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The impact of lateral carbon fluxes on the European carbon balance

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Abstract

To date, little has been written about the important role played by processes transporting carbon laterally over continents, and from continents to oceans. These processes have an impact on the CO_2 budgets and on the carbon budgets at local, regional and continental scales. We estimated the impact on the European carbon balance of the transport of carbon by the trade of wood and food products, by the emission and oxidation of reactive reduced carbon species, and by rivers and freshwater systems up to estuaries. The analysis is completed by new estimates of the carbon fluxes of coastal seas. The magnitude of the CO_2 and carbon fluxes caused by lateral transport over Europe is comparable to current estimates of carbon gain by European ecosystems. At the continental level, we estimate a CO_2 sink over Europe of 140 TgC yr^{-1} and a carbon sink of 50 TgC yr^{-1} being caused by lateral transport processes.

1 Introduction

Lateral carbon transport moves carbon away from where CO_2 is withdrawn from the atmosphere. This induces differences between regional changes in carbon stocks and regional CO_2 fluxes (Tans et al., 1995; Sarmiento et al., 1992). Comparing CO_2 fluxes resulting from atmospheric inversion models with bottom-up carbon flux estimates (Pacala et al., 2001; Janssens, et al., 2003; Peylin, et al., 2005) is thus complicated further by lateral carbon transport. Some bottom up methods (e.g. extensive forest biomass inventories) estimate carbon stock changes, while some directly measure CO_2 fluxes (e.g. eddy covariance flux towers). This paper has three main goals. The first is to describe the mechanisms of lateral carbon transport and their implications for regional carbon budgets. The second objective is to quantify the flux of carbon displaced within and from the European continent, and to place it in the context of inversion results. The third goal is to project the CO_2 fluxes associated with lateral displacement into spatially explicit maps, whenever this is possible.

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We consider four processes linking CO_2 fluxes with lateral carbon transport either within the European continent or across its boundaries. These processes are 1) the trade of food, feedstuff and wood products (Ciais et al., 2006[1]; Imhoff et al., 2004), 2) the emissions of reduced atmospheric carbon compounds such as CO, CH_4, terpenes, isoprene by ecosystems and human activities, which get transported by winds and oxidized by chemical reactions in the atmosphere outside of the study area (Enting et al., 1991; Folberth et al., 2005; Suntharalingam et al., 2005), 3) the river transport of carbon from land to the ocean (Aumont et al., 2001; Meybeck, 1987), and 4) the CO_2 fluxes in coastal seas (Borges et al., 2006[2]). This latter process does not always match a lateral carbon flux from land to sea, but it is addressed here, as a necessary flux component to reconcile large-scale atmospheric inversion results with bottom-up estimates. In the following, the first four sections treat each of these process separately, with quantitative estimates of the CO_2 fluxes associated to lateral carbon displacement. The discussion section summarizes the contribution of the different mechanisms to the carbon balance of Europe.

2 Crop and forest products trade

2.1 Food and feedstuff products

Cultivated ecosystems take up CO_2 from the atmosphere. Carbon incorporated into the biomass of cultivars is harvested and transported to supply human or animal consumption (Fig. 1). The consumption of food or feed products releases CO_2 back to the atmosphere. Over the globe, such transport of carbon in food products is neu-

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tral for the atmosphere, given the fact that storage of food and feedstuff is negligible compared to the displaced fluxes. Regionally however, croplands are net annual CO_2 sinks (e.g. Anthoni et al., 2004) while populated areas where food is consumed are net annual sources. International trade of food and feed products moves carbon in and out of Europe, which affects the carbon balance of the continent. Intra-European trade also redistributes carbon, creating regional patterns of CO_2 fluxes to and from the atmosphere.

We analyzed the agricultural statistics from FAO (2004) to infer which crop types and which countries contribute most to the lateral carbon transport via food trading. We found that cereals, essentially maize, wheat and barley, are responsible for nearly all of the CO_2 sink in European croplands. The corresponding source is derived from the consumption of a more diverse mix of crop products. On the perspective of individual countries, the situation is more contrasted (Fig. 2). The largest net CO_2 sink by the trade of crop carbon is France (9 $TgC\,yr^{-1}$), a large agricultural country which represents 90% of the total sink. The largest CO_2 sources are Portugal, Belgium, Netherlands, Italy and Spain (altogether +22 $TgC\,yr^{-1}$). Other countries are approximately neutral. We found no strong correlation between the harvest or the exported flux, and the net carbon budget of each country with regards to food products trading. At the continental level, Europe imports more carbon than it exports, thus being a net source to the atmosphere of 19.3 TgC yr-1, equaling 1% of its fossil fuel CO_2 emissions.

The patterns of CO_2 fluxes induced by crop trade is mapped using geographically-referenced information on 1) crop varieties (Ramankutty et al., 1998), 2) human population distribution and, 3) housed poultry, pigs and cattle populations. Statistical data (FAO, 2004) on feedstuff and food producers is projected on a 1° by 1° map, using the same methodology as in Ciais et al. (2006)[1]. The results are shown in Fig. 3. Agricultural plains with intensive cultivation of cereals (Northern France and Southern England, Hungarian plains, Po valley in Italy) are annual net sinks of CO_2, with uptake reaching up to 100 $gC\,m^{-2}\,yr^{-1}$ locally. Such a large net CO_2 uptake, equivalent to the one of European forests (see e.g. Janssens et al., 2003) reflects the high productivity and harvest index (ratio of yield to NPP) of crops compared to trees. In Fig. 3, it is also seen that the regions with dense population and intensive animal farming emit CO_2 to the atmosphere, at a rate of up to 50 gC m^{-2} yr^{-1}.

There are uncertainties on these maps. Using statistics for country totals may smooth out the fields. For instance, the feedstuff consumption by farmed animals is evenly distributed between different provinces of a given country according the animal density, while in reality animals may have regionally different reliance on feedstuff. Over large countries, the crop harvest data are projected evenly on the area distribution of each crop variety, neglecting regional differences in soil fertility or climate. Finally, the release of CO_2 by food consumption is assumed to follow the geographic distribution of human population, neglecting the transport of organic carbon in dejections to sewage water, and rivers.

2.2 Forest products

We include in this analysis all the forest products from coniferous and non-coniferous trees: industrial roundwood, sawn wood, wood panels and paper listed in the FAO (2004) database. The data in volume units are converted to mass of carbon using a mean wood density of 0.5, and a 0.45 carbon fraction in dry biomass. The forest products data in FAO (2004) indicate that Sweden and Finland export much more carbon in wood trade than they import, thus being net sinks of atmospheric CO_2. Portugal and the Czech Republic are also sinks, but of smaller magnitude. All other countries are CO_2 sources with respect to forest product trading. The largest sources are Italy, Spain, the Netherlands and the UK. It is apparent that the countries which export food products generally also export wood products (except for Nordic countries). Conversely, countries which import crop products (e.g. Mediterranean regions) import forest products as well.

To map the CO_2 fluxes from forest product trade, we projected the country-level data in (FAO, 2004) using a NPP model driven by remotely sensed information of the Normalized Difference Vegetation Index (NDVI) (Lafont et al., 2002) and a forest cover map (CORINE Land cover, 2000), at a 1° by 1° horizontal resolution. The geographic distribution of the CO_2 source caused by the decay or combustion of forest products is assumed to follow population density (assuming that landfills are part of the population density distribution).

There are large uncertainties around these maps. First, the forests with the inferred largest NPP from remote-sensing do not necessarily have the largest wood production, as expected, for instance, from the saturation of NDVI vs. Leaf Area Index, although (Myneni et al., 2001) showed a correlation between NDVI and biomass. Further, the areas where CO_2 is released by decaying wood-products may differ in their geographic location from the actual population density distribution (e.g. depending on regional practice for using wood as a construction material).

3 Reduced carbon compounds

3.1 Surface emissions

Ecosystems and antropogenic activities emit non-CO_2 reactive carbon compounds (RCCs). The RCCs include CO, CH_4, biogenic volatile organic compounds (BVOCs, such as isoprene, terpene), and anthropogenic volatile organic compounds (VOCs). The atmospheric lifetimes of RCCs vary over several orders of magnitude, from 9 years for methane, down to a mere few hours in the case of terpenes. Although the oxidation sequence of RCC can be complex, the main end product is CO_2. The global RCC flux from ecosystems is small compared to photosynthesis or respiration. It can however be significant compared to the net carbon balance of ecosystems (Kesselmeier, 2005). If the objective of a study is to determine the CO_2 flux of Europe by inverse modeling of CO_2 concentration data, then the RCC emissions can rightfully be ignored. On the other hand, if the objective is to determine the carbon flux of Europe, the RCC fluxes must be added to the CO_2 fluxes.

3.2 CO_2 production in the atmosphere

The lifetime of atmospheric RCCs with respect to their chemical sink in the atmosphere can easily exceed typical atmospheric transport time scales. The carbon carried by RCCs can thus be released as CO_2 away from its region of origin. Table 1 shows that the total European emissions of RCC are of 185 $TgCyr^{-1}$. A significant fraction of these emissions is transformed into CO_2 in the boundary layer, very shortly after emission. We estimated the CO_2 production rates from RCCs using a global 3-D chemistry transport model (Folberth et al., 2005; Hauglustaine et al., 2004). The model accounts for two major oxidation channels of RCC 1) the oxidation of primary CO and of secondary CO from the oxidation of CH_4 and VOCs, 2) the direct oxidation of peroxy-radicals into CO_2. An additional minor channel corresponding to the direct ozonolysis of alkenoid compounds into CO_2 is also taken into account. The total chemical CO_2 production from RCC in the atmosphere over Europe is given in Table 1. It amounts to 45 $TgC\,yr^{-1}$ and 57% of this flux (26 $TgC\,yr^{-1}$) occurs in the boundary layer. About 90% of the photochemical CO_2 production comes from CO oxidation by hydroxyl radicals (OH). A map of the CO_2 flux caused by RCC oxidation in the air column is shown in Fig. 4.

3.3 Surface deposition of carbon and impact on the net carbon balance

A sink of carbon into RCC occurs via the dry surface deposition processes and the wet scavenging by precipitation. This sink amounts to 22 $TgC\,yr^{-1}$ over Europe (Table 1). The net effect of the reduced carbon compounds on the European carbon flux can be estimated by the difference between the surface emissions of RCC (carbon source), and the photosynthetic uptake of CO_2 from which are derived the BVOCs emissions (carbon sink) plus the dry and wet RCC deposition flux (carbon sink). Based on our chemistry-transport model results, we estimate a net carbon loss of 76 $TgC\,yr^{-1}$ (Table 2). The impact of RCCs on the CO_2 flux of Europe is different. It is the difference between the flux of CO_2 into the boundary layer and the CO_2 sink by photosynthesis from which are derived the BVOCs emissions. We note a net CO_2 sink of 60 $TgC\,yr^{-1}$,

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available for long-range transport outside the European domain (Table 2).

4 Rivers and estuaries carbon transport

4.1 Processes controlling the transport of atmospheric carbon by rivers

River systems (streams, lakes, river main stems, floodplains and estuaries) transport carbon laterally from the land to the ocean and vertically as CO_2 degassing to the atmosphere and as carbon burial in sediments (Fig. 1). Rivers transport carbon under dissolved and particulate organic forms (DOC and POC) and under inorganic forms (DIC, PIC and CO_2). The sources and sinks of river carbon in natural conditions are : (1) wetlands and peat drainage (A in Fig. 5a), (2) soil leaching and erosion (B), and (3) chemical weathering of soil minerals (C and D). This carbon is originally taken up from the atmosphere by photosynthesis ($CO_2+H_2O \rightarrow Corg+O_2$), by carbonate rock weathering ($CO_2+H_2O+MCO_3 \rightarrow 2HCO_3^-+M^{2+}$) and by silicate rock weathering ($2CO_2+H_2O+MSiO_3 \rightarrow 2HCO_3^-+M^{2+}+SiO_2$). During the weathering of silicate rocks, 100% of river DIC originates from the atmosphere. In contrast, during weathering of carbonate rocks, only half of the DIC originates from the atmosphere, and half derives from fossil carbonates stored in rocks. Therefore the nature and age of river carbon species is very different (Meybeck, 1993, 2005). Particulate organic carbon (PIC) is derived from mechanical erosion. While being transported downstream to the coast, PIC is gradually trapped in lowlands, floodplains, lakes, estuaries and on the continental shelf (Fig. 5a fluxes f and h). This relocation of rock PIC does not generally affect the CO_2 cycle. Also, under arid conditions and high pH, some DIC may precipitate on its way to the sea as calcite in soils and sediments.

Factors controlling the river export of atmospheric carbon (DOC+POC+atmospheric derived DIC) are first evident in river runoff, then rock type (occurrence of carbonate rocks) and finally in the presence of wetlands (also large lakes). A preliminary comparison of river carbon fluxes in Northern, Central and Southern Europe shows strong

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regional contrasts. Northern catchments show high DOC export (most POC is trapped in lakes which cover 5–20% of these basins). The age of this DOC derived from wetlands and peat bogs probably ranges from 100 to 6000 yrs. Southern catchments show DIC as the dominant form of river carbon. Central European catchments are intermediate with carbon fluxes depending on river runoff and rock type.

4.2 Human perturbation of the river carbon transport

Human intervention on river catchments may greatly modify carbon fluxes (Figs. 5b). The exploitation of peat bogs generally increases DOC contents in head waters (Figs. 5b, b). Increased soil erosion by agricultural practices increases the POC inputs. Untreated organic waste water (Figs. 5b, c) and eutrophication of river and lakes (Figs. 5b, d) are additional sources of very labile DOC and POC. The ages of these carbon species are highly variable (from a few days for river algal carbon to 1000 yrs for peat DOC). The CO2 evasion from freshwaters greatly depends on the reactivity of the organic carbon carried by rivers. During the 1970's, when rivers were receiving untreated waste waters, river respiration (R) exceeded river production (P) related to eutrophication. This resulted into a net CO2 source to the atmosphere (see Kempe, 1984 for the Rhine river). Nowadays, due to waste water treatment, the same river may have multiple changes of P/R ratio from headwaters to estuary. This is the case for the Scheldt and Seine rivers.

As an integral part of human activity, river damming and irrigation control the carbon fluxes to oceans. Reservoirs store up to 99% of particulate river material (Vörösmarty et al., 2003) including POC and may degrade DOC and retain part of DIC as calcite precipitation. Irrigation canals continuously transfer river carbon to agricultural soils. In Southern Europe, most river flows of carbon to the ocean have been decreased (e.g. up to 90% for the Nile). However, the impact of water withdrawal for irrigation on river carbon fluxes to the Mediterranean Sea or the Portuguese Coast is unknown because the last gauging and water quality stations are located upstream of the major irrigation areas (e.g. deltas of Ebro, Rhone, Axios; see Ludwig et al., 2004).

4.3 CO_2 fluxes from rivers and freshwater systems

In Europe, freshwater systems are net sources of CO_2 to the atmosphere. Except for a few cases occurring seasonally, CO_2 super-saturation in the water prevails in streams (Hope et al., 2001; Billet et al., 2004), lakes (Cole et al., 1994), rivers (Kempe, 1982; Jones and Mulholland, 1998; Abril et al., 2000; Cole and Caraco, 2002), and estuaries (Frankignoulle et al., 1998; Abril and Borges, 2004). Such high CO_2 concentrations in continental waters corresponds either to CO_2 produced on land by soil respiration, followed by surface runoff and riparian transport, or to the oxidation of terrestrial organic carbon in the aquatic system itself, by microbial respiration and photochemistry (Granéli et al., 1996; Jones and Mulholland, 1998; Abril and Borges, 2004; Gazeau et al., 2005). Temperate rivers in western Europe show a positive pCO_2 vs. DOC relationship (Fig. 6), as a result of anthropogenic loads increasing the DOC, enhancing aquatic respiration, and increasing pCO_2 (Neal et al., 1998; Abril et al., 2000). In contrast, boreal headwaters (e.g. Scottish peatlands) show low pCO_2 in comparison with a very high DOC. This is due to the more recalcitrant nature of the DOC, which originates from old peat soils, and to the rapid evasion of CO_2 to the atmosphere in these fast flowing waters (Hope et al., 2001; Billet et al., 2004). In lakes, DOC is negatively correlated with water residence time, showing the predominant role of microbial and photochemical oxidation (Tranvik, 2005). In some temperate eutrophic rivers, a seasonal and sometimes annual uptake of atmospheric $CO_2$is observed (Fig. 6). Atmospheric carbon fixed by aquatic primary production is then transported downstream as organic carbon. The Loire river, for instance, transports large quantities of algal carbon which are mineralized in the estuarine turbidity maximum, leading to high CO_2 degassing (Meybeck et al., 1988 ; Abril et al., 2004). In fact, many European macrotidal estuaries behave as "hotspots" for CO_2 degassing, owing to the quantity of organic carbon they receive and to the long residence time of waters and suspended sediments (Frankignoulle et al., 1998; Abril et al., 2002; Abril and Borges, 2004). The relative scarcity of pCO_2 data in continental waters, and the high spatial and temporal variability, renders a bottom-up estimate at the European scale rather uncertain. In addition, the surface areas of some ecosystems are uncertain and the highest CO_2 fluxes occur in ecosystems with the smallest surface areas (estuaries and rivers).

4.4 River carbon transport and the European carbon balance

The lateral transport of river carbon was compiled using the main European rivers database (Meybeck and Ragu, 1996) and extrapolated for the European seas catchment (8.16 Mkm^2) on the basis of runoff, land cover and rock types similarities. Estuarine filters are included in this calculation. Southern, Central and Northern European rivers show marked diversity in export rates and carbon species (Table 3). Table 2 compares (on an order-of-magnitude basis) the river lateral carbon transport with the CO_2 outgassing flux. The CO_2 fluxes from freshwater sub-ecosystems (peatland streams, lakes, rivers, and estuaries) are compiled from published pCO_2 distributions, using typical gas transfer velocities, and available information on surface areas of sub-ecosystems. Because the river transport (Table 3) is based on non-tidal river sampling and is calculated for the entrance of estuaries, we distinguished the CO_2 degassing in freshwaters from those in estuaries. Overall, European rivers transport laterally 53 $TgC\,yr^{-1}$ to estuaries, and they emit 90 $TgC\,yr^{-1}$ of CO_2 to the atmosphere. A majority of this outgassing occurs at northern latitudes. Lakes contribute up to 35% of the total CO_2 outgassing from European freshwaters (excluding wetlands and estuaries) owing to their large surface area (183 $10^3\,km^2$ in total) despite their lower CO_2 flux density. CO_2 degassing from European estuaries has been previously estimated to 30–60 $TgC\,yr^{-1}$ (Frankignoulle et al., 1998). This range is probably an overestimate for two reasons: (1) the surface area of European estuaries used by Frankigoulle et al. (1998) (112 $10^3\,km^2$) was much higher than recent estimates (36 $10^3\,km^2$) from the Global Lakes and Wetlands Database (GLWD) of Lehner and Döll (2004), (2) the investigated estuaries were in majority macrotidal, where net heterotrophy and CO_2

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degassing are favored (Abril and Borges, 2004; Borges et al., 2006[2]). Little or no CO_2 data are available in fjords, fjärds, deltas and coastal lagoons. Scaling up the available CO_2 fluxes to the surface area of coastal wetlands and estuaries from GLWD gives a CO_2 source of 10–20 $TgC\,yr^{-1}$. This value is close to the organic carbon transport by European rivers before the estuarine filter of 20 $TgC\,yr^{-1}$ (Table 3).

5 Coastal seas

Coastal seas receive nutrient and organic matter inputs from estuaries, and exchange water and matter with the open ocean across marginal slopes. For European coastal seas, the gross water fluxes across marginal slopes are 250–2000 times larger than the fresh water input (Huthnance, 2006). The budget of carbon will also depend on the content that is much higher in estuaries than in the adjacent open ocean. Nevertheless, the inputs of carbon from the open ocean to the coastal seas are significant due to the much higher water fluxes involved. In the North Sea, the inputs of DOC and DIC through the northern boundary from the North Atlantic Ocean are 45 and 140 times higher in respect to the inputs of the same quantities from estuaries. The input of the same species from the Baltic Sea is roughly equivalent to those from estuaries. The input of DOC and DIC from the English Channel are, 3 and 13 times higher respectively, than the inputs from estuaries (Thomas et al., 2005).

Unlike macrotidal estuaries which emit CO_2 to the atmosphere throughout the year (see above), coastal seas usually exhibit a distinct seasonal cycle of air-sea CO_2 fluxes. They shift from a CO_2 source to a sink, depending on biological activity. The coastal air-sea fluxes are hence predominantly controlled by the net ecosystem production (NEP). This is illustrated in Fig. 7 for the Southern Bight of the North Sea. This region acts as a sink of CO_2 in April-May during the phytoplankton blooms, and as a source during the rest of the year due to the degradation of organic matter. However, overall this region is a net sink of atmospheric CO_2 due to the seasonal decoupling of organic

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matter production and degradation, with a probable export of organic matter to the adjacent areas.

Besides NEP, air-sea CO_2 fluxes in coastal seas are also modulated by other factors, such as $CaCO_3$ precipitation/dissolution, decoupling of carbon production and degradation across the water column in presence of stratification, temperature and salinity changes, Revelle factor, exchange of water with adjacent aquatic systems, water residence times (see Borges et al., 2005, 2006[2]). Fig. 8 shows the annually integrated air-sea CO_2 flux of various European coastal seas. The spatial heterogeneity is clearly apparent. Seasonal patterns also differ from one coastal sea to another (not shown; see Borges et al., 2005, 2006[2]). In general, we estimate that the European coastal seas are a net CO_2 sink of atmospheric of 68 $TgC\,yr^{-1}$. This value is comparable to the continental carbon sink of 111±279 $TgC\,yr^{-1}$ of (Janssens et al., 2005).

6 Discussion

6.1 Lateral carbon transport at diverse scales

The continental carbon budget is more complex than just the sum of photosynthesis, respiration, combustion, and anthropogenic fluxes. Key processes transport carbon away from ecosystems after fixation by photosynthesis. Carbon entrained in lateral transport can travel over long distances, but eventually becomes oxidized and is released back to the atmosphere as CO_2, thus closing the cycle initiated by photosynthesis. This is illustrated in Fig. 1. At the scale of the European continent, lateral carbon transport creates regional imbalances between CO_2 sources and sinks. Transport also occurs across the borders of the continent, which, in this case results in a net CO_2 sink into Europe, balanced by a source elsewhere. In inverse modelling studies, ignoring the patterns of CO_2 fluxes caused by lateral transport processes may bias the inferred fluxes. When comparing different approaches to quantifing regional carbon budgets using methods based either on stock changes or on CO_2 flux observations, lateral fluxes must be included. We show in Table 2 that the "correction" from CO_2 fluxes to carbon stocks changes over the European continent is of the same magnitude as the measured CO_2 fluxes. At the local level, due to the imbalance between respiration and photosynthesis, CO_2 fluxes created by carbon lateral transport can be very large, especially over croplands and managed forests. At the regional level, we found significant (and diverse) impacts of the trade of food and forest products on the regional distribution of CO_2 fluxes. Northern countries tend to be larger sinks and southern countries larger sources of CO_2, due to trade.

6.2 Lateral carbon fluxes at the continental level

At the continental level, food and forest product trade fluxes result only in a very small net source of CO_2 (+29.2 TgC yr^{-1}). This is because the 'gross' fluxes of import, equaling CO_2 sources, and those of export, equaling CO_2 sinks where the exported biomass is grown, are approximately in balance. We found that the gross flux of carbon released to the atmosphere in the form of reduced carbon (RCC) is large (+184 TgC yr^{-1}), equaling 10% of the annual fossil fuel CO_2 emissions. The impact of RCC on the net carbon balance of Europe is complex as a large fraction of these compounds becomes rapidly oxidized to produce CO_2 in the boundary layer, while another fraction is deposited at the surface. Overall, we estimated that the reduced carbon compounds cause a net carbon loss of −87 TgC yr^{-1}, but induce a net CO_2 sink of −50 TgC yr^{-1}. The difference in the sign again illustrates the fact that carbon budgets differ significantly from CO_2 budgets. Rivers transport carbon of atmospheric origin from ecosystems to the ocean. This process requires a matching terrestrial CO_2 sink of −176 TgC yr^{-1} by photosynthesis. This sink is large the compared to the carbon storage of European ecosystems (Janssens et al., 2003). The carbon transported by rivers is partly outgassed to the atmosphere in freshwater systems, partly buried in lakes, dam and estuarine sediments, while the rest is delivered to inner estuaries. At the level of estuaries, a significant flux of CO_2 is outgassed and returns to the atmosphere. Thus, the river transport of carbon implies the existence of a CO_2 sink over ecosystems, partly mirrored by a CO_2 source from freshwater aquatic surfaces and estuaries. The CO_2 flux emitted by the European river systems is of +90 TgC yr^{-1}, while the flux buried in riverine sediments is 33 TgC yr^{-1}. The flux exported to estuaries is of 53 TgC yr^{-1}, and the estuaries outgas CO_2 with a flux of 10–20 TgC yr^{-1}. In total, the "river carbon cycle" including inner estuaries act as a net sink of CO_2 in the range −33 to −43 TgC yr^{-1}.

6.3 Coastal seas and lateral carbon fluxes

We included coastal seas in the analysis, because they receive a "lateral" carbon flux from the continents. Because coarse resolution atmospheric inversions encompass the coastal seas in their estimate of the "European" CO_2 balance. The European coastal seas are net sinks for atmospheric CO_2, in the range of −100 TgC yr^{-1}. This sink is comparable in magnitude to the terrestrial carbon uptake by ecosystems (111±279 TgC yr^{-1} in Janssens et al., 2003). Coastal seas are a CO_2 sink despite the fact that they receive a flux of carbon from rivers of 53 TgC yr^{-1} (Table 3). This is because the fluxes exchanged with the adjacent open oceans are controlling the budget of coastal seas. The CO_2 fluxes of coastal seas are significantly different from those in the adjacent open ocean (from Takahashi et al., 2002). The latter is commonly used in atmospheric CO_2 inversion models, which likely will lead to a significant but yet not quantified bias in the flux estimated derived by these models. In particular, large biases are expected for terrestrial regions adjacent to extensive coastal seas, such as, e.g., the Gulf of Biscay and the North Sea.

7 Conclusions

In conclusion, the lateral carbon fluxes induced by crop and forest product trade, photo-oxidation of RCC, and river transport are significant contributors to the regional carbon budget of the European continent. This indicates that a substantial amount of carbon is displaced in proportion to the NPP (about 20% of the NPP of the European continent).

The contribution of these fluxes to the continental carbon balance is not negligible either. Taking the synthesis of Janssens et al. (2003) for the "normal" long-term carbon sink of the European continent, the RCC emissions, the outgassing of CO_2 by freshwater systems amounts to 1/3 of its value. Therefore, these component fluxes must be accounted for to accurately assess the European carbon balance, in particular to translate inversion based CO_2 fluxes into carbon budgets. They should also be accounted for in inversion studies, by prescribing a more realistic a priori flux structure which accounts for food and forest product trade, reduced carbon and freswater or estuarine CO_2emissions. In future work, one should also investigate how the lateral carbon fluxes will respond to changes in economic, land use drivers and to future climate change.

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Table 1. Component fluxes of non-CO_2 reduced carbon compounds (RCC) over the European continent, an area bounded by 32° N and 73° N in latitude and −10° W and 40° E in longitude. Sources to the atmosphere are counted as positive and sinks as negative. These numbers are estimated by a global chemistry transport model (see text).

Reduced carbon compounds emissions ($TgC\,yr^{-1}$)	
Methane	60.0
CO	82.0
BVOCs	27.0
Other VOCs	15.5
Total	184.5
CO_2 production from RCC oxidation over Europe ($TgC\,yr^{-1}$)	
Boundary layer	25.7
Free troposphere	19.3
Total	45.0
Carbon deposition over Europe ($TgC\,yr^{-1}$)	
Surface dry deposition	−12.0
Wet deposition	−9.6
Total carbon deposited	−21.6

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Table 2. Carbon fluxes and CO_2 fluxes caused by lateral transport processes. The European "continent" includes its atmospheric boundary layer and its inner estuaries. A quality index of each estimate is given in the right hand column.

All units are TgC yr^{-1}, (source >0, sink <0)	Estimated flux	Quality index
Crop and forest products trade		
Crop and forest product import & use	+110.3	+++
Crop and forest product export	−81.2	+++
Total CO_2 flux (a)	+29.1	+++
Total carbon flux (a)	+29.1	++
Non-CO_2 atmospheric reduced carbon compounds		
RCC total emissions=(1)	+184.5	++
RCC emissions of biogenic origin=(2)	+87	++
CO_2 flux produced in boundary layer from RCCs (3)	25.7	++
Carbon sink from wet and dry RCC deposition=(4)	−21.6	+
Total net CO_2 flux=(3)–(2) (b)	−61.3	+
Total net carbon flux=(1)+(4)–(2) (b)	+75.9	++
River carbon transport (c)		
CO_2 outgassing in river systems (4)	+90	++
Carbon burial in lakes,dams and estuarine sediments (5)	–33	++
Net export from rivers into estuaries (6)	−53	+++
CO_2 outgassing in estuaries	+10 to +20	+
Total CO_2 flux from rivers (d)	110 to 123	
Coastal seas		
Total CO_2 flux from coastal seas	−68	++
Total from all processes		
Total net CO_2 flux	−141.8	+
Total net carbon flux	−48.8	+

1. Assumes that the consumption of crop and forest products generates 100% of CO_2 which is emitted to the atmosphere.
2. Assumes that 100% of the biogenic emissions of reduced compounds (e.g. terpenes, methanol, methane...) are formed by plant carbon derived from photosynthesis, causing a sink of CO_2.
3. The sum of (4)+(5)+(6) is assumed to be balanced by an uptake of CO_2 by photosynthesis over European ecosystems.
4. Established for an area of 8.16 Mkm^2, including the Barentz sea and Black Sea river catchments.

Table 3. Fluxes and origin of river carbon reaching the continental shelf after estuarine filters. Irrigation is not taken into account.

	Drainage area 103 km^2	Water flow $km^3\,yr^{-1}$	River carbon $TgC\,yr^{-1}$	Carbon yield $gCm^{-2}\,yr^{-1}$	% DOC	% POC	% DIC [(a)]
Northern Europe	2528	806	13.6	5.4	54.3	4.4	41.1
Temperate Europe	4699	1188	24.5	5.2	23.3	9.0	67.6
Southern Europe	936	360	10.2	10.8	9.2	11.5	79.2
Total Europe	8163	2355	48.3	5.9	29.1	8.3	62.6

[(a)] percent of total carbon of atmospheric origin

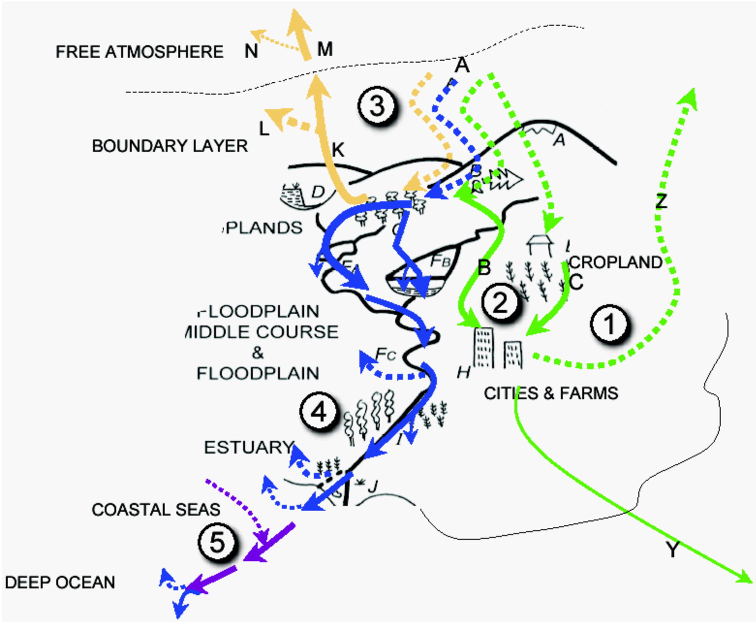

Fig. 1. Carbon cycle loops involving lateral transport. The associated sources/sinks of atmospheric CO_2 are represented by dotted lines, and horizontal fluxes of carbon in solid lines. Green. Loop 1=Cycle associated to photosynthesis (A), harvest of wood and crop products, transport by domestic (B, C) and international (Y) trade circuits, and human consumption (Z) release of CO_2. Loop 2=same, but for forest products (2). Light brown. Loop 3=Cycle associated to photosynthesis (A), RCC emissions and atmospheric transport in the boundary layer (K) and in the free atmosphere (M), with oxidation to CO_2 in the boundary layer (L) or in the free atmosphere (N). Blue. Loop 4=Cycle of carbon of atmospheric origin (A) transported under the form of DIC, DOC, POC by river systems from river uplands to inner estuaries, includes outgassing of CO_2 by freshfwaters (F_C) and carbon storage in reservoirs (F_B). Purple. Loop 5=Fluxes of carbon and CO_2 source/sink from coastal seas.

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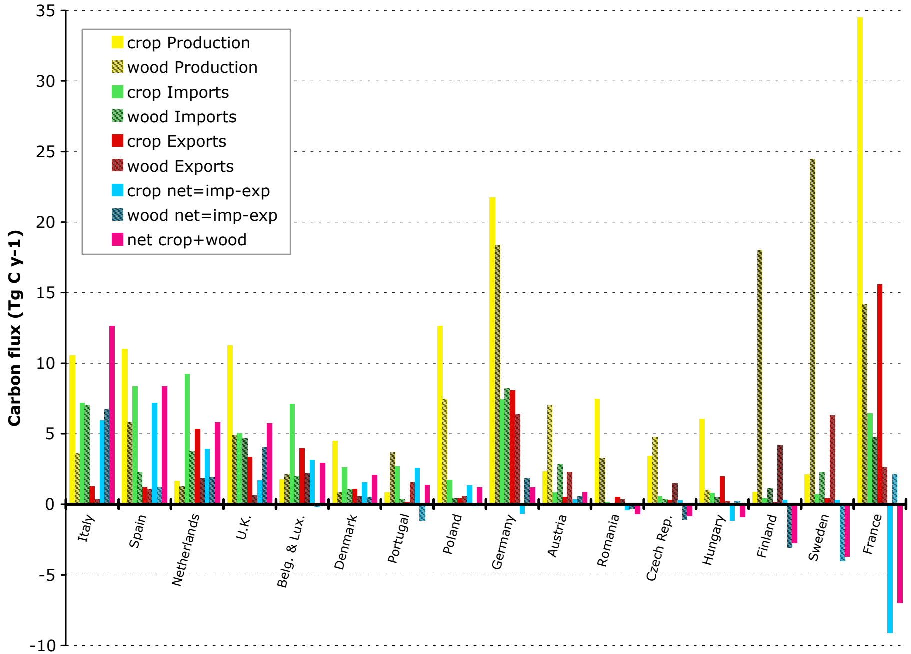

Fig. 2. Component carbon budget of crop and forest products trade for various countries. Yellow=production (harvest), implying a CO_2 uptake to form crop and wood biomass. Green=imported flux from non EU countries, oxidized into CO_2 within Europe, equaling a net CO_2 source. Red=exported flux, yielding a net CO_2 sink. Magenta=net balance resulting of import and export. Hatched bars are for forest products and plain colors are for crop products.

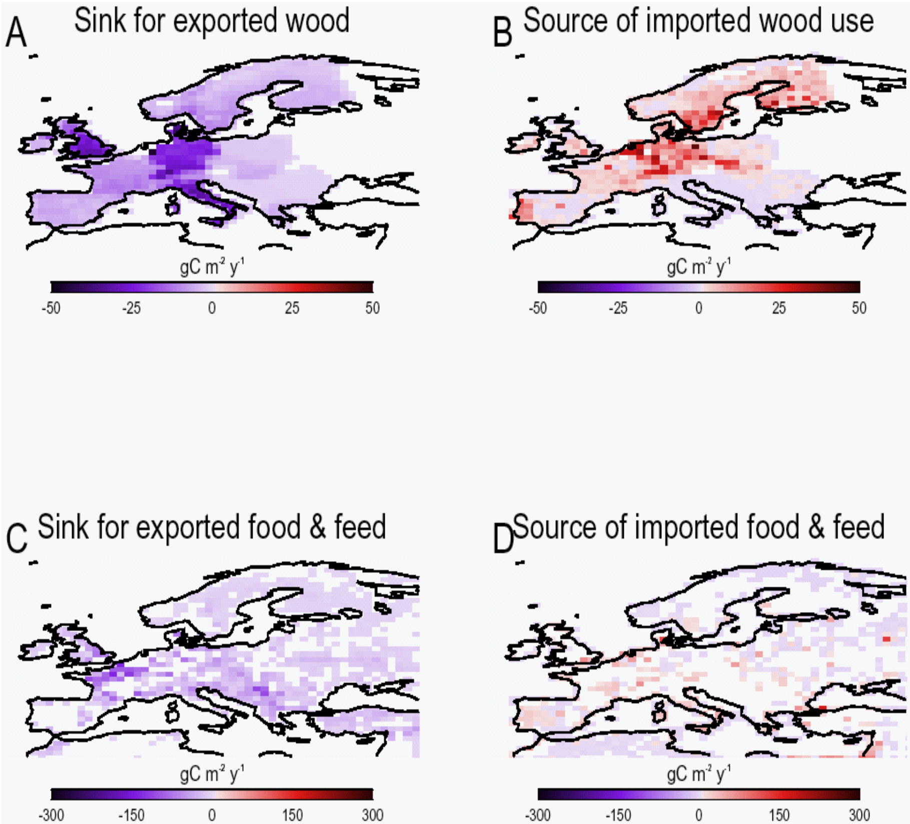

Fig. 3. Spatial patterns of trade induced CO_2 fluxes with the atmosphere. Sources of CO_2 are positive and sinks negative (in $gC\,m^{-2}\,y^{-1}$). **(a–b)** CO_2 fluxes associated to wood products export and import, respectively **(c–d)** Same for food and feed products.

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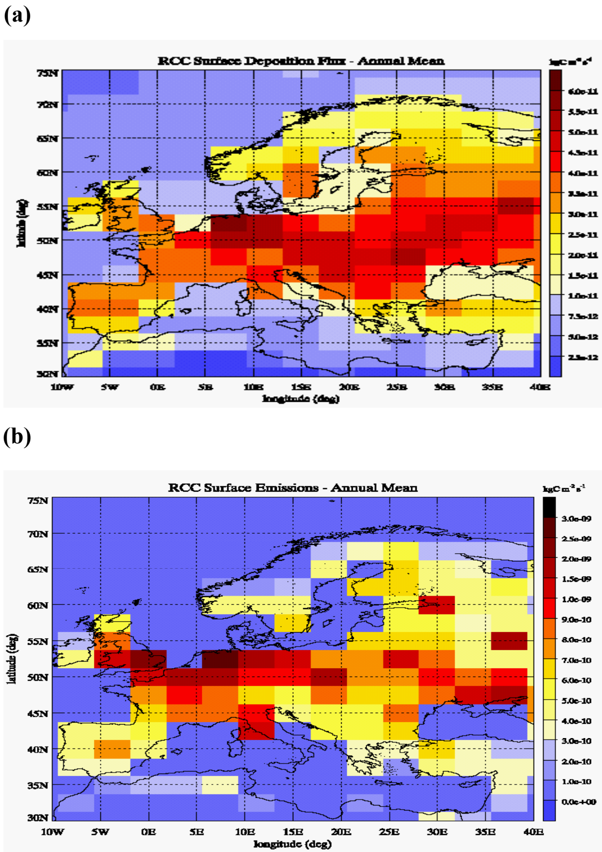
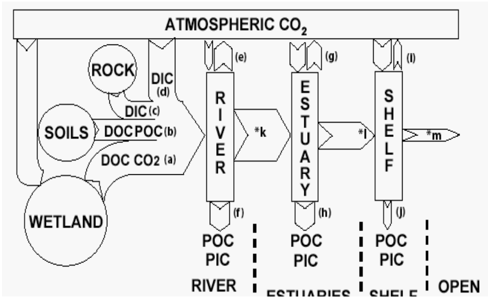


Fig. 4. **(a)** Spatial patterns of the surface deposition (sink) of carbon from reduced carbon compounds (RCC). **(b)** Patterns of reduced carbon coumpounds emissions to the atmosphere from antropogenic and biospheric sources.

(a)



(b)

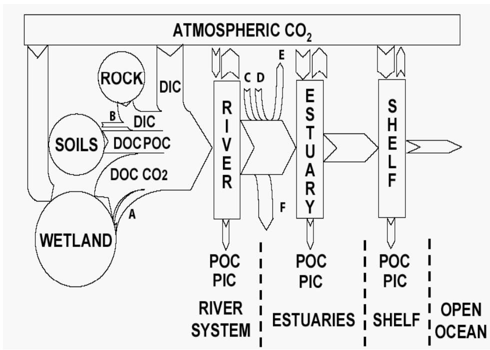


Fig. 5. Transport of river carbon along the aquatic continuum. **(a)** Under natural conditions. **(b)** With multiple human impacts. See text for indications.

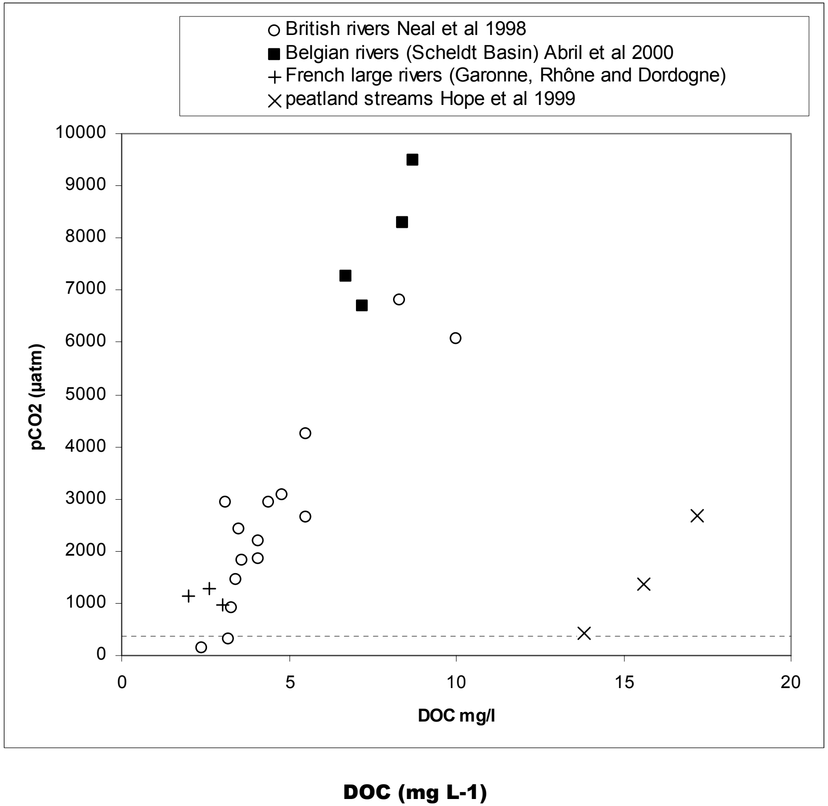


Fig. 6. Relationship between pCO_2 and DOC in selected European river systems. British lowland rivers from Neal et al. (1998); Belgian lowland rivers (Scheldt watershed) from Abril et al., 2000; Large French rivers from Abril and Commarieu (G. Abril, personnal communication) (Garonne and Dordogne), and from Aucour et al. (1999) and Sempéré et al. (2000) (Rhône); Scottish Upland peat streams from Hope et al. (2001).

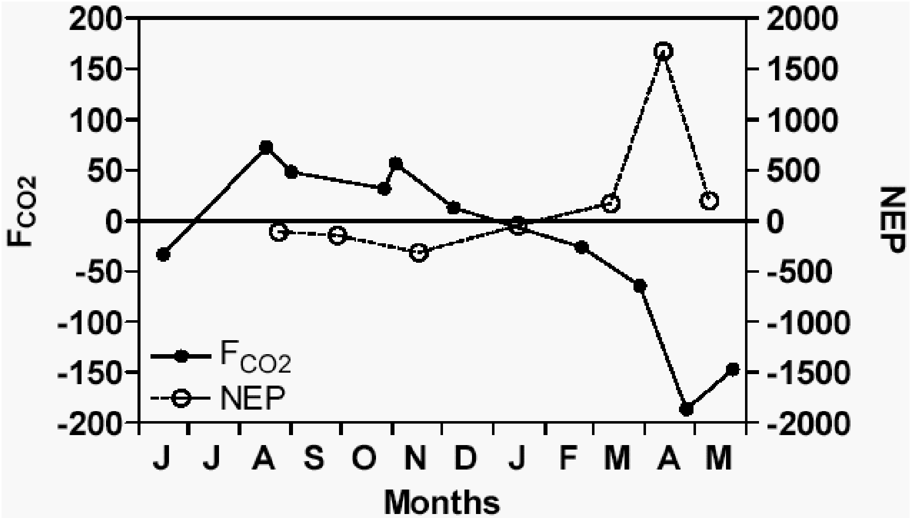


Fig. 7. Annual cycle (June 2003–May 2004) of net ecosystem production (NEP in mgC m-2 d-1), air-sea CO2 fluxes (FCO2 in mgC m-2 d-1) and the partial pressure of CO2 (pCO2) in the Southern Bight of the North Sea (adapted from Schiettecatte et al., 2006[4]).

[4]Schiettecatte, L.-S., Thomas, H., Bozec, Y., and Borges, A. V.: High temporal coverage of carbon dioxide measurements in the Southern Bight of the North Sea, Marine Chemistry, submitted, 2006.

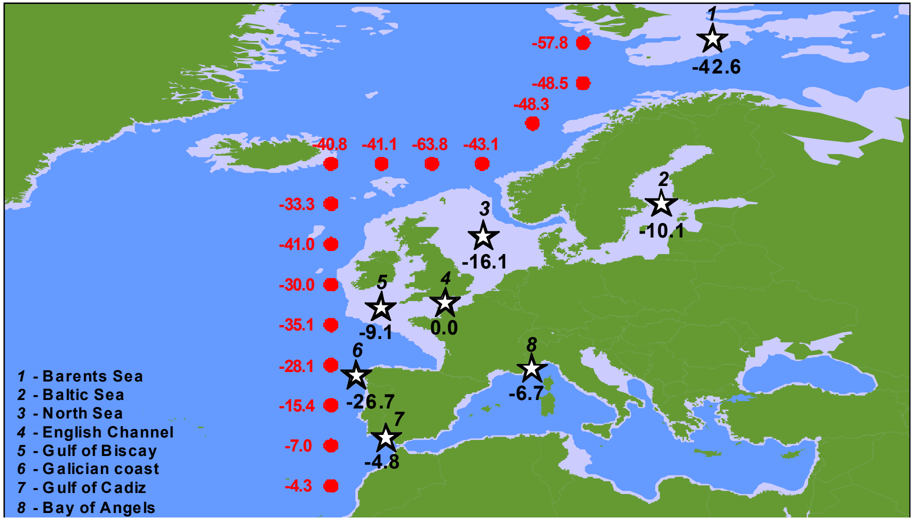


Fig. 8. Compilation of annually integrated air-sea CO_2 ($gC\,m^{-2}\,yr^{-1}$) fluxes in European coastal seas (stars and black numbers) (adapted from Borges et al., 2006[2]) and adjacent open ocean grid nodes from the Takahashi et al. (2002) air-sea flux climatology (red circles and numbers).