 years following afforestation, the total carbon balance was found to be negative. After that time the carbon storage in tree biomass balanced the soil carbon losses, but at that age the trees are close to harvest. A similar trend appeared in a meta-analysis of land-use change effects on soil carbon stocks (Guo & Gifford 2002).

Cropland NBP, as assessed through a full crop cycle, is distinct from that in grasslands and forests in that cropland soils appear to lose carbon through management. Per unit ground area, the net loss of carbon is of the same order of magnitude as the rate of soil carbon 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, NOx) (Steinkamp *et al.* 2009), and nitrous oxide (N_2O). Accounting for their GHG emissions, croplands most likely have a positive greenhouse gas balance (NGB) and thus contribute to an increase in the radiative forcing of the atmosphere (IPCC 2007). Also, GHG emissions partially offset the strength of the carbon sink of grasslands to the extent that their NGB is no longer higher than forests, as was the case for NBP (Table 1). However, in contrast to croplands, grasslands do remain a net sink for greenhouse gases. 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.

Table1 includes the carbon flow through peat-lands, 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 covered under forests. We must emphasize that the information on peat-lands is less integrated than the information on forests, grasslands and croplands. Our data average a transect study in Finland (Alm *et al.* 2002; A Lohila pers. comm.) without weighting the average by the area of the different peat-land types. 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 peat-lands. The CO_2-carbon equivalent CH_4 fluxes change the carbon sink (negative NBP) into a greenhouse gas source (positive NGB).

Ecosystems do not only exchange CO_2, but also need other elements, such as nitrogen for growth, and they 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 nitrogen. Per unit area croplands appear to require 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 1988) 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 (Jung *et al.* in preparation).

Because of the frequent removal of nutrient-rich biomass during harvest, crops and grasslands require almost twice as much nitrogen as forests to maintain their growth. Considering the combined use of all resources (carbon, nitrogen, and water), forests are the least demanding land-use with the highest efficiency at producing NBP and NGB. Pristine peat-lands have an even higher nitrogen use efficiency (per unit of carbon sequestered) than forests, but peat-lands remain a GHG source due to their methane emissions.

The comparisons of the flux balances between land-use types as 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. Fig. 1a clearly shows the shorter growing season and the larger variation of active photosynthesis in crops than in forests and grasslands. Winter wheat (2003) and oil seed rape (2004) have the shortest period of carbon 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 carbon uptake. During warm winters temperate coniferous ecosystems may act as sinks throughout the year (Dolman *et al.* 2002; Carrara *et al.* 2004). 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. Due to differences in albedo and Bowen ratio the sensible heat flux is about 50 to 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 land-use change on climate.

Fossil fuel emissions per unit area

Regional differences of fossil fuel emissions across Europe (Ciais *et al.* 2010c) 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. In total, and neglecting changes in bunkers, the fossil fuel emissions of continental Europe in the period of 2000 to 2004 average 1620 Tg yr^{-1}, amounting to 162 g m^{-2} yr^{-1} (Schulze *et al.* 2009). 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 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 carbon 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). Vehicle traffic produces not only CO_2 but also NOx, which is not a greenhouse-gas in the strict sense (IPCC 2007). However, NOx interacts with oxygen in the atmosphere and is the main catalyst for tropospheric ozone production and removal (Ravishkanara *et al.* 2009; Lelieveld & Dentener 2000). Attribution studies of the radiative forcing of chemically reactive species showed that globally the NOx emissions have a cooling effect on climate because they indirectly remove CH_4 through increased abundance of OH (Shindell *et al.* 2005). Eventually NOx will be 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. Higher NOx environments also show an increased conversion of SO_2 into sulphate aerosols, which again cool the climate (Shindell *et al.* 2009).

Ammonium nitrate is washed out of the atmosphere as “acid rain” (Schulze & Ulrich 1991), but at the same time stimulates plant growth through nitrogen fertilization. Evidence is accumulating that in the long run plant growth can only benefit from increased CO_2 when sufficient nitrogen is available (Oren *et al.* 2001). In nitrogen-limited regions, atmospheric wet deposition of ammonium nitrate, and dry deposition of NH_3 and NOx (Harrison *et al.* 2000; Nösberger *et al.* 2006; Reay *et al.* 2008) could be a major source of plant-available nitrogen. We emphasize through Fig. 2 that the carbon cycle strongly interacts with the nitrogen 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 non-greenhouse gas fluxes, such as NO, NOx 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 carbon cycle and its main drivers, we detailed an integrated flux balance of trace gases across the continent of Europe (Fig. 3, a de-convoluted version of Fig. 3 and the data-sources are presented in the supplement 1 and 2). This figure contains in its centre the carbon fluxes (black lines) of the main land-use types, i.e. forest, grassland, cropland and peat-land. In addition to this natural carbon-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 carbon which enters the carbon cycle as CO_2 from the production and consumption system. 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 nitrogen oxides, NOx, (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 (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). Fig. 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 carbon, nitrogen, 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 carbon 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 carbon cycle towards the outer envelope of non-greenhouse gases (see Section 3 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 contains about 360 10^{18} J yr^{-1}, which is 1.24% of 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 1994, 40 kJ g^{-1} C). Thus, total NPP represents about 180 10^{18} J yr^{-1}, which is only 6 ‰ of 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 to 36 Tg C yr^{-1}). In addition fossil fuel is needed for fertilizer production (11 to 20 Tg C yr^{-1}; www.fertilizer.org/ifa, Dalgaard *et al.* 2001; Hülsbergen *et al.* 2001). 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 other GHGs (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 440 Tg CO_2-C equivalent per year from croplands and grasslands, plus 30 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 440 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 (930 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 1 ‰ of solar radiation, which is a very low energy use efficiency when for example compared with solar cells (WBGU 2004).

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.* 2008). The highest rates of damage take place in forests, and the lowest in peat-lands. 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 carbon 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, 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 inter-annual variability. Although not all data we analyze cover the same period of time, our NBP estimate corresponds broadly to the period 2000 to 2005. We are aware of decadal variability in carbon fluxes reflecting decadal variability in climate (e.g. Piao *et al.* 2009). Thus, our estimate of NBP is still affected by climate variability. In particular, the North Atlantic Oscillation (NOA), 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 NOA 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 NOx are ignored). Additional amounts of CH_4 and N_2O are emitted from inland waters (Kroeze and Seitzinger, 1998; Transvik 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 peat-lands are carbon-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 carbon is in soils and inland water sediments. Our carbon balance suggests the carbon sink of forest and grassland soils (-83 Tg yr^{-1}) is negated by losses in crops and wetlands (+152 Tg yr^{-1}). Thus, the terrestrial soils are a net carbon-equivalent source totalling 69 Tg C yr^{-1}. Part of this loss is balanced by burial of carbon in sediments (-37 Tg CO_2- C equivalent per year). Nevertheless, European soils and sediments remain a net carbon-equivalent source of about 30 Tg CO_2- C equivalent per year. This demonstrates a substantial impact of humans on the carbon cycle of Europe.

Considerable re-allocation of land and associated carbon pools occurs when land-use changes, LUC. These changes are estimated to have created only an additional small carbon sink of 9 to 10 Tg yr^{-1} across Europe over the past 20 years (see Section 5 on LUC, below). Forests and grasslands gain carbon in the process of land-use change, but a loss of similar magnitude exists due to expansion of agriculture, settlements and infrastructure. Comparing this estimate with the carbon 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 land-use change.

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 Tg yr^{-1} in Europe is slightly higher than the total carbon in harvested products of forestry and agriculture (1400 Tg yr^{-1}). However, in terms of energy, the fossil fuel use of 75 10^{18} J yr^{-1} is eight times larger than the energy content of harvested net yield (harvest minus fossil fuel and GHG cost) and about half of the energy content in NPP. This demonstrates the importance of fossil fuel use on the European carbon cycle. 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 globally have a net warming effect. Human activities and fossil fuel burning also emit significant amounts of CH_4 and N_2O. CH_4 emission from fossil fuel burning and industry is about the same as from agriculture.

Three important non-greenhouse gases 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 (Lelievelt & Dentener, 2000; Jöckel *et al.* 2006; Versteng *et al.* 2004). 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 2 to 7 times higher than wet deposition (Harrison *et al.* 2000; M. Sutton pers. comm.). 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 nitrogen emissions of N_2O-N from agriculture and freshwaters (Seitzinger & Kroeze 1998), in total about 0.34 Tg N yr^{-1}. Thus, about 2.6% of the nitrogen input of fertilizer is emitted as N_2O, which is close to the estimate of 2.5% by Davidson (2009).

Human nitrogen inputs are a major disturbance of the carbon cycle. 13 Tg N yr^{-1} are added as mineral fertilizer, 9Tg N yr^{-1} through manure application and animal droppings, and 10 to 30Tg N yr^{-1} through wet deposition. Adding 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 nitrogen input on growth is still under discussion. De Vries *et al.* (2006) suggested that the carbon 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 carbon sink in forests (e.g. de Vries *et al*., 2008; Sutton *et al.*, 2008; Janssens and Luyssaert, 2009), the fact is that nitrogen is a major cause of variation in the net annual productivity, NEP, of forests. In a recent analysis of soil- and wood carbon changes in nearly 400 intensively monitored European forests, de Vries *et al*. (2009) reported that N deposition typically stimulated forest ecosystem carbon sequestration of by 20 to 40 gC g^{-1}N deposited, with lower efficiency of carbon sequestration at higher nitrogen deposition rates. According to Fig. 3, 20 Tg N yr^{-1} wet deposition would result in 400 to 800 Tg of added growth across all land-use types; 30% of which would be covered by forests. Thus, 200 Tg yr^{-1} nitrogen 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 carbon sink by dumping materials. Food waste (Hall *et al.* 2009) may represent as much carbon as dumping of carbon-containing products (1% of total agricultural yield). While food waste would decompose rapidly, 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 & Metthews 2003).

The entire carbon 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 carbon (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 returns to rivers via groundwater discharge and surface runoff. This river discharge contains a considerable amount of dissolved carbon. This carbon is processed, entrained or buried in inland waters and partly discharged into the coastal margins, where it interacts with the marine carbon 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).

3. Uncertainty of the carbon balances

The accuracy of regional carbon balances and their components can be quantified by estimating the same quantities using independent data. Luyssaert *et al.* (2010) and Ciais *et al.* (2010a,b,c) used field observations, remote sensing and ecosystem model simulations as largely independent approaches to estimate NPP and other components of ecosystem carbon 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 carbon balance based on atmospheric GHG concentration measurements on the one hand and land-based carbon stocks and fluxes on the other hand. Based on atmospheric measurements a terrestrial carbon sink of -120 Tg C yr^{-1} was estimated for the EU-25 whereas the land-based approach estimated a sink of -102 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 in quantifying the uncertainty of individual component fluxes.

Uncertainties of individual components are needed to quantify the importance of individual processes, their interactions and statistical significance. Large but uncertain component fluxes are typically the prime target when it comes to improving the overall uncertainty of the estimate. Heterotrophic respiration, for example, is a key flux in determining soil carbon sequestration in croplands. Partly due to the lack of spatially representative and reliable heterotrophic respiration estimates, models (i.e. -8.3 ±13 g C m^{-2} yr^{-1}) and soil inventories (13 ± 33 g C m^{-2} yr^{-1}) are both inconclusive whether croplands are a carbon sink or a carbon 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,c). 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 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 carbon 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 uncertainty, these are the two metrics that determine the reliability of flux components and eventually the carbon balance (see also Supplement 3). Given that a balance is most sensitive to its largest component, ideally these large components should have a high accuracy and low uncertainty, 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 independent estimates of the component fluxes (i.e. import of fossil fuel, harvest, farmyard and sawmill products, and dissolved organic and inorganic carbon), or by decreasing the uncertainty 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.

4. The role of soils

The importance of soils for carbon fluxes in terrestrial ecosystems is generally accepted (Bellamy *et al.* 2005; Don *et al.* 2008). Nevertheless, our knowledge about quantitative changes in SOC over time is still very limited. The sequestration of soil carbon (NBP_{soil}) is presently predicted mostly from top-down modelling of NBP and observations of carbon exchange between the atmosphere and the biosphere. In future it will be important to confirm and constrain these predictions with direct measurements of soil carbon changes (Schrumpf *et al.* 2008; von Lützow *et al.* 2006). Field-based measurements of soil carbon changes are scarce and hampered by the inherently high small-scale spatial heterogeneity of SOC stocks. Due to the long observation period necessary for observing changes in soil carbon against a very high background of carbon in soils, it is expected that it may take decades to verify soil carbon changes (Smith 2004; Meersmans *et al.* 2009). In addition, the carbon 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 carbon changes.

Regional assessments of soil organic carbon (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 carbon were directly determined in the field. Average bulk densities and stone contents, were derived from pedotransfer functions (Bellamy *et al.* 2005; Hopkins *et al.* 2009; Sleutel *et al.* 2003). 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 kg 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 re-growth following harvest can cause SOC changes in topsoils as well as in deeper soil layers (Diochon *et al.* 2009; Gál *et al.* 2007). SOC losses in topsoils may be balanced by gains in sub-soils, which are overlooked when only topsoils are analyzed 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 cover the small scale variability, which could override time-dependent changes. A total of 100 soil cores were taken at each of 3 cropland sites, 3 grassland sites, 3 deciduous forests, and 3 coniferous forests. The re-sampling of these sites is still ongoing. However, first data are available from the Hainich site, a deciduous forest reserve, which has been protected for the past 60 years, and which was re-sampled after 5 years; a short period considering soil processes. For the Hanich site, Mund and Schulze (2006) analyzed a transect study across age classes in that region and reported 20 to 50 g C m^{-2} yr^{-1} soil carbon accumulation. However, this estimate was not statistically significant. Kutsch *et al.* (2010) used CO_2 fluxes and tree growth studies to suggest a sequestration rate of 1 to 35 g C m^{-2} yr^{-1}. A soil survey (Schrumpf, unpublished) taking 100 repeated samples after 5 years, showed a significant carbon accumulation of 26 to 50 g C m^{-2} yr^{-1}. Thus we are confident, that this forest accumulates carbon in soils, even in the short term.

5. Regional distributions of greenhouse gas fluxes

The distribution of GHG fluxes obtained from inverse models (N_2O, fossil fuel) and from databases (NOx, NH_3) shows large regional variation (Fig. 5). Fossil fuel emissions are centred in mid-Europe with highest rates 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. Highways emerge as the main source. Because traffic is a main NOx source, the fossil fuel map is matched by the NOx map (see Fig. 5b). The input of organic and mineral fertilizer is the additional main input into ecosystems (Fig. 5f). It shows a maximum in the Benelux states, in 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 map is based on atmospheric measurements and inverse modelling, the emission database for NOx , 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 (JRC). The assumption that the maps for fossil fuel, NH_3 and NOx 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. 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 2nd 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 NOx 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.

5. Quantifying the effects of land-use change

Global LUC carbon balance of the EU 25

Assessing the carbon balance of land-use changes (LUC) 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 discounted, 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. 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. Thus, we cannot rule out that an unknown part of the NBP estimate contains fluxes that were caused by LUC.

According to the information contained in the 2009 GHG inventory reports, the total area reported under a "land-use change" category 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 a 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 land-use change 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 carbon 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 net small 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} carbon. 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 carbon 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 carbon 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 underestimated. The analysis indicates that despite the net carbon balance of all land-use changes being small, and despite the fact that the LUC areas are usually very small compared to 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 carbon 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 carbon stock changes (in some case the spatiotemporal variability of soil carbon 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 carbon in settlements. When buildings are constructed, whether soil carbon buried under concrete isolated from the atmosphere, or decomposed by microbes and quickly lost to the atmosphere will change the sign of the carbon balance of new settlements. At face value, gardens are productive and fertilized lands, which may be overlooked and yet are a significant carbon sink given the total urban and peri-urban area, which is about 7% of total land area. Despite these limits, the data from countries' GHG inventories are presently the best data available for LUC-induced carbon flux estimates.

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

7. Where does the excess carbon dioxide and nitrous oxide 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 non-reactive trace gases go, and what area outside Europe would be needed to assimilate this surplus? This would be the trace gas footprint of Europe.

Assuming that CO, CH_4, NH_3, and NOx are deposited in Europe, N_2O and CO_2 remain as the major trace gases being exported to other regions of the globe.

In total, Europe exports 0.4 Tg N_2O-N yr^{-1}. Assuming an uptake in forest equivalent to Europe of about 2 g N_2O-CO_2-C-eq m^{-2} yr^{-1}, the Siberian forests extending over 12.80 10^{12} m^2 (Shvidenko & Nilsson, 1994) would assimilate only about 20% of this excess, the remaining could interact with volatile organic carbon, would be mixed across the globe, or enter into the stratosphere.

The excess CO_2 of 1294 Tg yr^{-1} could be absorbed by oceans or the biosphere or add to the atmospheric increase in CO_2. According to Canadell *et al.* (2007) we may assume that 23% enters into the oceans, and 38% remains in the atmosphere. 39% or 504 Tg yr^{-1} is expected to be absorbed by vegetation of neighbouring continents. We may take Siberia as one candidate for this footprint. Shvidenko and Nilsson (2002) estimate a carbon sequestration rate for Siberian forest of 210 Tg C yr^{-1} and an additional 50 Tg C yr^{-1} may enter into soils (Shvideno & Nilsson, unpublished). Thus, the Siberian forest may re-assimilate 20% of the excess European CO_2-C, leaving about 244 Tg yr^{-1} to be assimilated in other regions. In any case, the European footprint on the global terrestrial surface may be twice as large as Siberia.

8. Conclusions

The carbon cycle shows a significant distortion from human impacts. We are extracting 30% of the carbon flow as harvest, which reduces the amount that could be stored in soils. The carbon balance of soils (excluding the carbon storage in forest biomass) is still a minor carbon sink. However, studying only the carbon cycle is not sufficient, if a mitigation of the global warming potential is anticipated. Not only greenhouse gases, but also non-greenhouse gases interact, mostly offsetting the apparent terrestrial sink. Although CO_2 from fossil fuel burning remains the most important greenhouse gas added into the atmosphere by human activity, CH_4, N_2O and CO contribute almost 50% to the total European global warming potential, and about 75% of this input originates from agriculture. Including these emissions of greenhouse gases, the European soils are a net source.

The human impact on the carbon cycle is significant and occurs everywhere. Harvest exceeds NBP by threefold, which means that more carbon is extracted from the natural carbon cycle than it is remaining in soils. Total harvest takes about 30% of NPP, but 10% of this is the hidden cost of production. On the other hand, growth of vegetation is stimulated by atmospheric nitrogen deposition. 50% of forest NBP and harvest could be due to the anthropogenic input of atmospheric nitrogen.

Europe creates an excess of N_2O and CO_2, which is re-assimilated 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 carbon balance (no climate mitigation). Obviously, Europe has a long way to go to reach climate neutrality.

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 in-house 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 non-ruminants, because each group has its own detrimental emissions. We also would not distinguish between organic and mineral fertilizer, because both have similar effects. However, the choices between using the biosphere as carbon 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 as to under what conditions and assumptions a certain option is to be recommended, and regional conditions are important.

At this moment a significant trend of greenhouse and non-greenhouse gas emission cannot be established from this study, but this study may be a benchmark against which to measure the anticipated mitigation policies for the period up until 2020.

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	Flux unit	Forest	Grassland	Cropland	Peat-land
Gross Primary Productivity, GPP	g C m^{-2} yr^{-1}	**-1107±55**	**-1343±269**	**-1120±224**	**-690±340**
- Autotrophic Respiration, Ra	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, Rh	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-C eq m^{-2} yr^{-1}	1±1	43±14	30±9	63±30
Net Greenhouse gas Balance, NGB	g CO_2-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

Table 2: Areas of land-use change in Europe (EU-25) which reported to the UNFCCC (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 Otherland	15	10	46	7	1		**80**
Total "from"	**91**	**658**	**740**	**29**	**54**	**155**	

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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 to 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}.

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

Fig. 3: A summary of greenhouse and non-greenhouse gas fluxes across Europe. **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**: NOx 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 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. The background picture is from J. Bruegel the elder (1568 to 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.

Fig 4. Flux magnitude for a 100-year horizon (surface of the bubble; Tg C yr^{-1}) as a function of current accuracy and uncertainty of the component flux. 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 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 greenhouse gas 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

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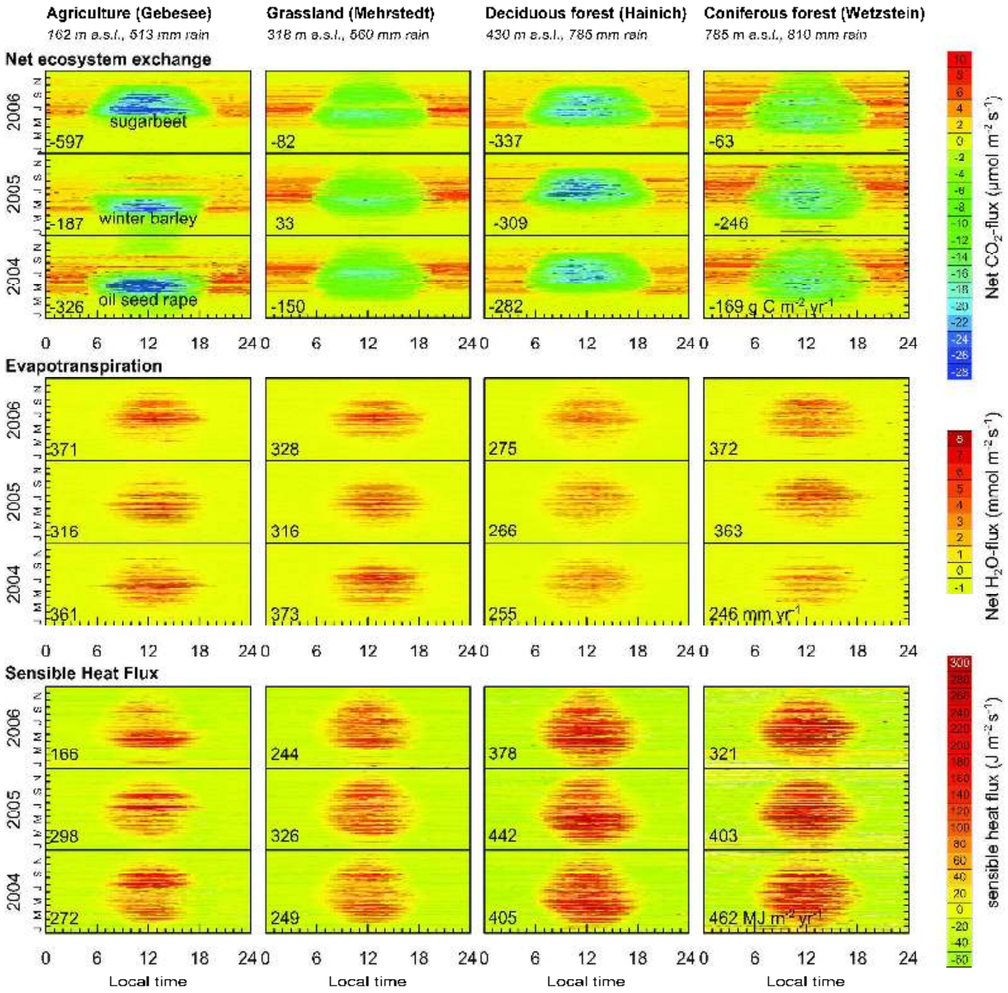

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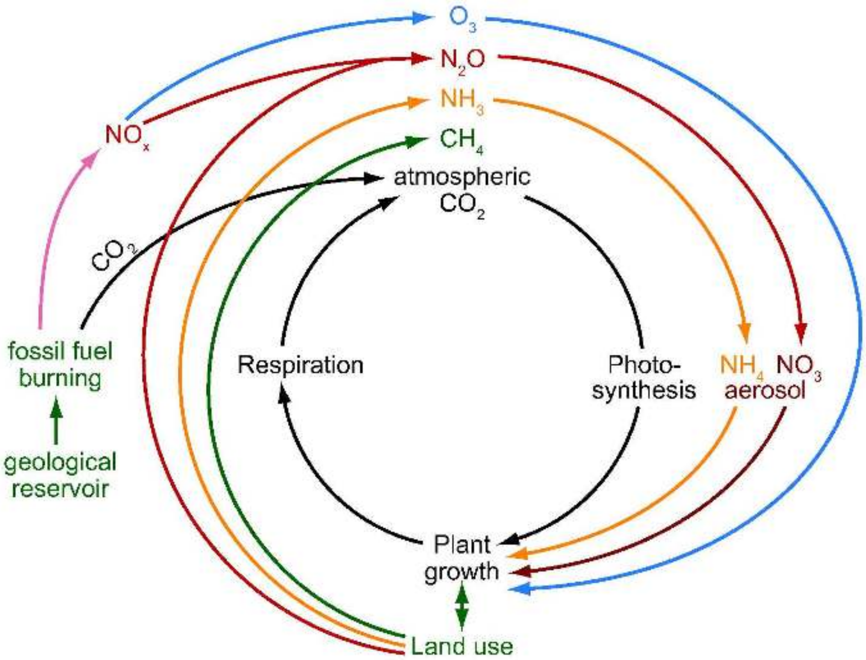

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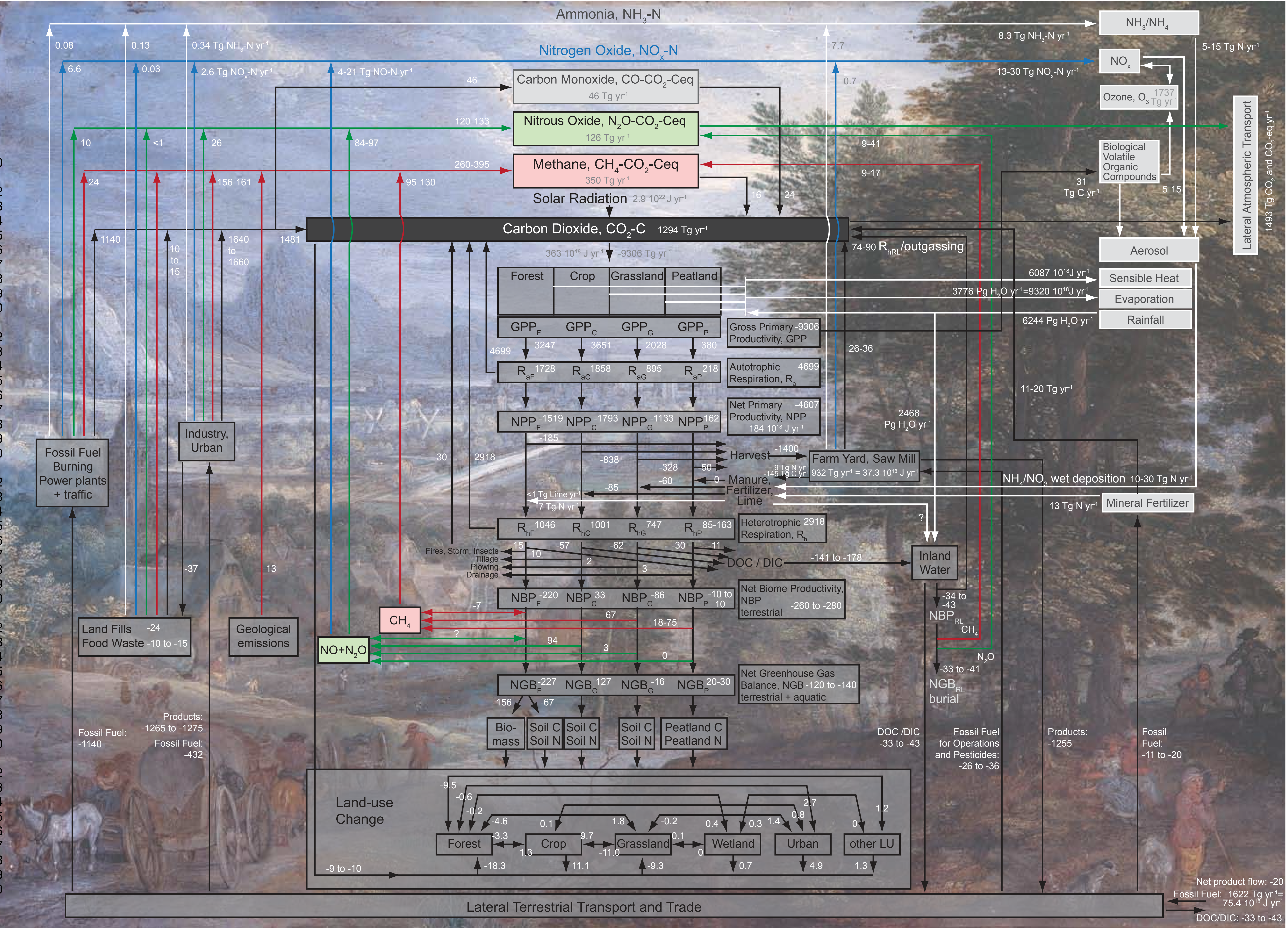

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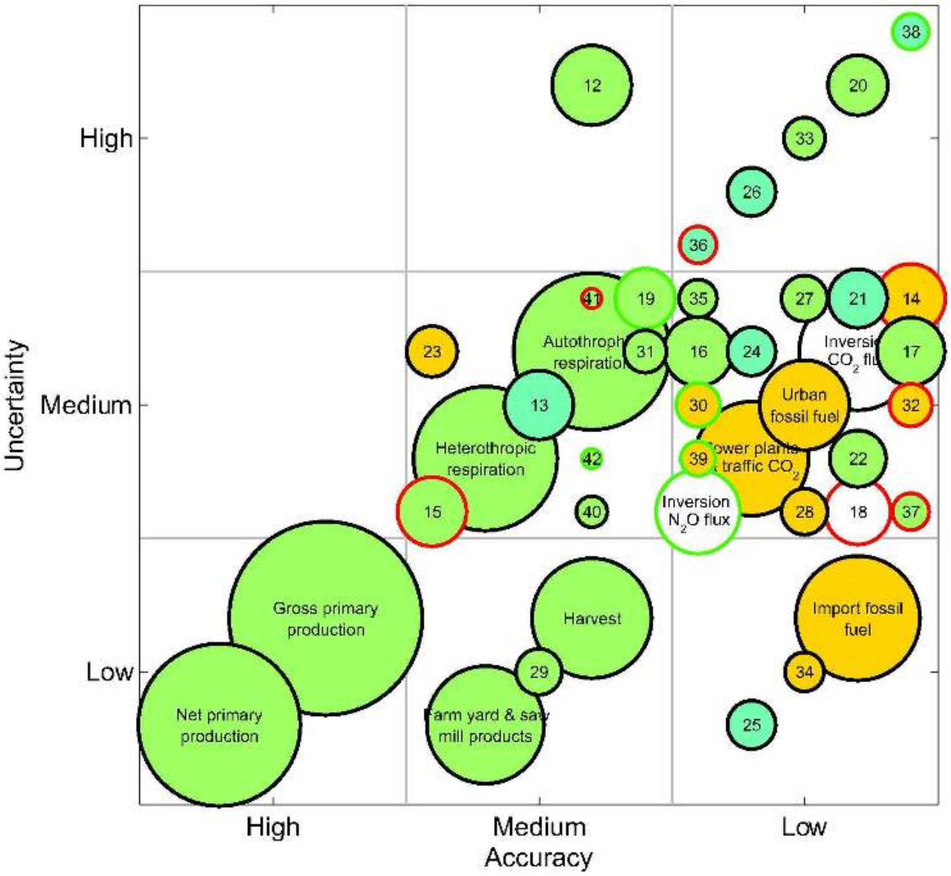

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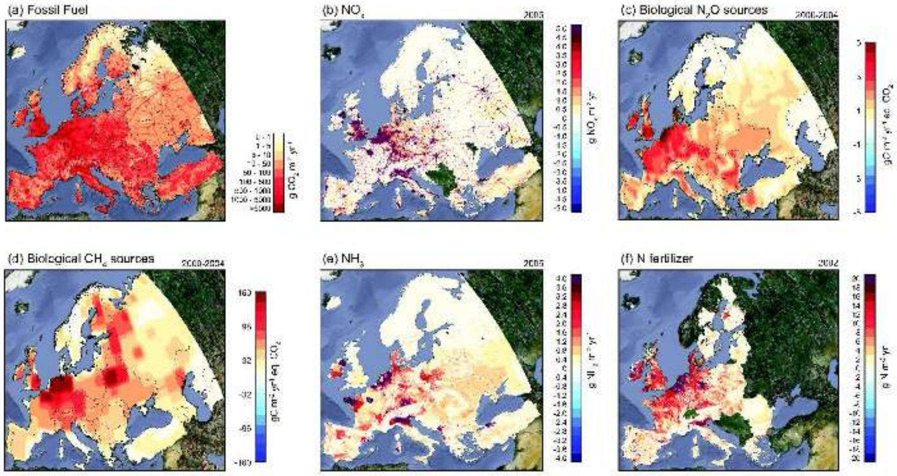

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