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The impact of lateral carbon fluxes on the European carbon balance

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Abstract. To date, little is known about the impact of processes which cause lateral carbon fluxes over continents, and from continents to oceans on the CO_2 – and carbon budgets at local, regional and continental scales. Lateral carbon fluxes contribute to regional carbon budgets as follows: Ecosystem CO_2 sink=Ecosystem carbon accumulation+Lateral carbon fluxes. We estimated the contribution of wood and food product trade, of emission and oxidation of reduced carbon species, and of river erosion and transport as lateral carbon fluxes to the carbon balance of Europe (EU-25). The analysis is completed by new estimates of the carbon fluxes of coastal seas. We estimated that lateral transport (all processes combined) is a flux of 165 Tg C yr^{-1} at the scale of EU-25. The magnitude of lateral transport is thus comparable to current estimates of carbon accumulation in European forests. The main process contributing to the total lateral flux out of Europe is the flux of reduced carbon compounds, corresponding to the sum of non-CO_2 gaseous species (CH_4, CO, hydrocarbons, …) emitted by ecosystems and exported out of the European boundary layer by the large scale atmospheric circulation.

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Lateral carbon transport moves carbon away from where CO_2 is withdrawn from the atmosphere.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).

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Lateral carbon transport contributes to the carbon budget of ecosystems as follows:

$$\text{Ecosystem } CO_2 \text{ sink=Ecosystem carbon accumulation} + \text{Lateral carbon flux.}$$

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), one may expect differences explained by lateral carbon transport. Some bottom-up approaches (e.g. 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 one is to describe the mechanisms of lateral carbon transport and some of their implications for regional carbon budgets. The second goal is to quantify the flux of carbon displaced within and from the European territory (here the EU-25), and to place it in the context of atmospheric inversion results. The third goal is to provide geospatial estimates of the CO_2 fluxes associated with lateral processes, whenever this is possible.

We consider three processes linking CO_2 fluxes with lateral carbon transport either within the EU-25 area or across its boundaries. These processes are (1) the trade of food, feed and wood products (Ciais, et al., 2006; Imhoff, et al., 2004), (2) the emissions of reduced atmospheric carbon compounds such as CO, CH_4, terpenes, and isoprene by ecosystems and human activities, which get transported by winds and oxidized by chemical reactions in the global atmosphere outside Europe (Enting et al., 1991; Folberth et al., 2005; Suntharalingam et al., 2005), and (3) the river transport of carbon from land to the ocean (Aumont et al., 2001; Meybeck 1987). In addition, CO_2 fluxes in coastal seas (Borges et al., 2006) are estimated. This exchange of atmospheric CO_2 by coastal

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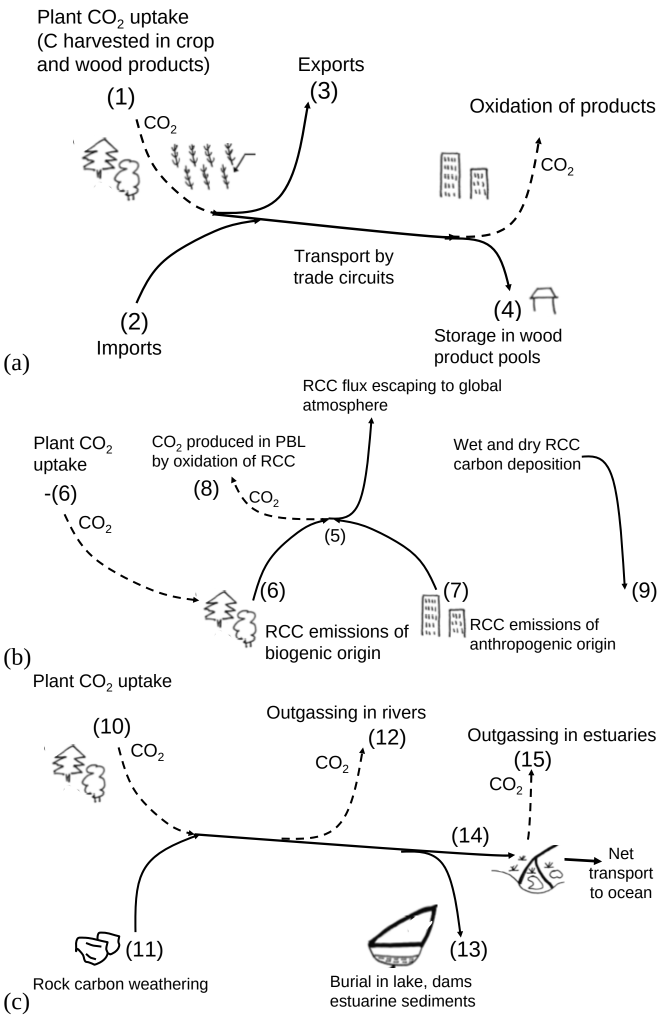

Fig. 1. Carbon cycle loops involving lateral transport. Numbers associated to each flux correspond to data in Table 2. The associated sources/sinks of atmospheric CO_2 are given by dashed lines, and the fluxes of carbon are given by solid lines. **(a)** Lateral transport by trade of crop and wood products. **(b)** Lateral transport by reduced carbon compounds (RCC) emissions and atmospheric chemistry and transport. **(c)** Lateral transport by river transport coupled to rock weathering.

seas does not *per se* originate from a lateral carbon flux, but it is considered here as a necessary flux component to reconcile large-scale CO_2 flux atmospheric inversion results with bottom-up inventory data. The first four sections below treat each lateral transport process separately. The discussion section summarizes the contribution of the different processes to the carbon balance of Europe. By convention, all fluxes of carbon gained by the continent are sinks for the atmosphere and counted negatively, while carbon lost by the continent is counted as a positive flux.

2 Crop and forest products trade

2.1 Food and feed products

Cultivated lands are long-term net sinks of atmospheric CO_2 because carbon incorporated into biomass is harvested and removed from ecosystems to supply human or animal consumption (Fig. 1a). The consumption of food or feed products releases CO_2 back to the atmosphere, away from ecosystems. Over the globe, the lateral transport of carbon in food products is neutral for the atmosphere, given the fact that storage of food products is negligible compared to harvested fluxes. At the regional scale, croplands are net CO_2 sinks (as confirmed by year-round eddy-covariance measurements, e.g. Anthoni et al., 2004) while populated areas where food is consumed are net CO_2 sources. At the continental level, international trade of crop products also intervenes into the net carbon balance.

We analyzed the agricultural statistics from FAO (2004) to infer harvest, lateral carbon transport and subsequent CO_2 land-atmosphere fluxes caused by food trading. We found that cereals, essentially maize, wheat and barley, are responsible for nearly all of the CO_2 sink in European croplands. In contrast, the CO_2 source derived from food consumption originates from a more diverse mix of crop products. From the perspective of individual countries, the situation is contrasted (Fig. 2). The largest CO_2 sink associated with the trade of crop carbon is France (–9 Tg C yr^{-1}), about 90% of the total European sink for that process. The largest CO_2 sources are Portugal, Belgium, Netherlands, Italy and Spain (altogether 22 Tg C yr^{-1}). Other countries are approximately neutral. We found no relationship between harvest and the net carbon balance in each country with regards to food trade. At the continental level, Europe imports more carbon in food and feed than it exports, thus being a net CO_2 source to the atmosphere of 24 Tg C yr^{-1}, about 2% of EU-25 fossil fuel CO_2 emissions.

The patterns of CO_2 fluxes induced by trade is mapped using geospatial information on (1) crop varieties (Ramankutty et al., 1998), (2) human population and, (3) housed poultry, pigs and cattle populations. Statistical data on feedstuff and food product harvest and trade (FAO, 2004) is converted to a geospatial dataset on a 1° by 1° grid, using the same methodology as in Ciais et al. (2006). Crop biomass data are converted into dry biomass and into carbon using crop-specific conversion factors (Goudriaan et al., 2001). The results are shown in Fig. 3. Agricultural plains with intensive cultivation (northern France, southern England, Hungarian plains, Po valley in Italy) are annual net sinks of CO_2, with uptake rates reaching up to 100 g C m^{-2} yr^{-1}. Locally, this CO_2 sink is larger than the mean European forest uptake flux (70 g C m^{-2} yr^{-1} in Janssens et al., 2003), which is not surprising given the slightly higher NPP and harvest index (ratio of yield to above-ground NPP) of crops compared to trees.

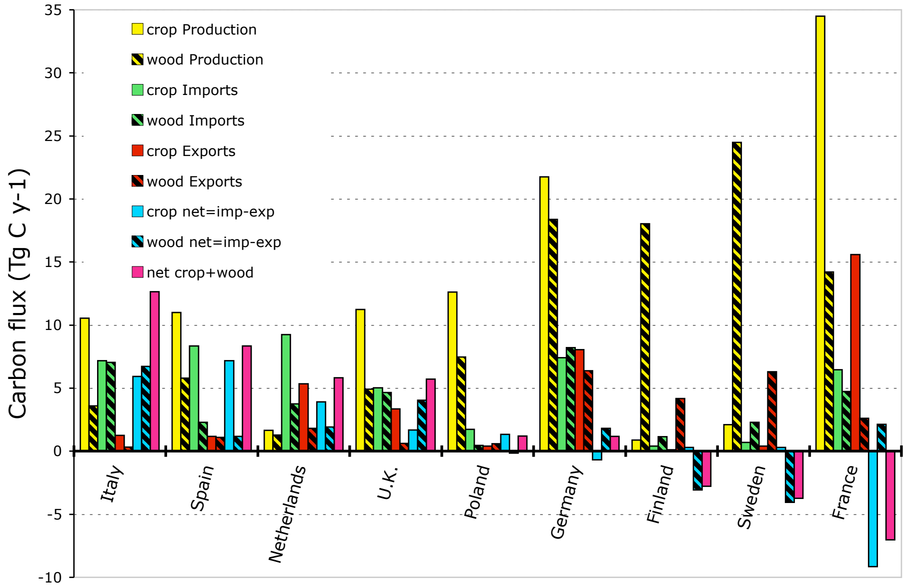

Fig. 2. Carbon fluxes associated with harvest and trade in various countries. Production (=harvest) requires plant CO_2 uptake to form biomass. Imported products are oxidized into CO_2, making a net CO_2 source in the importing country. Exported products require plant CO_2 uptake to form crop and wood biomass (included in production), making a CO_2 sink in the exporting country. The net flux is the balance between CO_2 sources and sinks (see Fig. 1a). convention, sources of CO_2 to the atmosphere are positive. By convention, sources of CO_2 to the atmosphere are positive.

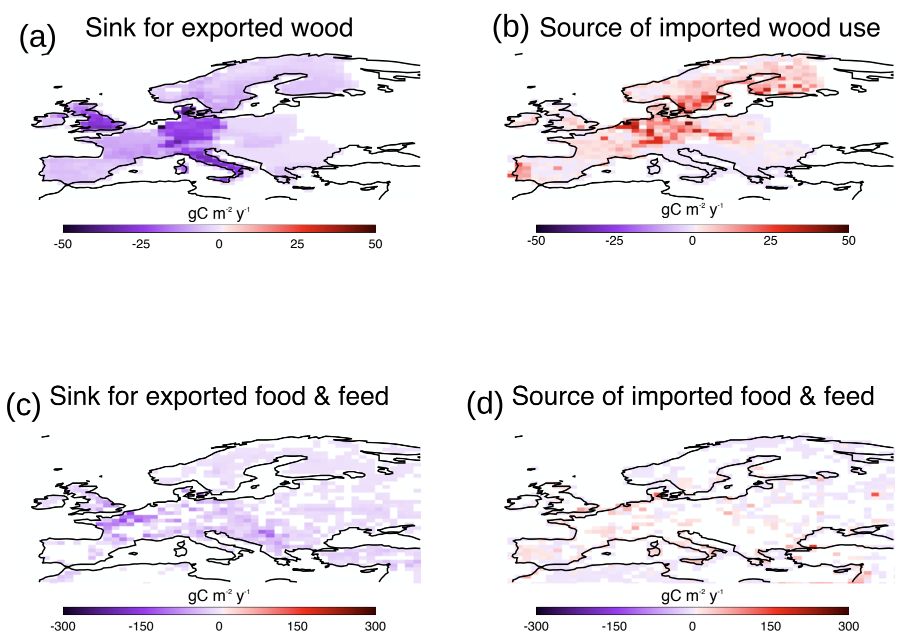

Fig. 3. Spatial patterns of trade induced CO_2 fluxes with the atmosphere. Sources of CO_2 are positive and sinks are negative (in g C m^{-2} y^{-1}). **(a–b)** CO_2 fluxes associated with wood products export and import. **(c–d)** CO_2 fluxes associated with food and feed products export and import.

Table 1. Component fluxes of the cycle of non-CO_2 reduced carbon compounds (RCC) over the European continent and its boundary layer, 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 >0 and sinks <0. Fluxes are estimated using a global chemistry transport model. Units are Tg C yr^{-1}.

RCC Reduced carbon compounds emissions	Tg C yr^{-1}
CH_4 emissions	60.0
CO emissions	82.0
BVOC emissions	27.0
Other VOC emissions	15.5
Total	184.5
CO_2 flux produced in PBL from RCC oxidation	
Boundary layer	25.7
Free troposphere	19.3
Total	45.0
Wet and dry RCC carbon deposition over Europe	
Surface dry deposition	–12.0
Wet deposition	–9.6
Total carbon deposited	–21.6

Urban regions in Fig. 3, and intensive farming regions, emit CO_2 to the atmosphere at a rate of 50 g C m^{-2} yr^{-1}.

There are uncertainties on these maps. Using statistics at the country level may smooth out the fields. For instance, feedstuff consumption by farm animals is distributed at the country level according to animal population maps, while in reality animals may have different regional reliance on feedstuff. National harvest of crop biomass is distributed evenly according to the area of each crop variety, neglecting regional differences in yields caused by soil fertility or climate gradients. Finally, food consumption is assumed to be a CO_2 source distributed according to human population, thereby neglecting the transport of organic carbon to sewage water and rivers.

2.2 Forest products

We consider forest products from coniferous and non-coniferous trees: industrial round wood, sawn wood, wood panels and paper, as listed in the FAO (2004) database. Wood product data in volumetric units are converted to carbon weight units using a mean wood density of 500 kg m-3, and a 0.45 carbon fraction in dry biomass, respectively. Sweden and Finland export more carbon in wood than they import, thus being net sinks of atmospheric CO_2 of –3 Tg C yr^{-1} and –4 Tg C yr^{-1} respectively (Fig. 2). Nearly all other countries are net CO_2 sources to the atmosphere with respect to wood products trade. The largest sources are in Italy (6 Tg C yr^{-1}), Spain, the Netherlands and the UK. Countries that export food products typically also export wood products (except for Nordic countries) and vice versa. At the EU-25 level, imports of wood products currentlysions exceed exports, inducing a net source of CO_2 of up to 7 Tg C yr^{-1}. This value is likely to be a maximum estimate because it assumes that wood products are decomposed into CO_2 instantly, neglecting storage. Using the mean residence times of wood products of Liski et al. (2005), typically 30 years for spruce wood and 40 years for oak sawn wood, we estimate that on a 10 years horizon, the trade of wood products results in a net source of CO_2 to the atmosphere of 2 Tg C yr^{-1} only, while the remaining 5 Tg C yr^{-1} is temporarily stored in product pools.

To map the CO_2 fluxes from forest product trade, we converted the country-level data (FAO, 2004) into a geospatial dataset on a $1^\circ \times 1^\circ$ grid using a remote-sensing driven NPP model (Lafont, et al., 2002) and a forest cover map of Europe (CORINE Land cover, 2000). The geographical distribution of the CO_2 source due to the decay of wood products is assumed to follow population density (i.e. assuming that landfills are distributed like population density). The results are shown in Fig. 3.

There are large uncertainties in these maps. First, forests with high greenness (NDVI) wil not necessarily have the largest biomass, nor wood production. For instance, the NDVI vegetation index is well known to saturate at high Leaf Area Index values, although Myneni et al. (2001) showed a positive correlation between NDVI and biomass over a wide range of forests. 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 anthropogenic activities emit non-CO_2 reduced carbon compounds, hereafter called RCC. RCC are the sum of CO, CH_4, biogenic volatile organic compounds (BVOC such as isoprene, terpene), and anthropogenic volatile organic compounds (VOC). These species are reactive and their atmospheric lifetimes vary over several orders of magnitude, from 9 years for methane, down to a mere few hours in the case of terpene. Although the oxidation sequence of an 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, become significant compared to the net carbon balance of an ecosystem (Kesselmeier et al., 2005). If the objective of a study is to determine the *CO_2 flux of Europe* by inverse modeling of CO_2 concentration, then RCC emissions can rightfully be ignored. On the other hand, if the objective is to determine the *carbon flux of Europe*, the RCC flux must then be added as a correction to the CO_2 flux calculated by inversions.

3.2 CO_2 production in the atmosphere

The lifetime of atmospheric RCC compounds with respect to their chemical sink in the atmosphere can easily exceed typical boundary-layer transport time scales. The carbon carried by RCC can thus be released as CO_2 away from surface emissions (Fig. 1b). Table 1 shows that the total EU-25 emissions of RCC are 185 Tg Cyr^{-1}. A small fraction of these emissions (14%) is transformed into CO_2 in the boundary layer, very shortly after emission (Fig. 1b and Table 1). We estimated the CO_2 production from RCC using a global 3-D chemistry transport model (Folberth, et al., 2005, Hauglustaine et al., 2004). This 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 Volatile Organic Compounds (VOC), and (2) the direct oxidation of peroxy-radicals carbon into CO_2. An additional minor channel corresponds to the direct ozonolysis of alkenoid compounds into CO_2 and is also taken into account. The total 'photochemical' CO_2 production from RCC in the atmospheric column over Europe amounts to 45 Tg C $yr^{-1}$and 57% of this flux (26 Tg C yr^{-1}) occurs in the boundary layer, as reported in Table 1. About 90% of the photochemical CO_2 production comes from CO oxidation by hydroxyl radicals (OH). A map of RCC deposition and emission is given in Fig. 4.

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

A gain of carbon by the European surface occurs via the dry surface deposition processes and the wet scavenging by precipitation (Fig. 1b). This sink amounts to 22 Tg C yr^{-1} (Table 1). The net effect of RCC on the *European carbon flux* can be estimated by taking the difference between surface emissions (carbon source) and the photosynthetic uptake of CO_2 from which the biogenic VOC emissions are derived (carbon sink) plus the dry and wet RCC deposition flux (carbon sink) must be derived (Fig. 1b). We estimate a net carbon loss to the atmosphere of 76 Tg C yr^{-1} (Table 2). The impact of RCC compounds on the *European CO_2 flux* is different. It is the difference between the photochemical flux of CO_2 into the boundary layer (oxidation of RCC) and the CO_2 uptake photosynthesis which fuels the biogenic RCC emissions. We note a corresponding net CO_2 sink of 61 Tg C yr^{-1} (Table 2).

4 Riverine carbon transport

4.1 Processes controlling the transport of atmospheric carbon by rivers

Rivers (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. 1c). Rivers transport carbon in dissolved and particulate organic forms (DOC, POC) and under inorganic forms (DIC, PIC and dissolved CO_2). The source and sink processes of river carbon in natural conditions are: (1) wetlands and peat drainage, (2) soil leaching and erosion, and (3) chemical weathering of soil minerals. This carbon is originally taken up from the atmosphere by photosynthesis (CO_2+H_2O–>CH_2O+O_2), or by direct carbonate rock weathering ($CO_2+H_2O+MCO_3 \rightarrow 2HCO_3^- + M^{2+}$) or 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, but 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 inorganic 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. This relocation of PIC does not generally affect the CO_2 cycle. Also, under specific arid conditions and high pH, some DIC may precipitate on its way to the sea as calcite in soils and sediments.

Factors controlling river export of atmospheric carbon (DOC+POC+atmospheric derived DIC) are first river runoff, then rock type via the occurrence of carbonates, and finally the presence of wetlands and large lakes. A preliminary comparison of river carbon fluxes in northern, central and southern Europe shows strong regional contrasts. Northern catchments show high DOC export, but most POC is trapped in lakes which cover 5–20% of these basins (Meybeck et al., 2005). The age of this DOC derived from wetlands and peat bogs typically ranges from 100 to 6000 years. Southern catchments show DIC derived from the atmosphere 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 river carbon transport

Human intervention in river catchments may substantially modify river carbon transport (Fig. 5b). The exploitation of peat bogs generally increases DOC contents in head waters (Fig. 5a–b). Increased soil erosion by agricultural practices increases the POC inputs. Untreated organic waste water (Fig. 5b–c) and eutrophication of rivers and lakes (Fig. 5b,

Table 2. Carbon fluxes and CO_2 fluxes caused by lateral transport processes. The European "continent" is defined as including its atmospheric boundary layer and its inner estuaries. A flux lost by the European continent is counted >0, and a carbon gain is counted <0. An uncertainty index of each estimate is given in the right hand column (low uncertainty +++, high uncertainty +). The numbers in parenthesis associated to each flux correspond to those shown in Fig. 1. By convention, sources for atmosphere are shown as positive values whereas sinks are shown as negative values.

Estimated flux (Tg C yr^{-1})		Quality index
Crop and forest products trade		
Ecosystem CO_2 sink located in crop+wood product (1)	–250	+++
Imports of crop + wood products (2)[a]	110	+++
Export of crop + wood products (3)[b]	–81	+++
Storage in wood products (4)	5	+
Net CO_2 release by oxidation of products=–(2)+(1)+(3)–(4)[c]	274	++
Total net CO_2 flux of river transport	24	++
Total net carbon flux of river transport	24	++
Atmospheric reduced carbon compounds		
RCC total emissions (5)	185	++
RCC emissions of biogenic origin (6)[d]	87	++
RCC emissions of anthropogenic origin (7)	98	++
CO_2 flux produced in PBL from RCC oxidation (8)	26	++
RCC flux escaping to the global atmosphere=(5)–(8)	159	++
Wet and dry RCC carbon deposition=(9)	–22	+
Ecosystem CO_2 sink required to compensate for (6)[d]	–87	+
Total net CO_2 flux of river transport	–61	+
Total net carbon flux of river transport[d]	76	+
River carbon transport		
Ecosystem CO_2 sink which is transported by rivers (10)	–160	+
Rock C weathering which is transported by rivers (11)	–16	+
CO_2 outgassing in rivers (12)	90	++
Carbon burial in lakes, dams, estuarine sediments (13)	–33	++
Net transport to estuaries (14)[f]	53	+++
CO_2 outgassing in estuaries (15)	10 to 20	+
Total CO_2 outgassing=(12)+(15)[e]	100 to 110	
Net carbon transport to ocean=(14)–(15)[f]	43 to 33	
Total net CO_2 flux of river transport	–60 to –50	
Total net carbon flux of river transport	–113	
Coastal seas		
Uptake of atmospheric CO_2 by coastal seas	–68	++
Grand total including coastal seas		
Net European CO_2 flux	–165 to –155	+
Net European carbon flux	–81	+

[a] Imported carbon corresponds to a plant uptake of CO_2 outside Europe, thus not being included in (1)
[b] Exported carbon corresponds to a plant uptake of CO_2 inside Europe, thus being included in (1)
[c] Assumes that the decomposition of crop and wood products generates CO_2 which is emitted to the atmosphere
[d] Assumes that 100% of biogenic RCC emissions comprising terpenes, methanol, methane, are formed by plant carbon derived from photosynthesis, causing a compensating sink of CO_2.
[e] Established for an area of 8.16 Mkm^2, including the Barentz sea and Black Sea river catchments.
[f] Although this carbon is not lost by the continent to the atmosphere as CO_2, but lost to estuaries in the case of (14) and to coastal oceans in the case of (14)–(15), it is counted as source (>0) in the table.

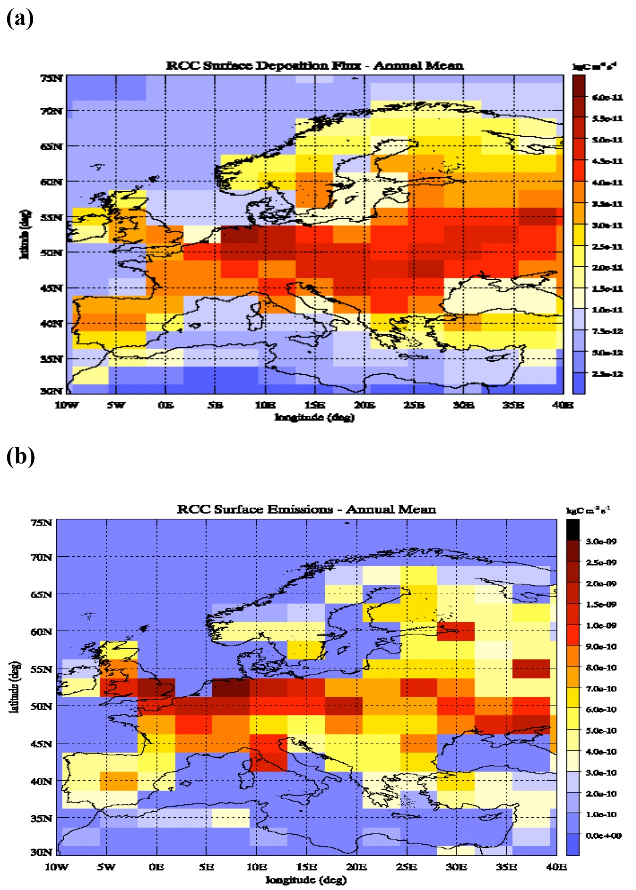

Fig. 4. (a) Spatial patterns of the surface deposition (sink) of carbon from reduced carbon compounds (RCC). **(b)** Patterns of reduced carbon compounds emissions to the atmosphere from antropogenic and biospheric sources.

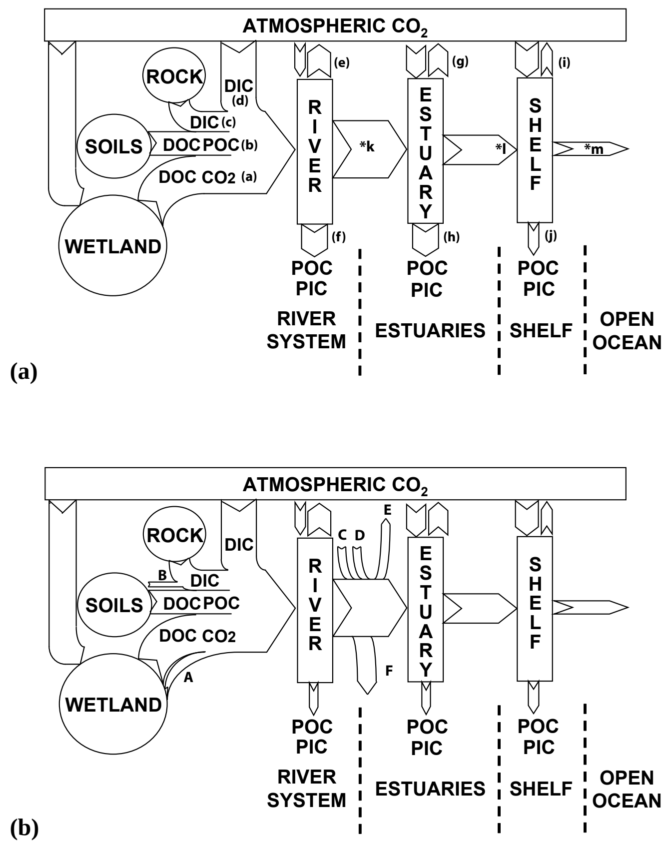

Fig. 5. Transport of river carbon along the aquatic continuum. **(a)** Under natural conditions. **(b)** With multiple human impacts. See text for indications.

d) are additional sources of very labile DOC and POC. The ages of these carbon species are highly variable (a few days for river algal carbon to 1000 years for peat DOC). The CO_2 evasion from freshwaters strongly depends on the reactivity of the organic carbon carried by rivers. During the 1970's, when rivers were receiving untreated waste water, river respiration R exceeded river production P(Gross primary production), resulting in eutrophication and in a net CO_2 source to the atmosphere (Kempe, 1984). Nowadays, due to waste water treatment, the same river may have multiple changes of P/R ratio from headwaters to estuary, as observed for the Scheldt and Seine rivers (Meybeck et al., 2005).

As 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, the export of riverine carbon to the ocean has decreased in most rivers (e.g. by 40% for the Ebro). 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 gaging and water quality stations are located upstream of the major irrigation areas (e.g. deltas of Ebro, Rhone, Axios) as noted by Ludwig et al. (2004).

4.3 CO_2 fluxes from rivers and freshwater systems

In the EU-25, 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 generally 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 correspond to either to CO_2 derived from soil respiration, followed by runoff and riparian transport, or to CO_2 derived from 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)

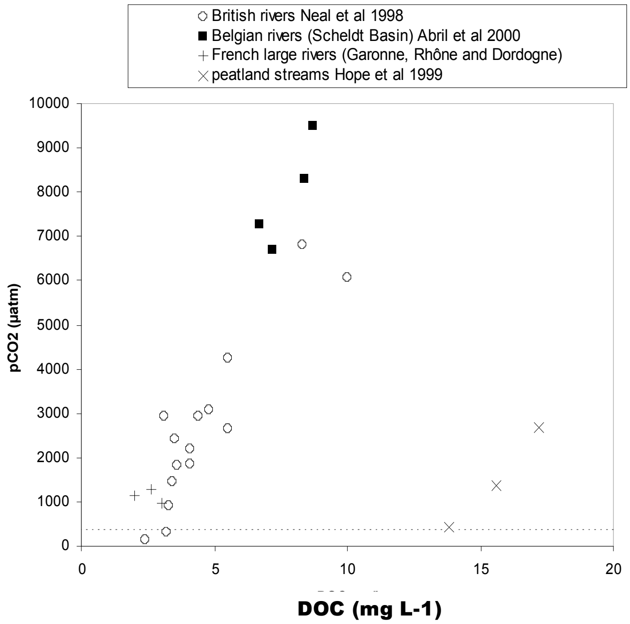

Fig. 6. Relationship between pCO_2 and DOC in selected European river systems. British lowland rivers from Neal et al., 1998, Belgian lowland rivers (Scheldt watershed) from Abril et al., 2000, Large French rivers from Abril and Commarieu (Unpublished) (Garonne and Dordogne), and from Aucour et al.,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

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, northern headwaters (e.g. Scottish peatlands) show low pCO_2 values and very high DOC content. This is due to the more recalcitrant nature of DOC leached 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 EU-25 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 ($8.16\ 10^6$ km^2) and the EU-25 on the basis of runoff, land cover and rock types similarities. Estuarine filters are included in this calculation (Abril and Meybeck, in preparation). Southern, central and northern European rivers show marked diversity in export rates and carbon species (Table 3). Table 2 compares the order of magnitude of the lateral carbon transport in rivers with the outgassed CO_2 flux. Fluxes of CO_2 from freshwater sub-ecosystems in peatland streams, lakes, rivers, and estuaries are compiled from published pCO_2 distributions, using typical gas transfer velocities and information on surface areas of sub-ecosystems (Abril and Meybeck, in preparation). Because river transport is based on non-tidal river sampling and is calculated for the entrance of estuaries (Table 3), CO_2 degassing in freshwaters and in estuaries are distinguished in Table 2. Overall, European rivers transport laterally 53 Tg C yr^{-1} to estuaries, and they emit 90 Tg C yr^{-1} of CO_2 to the atmosphere (Table 2). A majority of the degassing occurs at northern latitudes. Despite their lower CO_2 flux density, lakes contribute up to 35% of the total CO_2 freshwater degassing (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 Tg C 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., (112×10^3 km^2) was much higher than recent estimates (36×10^3 km^2) from the Global Lakes and Wetlands Database of Lehner and Döll (2004), and (2) the investigated estuaries were mainly macrotidal, wherein net heterotrophy and CO_2 degassing were favored (Abril and Borges 2004; Borges et al., 2006). Little or no CO_2 data are available for fjords, fjärds, deltas and coastal lagoons. Scaling up the available CO_2 flux estimates to the surface area of coastal wetlands and estuaries from Global Lakes and Wetlands Database gives a CO_2 source estimate of 10–20 Tg C yr^{-1}. This value is similar to the estimate of organic carbon transported by European rivers up to the estuarine filter of 20 Tg C yr^{-1}(Table 3).

Table 3. Fluxes and origin of river carbon fluxes reaching the continental shelf after estuarine filters. Irrigation is not taken into account. By convention a negative sign is given to fluxes representing C initially withdrawn from the atmosphere by plant CO_2 uptake.

	Drainage area (10^3 km^2)	Water flow (km^3 yr^{-1})	River carbon (Tg C yr^{-1})	Carbon yield (g C m^{-2} yr^{-1})	DOC (%)	POC (%)	DIC[a] (%)
Northern Europe (>50° N)	2528	806	–13.6	–5.4	54.3	4.4	41.1
Temperate Europe (42–50° N)	4699	1188	–24.5	–5.2	23.3	9.0	67.6
Southern Europe (<42° N)	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 in DIC of atmospheric origin.

5 Coastal seas

Coastal seas receive nutrient and organic matter inputs from estuaries, and exchange water and matter with the open ocean waters 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, 2008). Carbon in coastal waters also depends on the carbon content, which strongly decrease between estuaries and the open ocean. Nevertheless, the inputs of carbon from the open ocean to the coastal seas are significant because of the much higher water fluxes involved. In the North Sea, the inputs of DOC and DIC through the northern boundary of the North Atlantic Ocean are, respectively, 45 and 140 times higher than 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, respectively, 3 and 13 times higher than the inputs from estuaries (Thomas et al., 2005).

Unlike macrotidal estuaries which emit CO_2 to the atmosphere throughout the year (see Sect. 4.4), 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, on an annual basis it is a net sink of atmospheric CO_2 due to the seasonal decoupling of organic 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 $CaCO_3$ precipitation/dissolution, decoupling of carbon production and degradation within the water column in presence of stratification, temperature and salinity changes, Revelle factor, exchange of water with adjacent aquatic systems, water residence times (Borges et al., 2005, 2006). Figure 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 (Borges et al., 2005, 2006). In general, we estimate that the European coastal seas are a net CO_2 sink of atmospheric of 68 Tg C yr^{-1}, with an uncertainty of 20%. This value is equivalent to 60% of the continental wide European carbon sink of 111±279 Tg C yr^{-1} (Janssens et al., 2005).

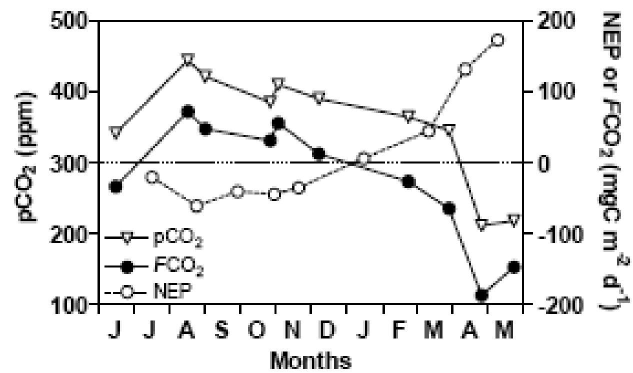

Fig. 7. Annual cycle (June 2003–May 2004) of net ecosystem production (*NEP* in m g C m-2 d-1), air-sea CO_2 fluxes (FCO_2 in m g C m-2 d-1) and the partial pressure of CO_2 (pCO_2) in the Southern Bight of the North Sea (adapted from Schiettecatte et al., 2006).

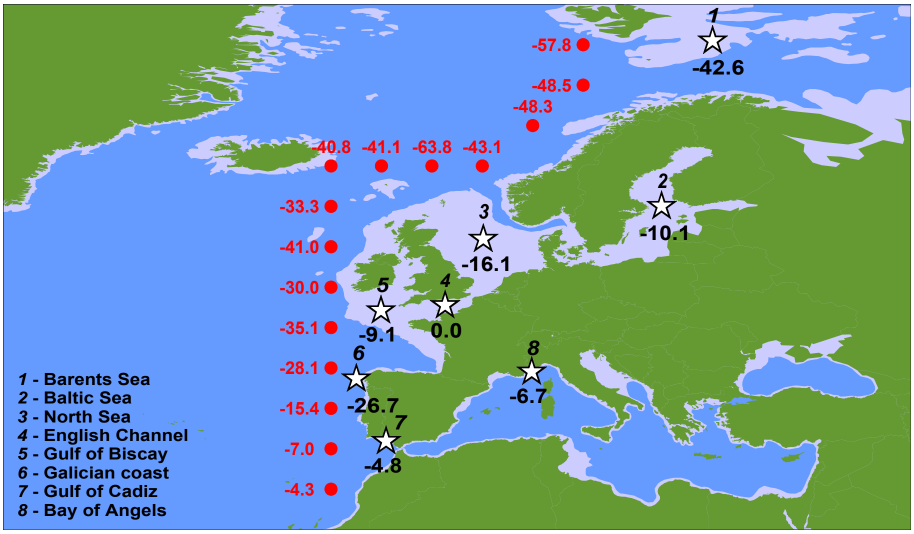

Fig. 8. Compilation of annually integrated air-sea CO_2 (g C m^{-2} yr^{-1}) fluxes in European coastal seas (stars and black numbers) (adapted from Borges et al., 2006) and adjacent open ocean grid nodes from the Takahashi et al. (2002) air-sea flux climatology (red circles and numbers).

6 Discussion

6.1 Lateral carbon transport at diverse scales

The carbon budget of a continent is more complex than just the sum of photosynthesis, respiration, combustion, and anthropogenic fluxes. Key processes transport carbon away from ecosystems where it was fixed by photosynthesis, with resultant increased variability in estimates for temporal storage and transformation. Carbon can be transported horizontally over long distances (100–1000 km), 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 for three lateral transport processes: crop and wood product trade, reduced carbon compounds atmospheric transport and river carbon fluxes. Within the EU-25 territory, lateral transport creates and accentuates regional imbalances between CO_2 sinks and CO_2 sources. At the continental level, the transport of carbon by rivers, by trade and by the atmospheric RCC fluxes results in a net CO_2 sink, balanced by a source elsewhere in the world. In atmospheric CO_2 flux inversions, ignoring the patterns of CO_2 fluxes due to lateral transport may bias the inferred continental-scale flux. When comparing different approaches to quantify regional carbon budgets, methods based on carbon stock changes (forest biomass and soil carbon inventories) will have to be corrected from lateral fluxes in order to be compared with methods based on CO_2 flux observations (eddy covariance, atmospheric inversions). At the continental scale, the correction of carbon stocks changes into CO_2 fluxes, is of the same magnitude as the mean CO_2 flux estimate itself (Table 2)! At the local scale, due to imbalance between respiration and photosynthesis, this correction can be very large as well, especially over croplands and managed forests from which carbon is harvested. At the regional scale, the impact of the trade of food and wood products on CO_2 fluxes is diverse. Northern countries tend to be larger sinks and southern countries larger sources of CO_2, due to food and wood trade.

The main implication of lateral carbon fluxes in the context of carbon trading is that measurement of vertical CO_2 fluxes exchanged with the atmosphere do not exactly match measurement of ecosystem stock changes. The question is thus to assess the fate of this missing carbon entrained in lateral transport circuits. Carbon transported in food trade will be oxidized in a year, and should not be counted as a sink globally. A fraction of carbon transported in wood trade will form a long-term sink into long-lived products. Should this carbon sink be credited to the host country or to the country of origin for the wood? For instance, a given carbon credit could be attached to the exported wood. A fraction of the carbon transported by rivers originates from rocks, being part of the slow geological carbon cycle. This background flux should correspond to no carbon credit. The remainder of river carbon originates from ecosystems, but can have different lifetimes through the river filters, being either degassed to the atmosphere within less than a year, or sequestered in long-lived organic sediments. Our calculations suggest that a minimum fraction of 70% of the ecosystem carbon transported by European rivers is returned rapidly to the atmosphere (Table 2).

6.2 Lateral carbon fluxes at the continental level

At the continental level, food and forest product trade fluxes result only in a small net source of CO_2 to the atmosphere

(24 Tg C yr^{-1} in Table 2). This is because the gross fluxes of import implying a CO_2 source, and the one of export implying a CO_2 sink 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 RCC is large (185 Tg C yr^{-1}), about 15% of the annual fossil fuel CO_2 emissions in EU-25. The impact of RCC on the net carbon balance of Europe is complex (Table 2) because a fraction of the RCC emissions is rapidly oxidized into CO_2 in the boundary layer, while another fraction is re-deposited at the surface. Overall, we estimate that RCC cause a net carbon source of 76 Tg C yr^{-1} over the continent but correspond to a net CO_2 sink of 61 Tg C yr^{-1}. This difference in sign illustrates the fact that C fluxes differ significantly from CO_2 fluxes. The riverine transport of atmospheric carbon from ecosystems into the estuaries must be fueled at steady state by a corresponding plant CO_2 uptake of 160 Tg C yr^{-1}. The magnitude of this CO_2 uptake is large when compared to the net carbon storage of European ecosystems of 111 Tg C yr^{-1}, Janssens et al. (2003). A large fraction (76%) of carbon transported by rivers is outgassed to the atmosphere in waterscapes or buried in lakes, dam and estuarine sediments, while the rest is delivered to inner estuaries. At the level of estuaries, a further outgassing of CO_2 will occur. Overall, we estimate that the river transport of carbon implies a net CO_2 sink over ecosystems at the continental scale (60 Tg yr^{-1} in Table 2) while almost the same amount gets exported to the oceans in a dissolved or particulate form (Table 2). The reason why the land CO_2 sink does not match exactly the export flux exported to the ocean is because a small fraction of the river carbon is coming from rocks (Table 2).

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 and because coarse-resolution atmospheric inversions encompass coastal seas in their estimate of what is usually called the European CO_2 flux. European coastal seas are net sinks for atmospheric CO_2, in the range of 100 Tg C yr^{-1}. This coastal CO_2 sink is comparable in magnitude to the terrestrial carbon uptake by ecosystems (111±279 Tg C yr^{-1} , Janssens et al., 2003). Coastal seas are CO_2 sinks despite the fact that they receive a flux of carbon from rivers of 53 Tg C 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 not yet quantified) bias in the flux estimates derived by these models. In particular, large biases are expected for terrestrial regions adjacent to extensive coastal seas, such as the Gulf of Biscay and the North Sea.

7 Conclusions

The lateral carbon fluxes induced by crop and forest product trade, atmospheric oxidation and atmospheric transport of RCC and river transport are important contributors to the carbon budget of EU-25, at the regional and continental level. At the continental level, we estimate that lateral transport fluxes amount to 165 Tg C yr^{-1}, including the carbon sink of coastal seas. Most of this lateral flux consists of RCC emitted to the atmosphere and exported out of Europe by winds. The RCC emission requires a CO_2 photosynthetic uptake of equivalent magnitude, hence being larger than the biomass accumulation in forests deduced from inventories. Including this CO_2 photosynthetic uptake which is used to make RCC, doubles the imbalance between photosynthesis and ecosystem respiration of European forests. In this work, we only attempted to estimate lateral transport processes at the continental level, but these fluxes should also be taken into account at the site and regional levels, for instance to reconcile eddy covariance estimates of the CO_2 fluxes and biometric measurements of changes in biomass and soil carbon stocks. This work also demonstrates that a substantial amount of carbon is displaced in proportion to the NPP, roughly about 10% of the NPP of the EU-25 territory.

Lateral carbon transport may also explain why inverse modeling estimates of the CO_2 sink are nearly always systematically higher than forest inventory numbers of carbon stock changes. Maps of CO_2 sinks required to match lateral transport fluxes should be accounted for in inversion studies, for instance by prescribing an adapted a priori flux structure. In future work, investigations of lateral carbon fluxes should also reflect changes in economic and land use drivers in the context of implications for future climate change.

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