Chapter 16
The Lateral Carbon Pump, and the European Carbon Balance

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16.1 Introduction

Comparing atmospheric inversion estimates of the carbon fluxes of continents with bottom-up estimates (Pacala et al. 2001; Janssens et al. 2003; Peylin et al. 2005) is no easy task because (1) inversion fluxes always contain a certain amount of a priori information from bottom-up studies, so that the two approaches are not independent, (2) the time period for which inversion models and bottom-up estimates are produced is generally not the same, in the presence of substantial interannual variability, and (3) lateral carbon displacement makes some bottom-up estimates differ from inversions. Lateral displacement processes form a "carbon pump" which moves carbon away from the area where CO_2 was fixed from the atmosphere by photosynthesis with a very small additional sink from rock weathering. Lateral pumping of carbon implies that regional changes in *carbon storage* must differ from regional mean CO_2 fluxes (Tans et al. 1995; Sarmiento and Sundquist 1992). In presence of the lateral transport, one can write that

$$\text{Ecosystem } CO_2 \text{ budget} = \text{Ecosystem carbon budget} + \text{Lateral carbon flux} \quad (16.1)$$

Bottom-up inventory methods measure the carbon budget (first right hand term), while eddy covariance directly measure locally CO_2 fluxes (left hand term, excluding advection). Atmospheric inversions also measure CO_2 fluxes at continental level. This chapter has three major goals. The first objective is to analyze the lateral carbon flux underlying processes, and their implications for understanding regional carbon fluxes, and for designing an observing system to measure the European carbon balance. The second objective is to quantify the carbon pump of carbon within and across the borders of the European continent. The third goal is to produce spatially explicit maps of the land–atmosphere CO_2 fluxes associated with the lateral carbon pump. Janssens et al. (2003, 2005) accounted for some lateral carbon fluxes in their analysis of the European ecosystem carbon budget, but not for all of them, and their analysis did not map spatial distributions, so this study completes and enhances their analysis.

We consider the three mechanisms linking ecosystem–atmosphere CO_2 fluxes to the horizontal "carbon pump":

1. the trade of food, feedstuff, and wood products harvested,
2. the emissions of reduced carbon atmospheric compounds,
3. the river transport of dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC).

In addition, CO_2 fluxes in coastal seas (Borges et al. 2006) are analyzed. This flux does not strictly correspond to an horizontal displacement from land to sea, but it is addressed here, as one possible flux needed to reconcile large-scale atmospheric inversion results with bottom-up estimates. Note that we do not treat the lateral atmospheric transport fluxes of CO_2. The first four sections treat each lateral transport process separately, and associated estimates of CO_2 fluxes. Sect. 16.6 summarizes the contribution of the lateral carbon pump to the carbon balance of Europe.

16.2 Crop and Forest Products Trade

16.2.1 Crop Products

Cultivated ecosystems remove CO_2 from the atmosphere during their growing season. Carbon incorporated into the biomass of crops is harvested and displaced to supply human and (some) animal consumption (Imhoff et al. 2004). After displacement, the consumption of food/feed products releases CO_2 back to the atmosphere. Over the globe, the annual displacement of harvested carbon remains approximately neutral for the atmosphere, given that the storage of food and feedstuff is negligible compared to harvested amounts. Locally, croplands are net annual CO_2 sinks (e.g., Anthoni et al. 2004). Conversely, populated areas where food and feedstuff is consumed are net sources of CO_2. This is illustrated in Fig. 16.1. International crop product trade transports carbon across the border of Europe, therefore, affecting the net carbon balance of the continent. Carbon exported corresponds to a CO_2 sink and carbon imported corresponds to a CO_2 source. Intra-European trade has similar consequences, and acts to redistribute carbon and generate CO_2 fluxes to and from the atmosphere within the continent, but with a zero effect on the net carbon balance of the continent.

We analyzed agrocultural trade statistics from FAO (2004). Cereals, essentially maize, wheat, and barley, explain nearly all the CO_2 sink matching the grain export. The corresponding source, on the other hand, is explained by the use (oxidation) of a mix of diverse crop products. On the perspective of individual countries, the situation becomes much more contrasted (Fig. 16.2). The largest CO_2 sink from the trade of crop products is France (9 TgC year^{-1}), accounting for 90% of the total European sink. The largest CO_2 sources are Portugal, Belgium, Netherlands, Italy, and Spain (altogether more than 22 TgC year^{-1}). No significant correlation was

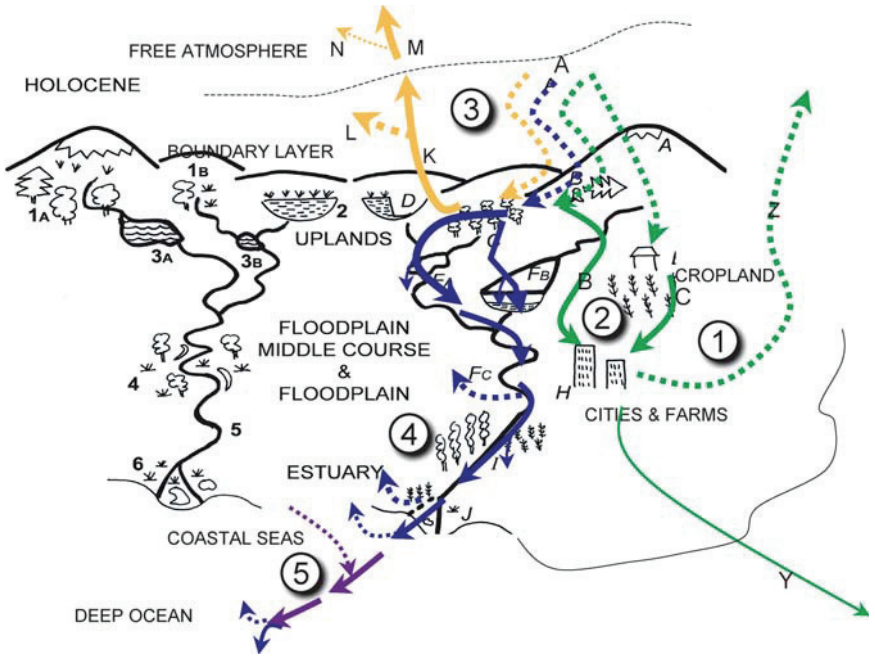

Fig. 16.1 Carbon cycle branches involving some lateral transport of carbon. Associated fluxes of atmospheric CO_2 are in dotted lines, fluxes of transported carbon in solid lines. **Green**. Cycle associated to photosynthesis (A), harvest of wood and crop products, transport by domestic (B, C) and international (Y) trade circuits, and consumption (Z) of carbon in crop products (1) and forest wood products (2). **Brown**. Cycle associated to photosynthesis (A), emissions and atmospheric transport in the boundary layer (K) and transport in free atmosphere (M), and oxidation in the boundary layer (L) and in the free atmosphere (N) of chemically reactive reduced carbon compounds (RCCs). **Blue**. Transport of carbon of atmospheric origin as dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), and particulate organic carbon (POC) by river systems from river uplands to inner estuaries (see text for letters explanation) (4). **Purple**. Fluxes of carbon and CO_2 from coastal seas (5) (*See Color Plate* 9).

found between either the harvest (production) or the exported flux and the net carbon balance of each country.

Overall, Europe imports more food and feed carbon than it exports, thus being a net source to the atmosphere of 24 TgC $year^{-1}$. This flux represents 13% of the annual crop harvest and is equivalent to about 1% of the fossil fuel emissions.

The geographic pattern of CO_2 fluxes is calculated using geospatial information on (1) the main crop types (Ramankutty and Foley 1998), (2) human population distribution, and (3) housed poultry, pigs, and cattle populations, using the same methodology as in Ciais et al. (2006). Figure 16.3 shows the resulting geographic distribution of CO_2 fluxes. Major agricultural plains with intensive cultivation of cereals in northern France and southern England, Hungary, Po valley, and Denmark

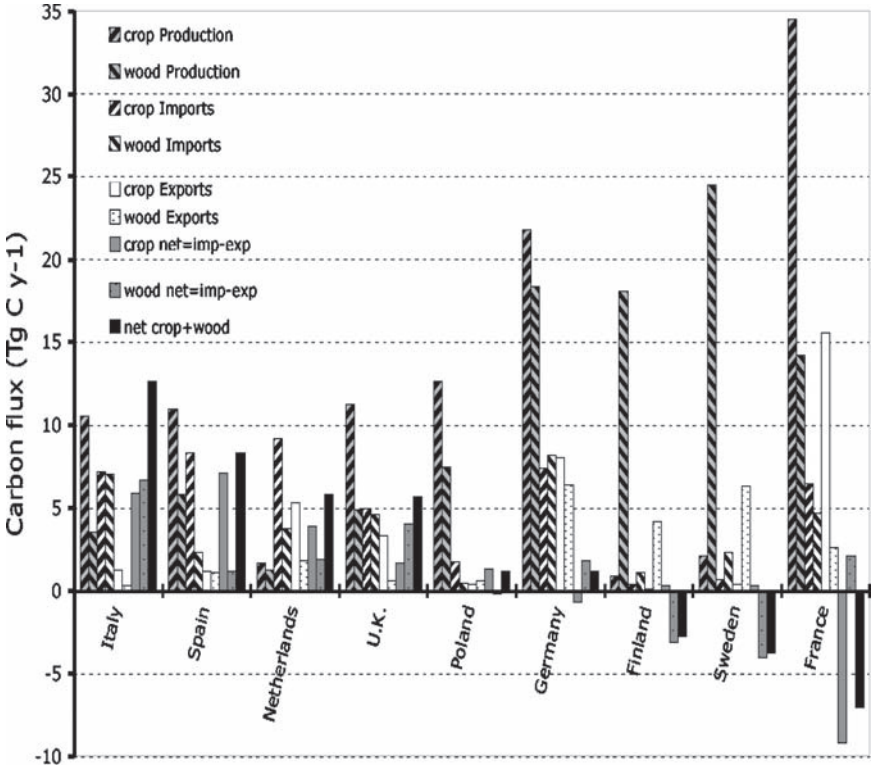

Fig. 16.2 Component carbon budget of crop and forest products trade for selected European countries, those with the largest such fluxes. Yellow is the production, equating the CO_2 uptake necessary to form crop and forest product biomass. Green are imports from outside Europe, oxidized into CO_2 within Europe and yielding a net CO_2 source. Red are exported products by Europe, yielding a net CO_2 sink. Magenta is the net balance resulting of import and export. Hatched bars are for forest products and plain colors for crop products.

are annual net CO_2 sinks, with uptake flux reaching up to 100 gC m^{-2} $year^{-1}$ locally. This uptake flux is large, equivalent to the mean sink of forests [96 gC m^{-2} $year^{-1}$ after Janssens et al. (2003)]. This reflects the higher productivity and harvest index [ratio of yield to net primary production (NPP)] of crops compared with trees. In Fig 16.3, regions with dense population and intensive animal farming emit CO_2 to the atmosphere, up to 50 gC m^{-2} $year^{-1}$.

There are some uncertainties on these maps. Using statistics on country totals may smooth the fields. For instance, the feedstuff consumption by farmed animals is distributed equally in the same country on the basis of the animal density, while in reality, animals have regionally different reliance on feedstuff (e.g., dairy cows receive more feedstuff complements than do grazing cattle). Similarly, in large countries, crop harvest is distributed evenly on cropland area, neglecting regions where lower soil fertility or defavorable climate conditions induce lower yields.

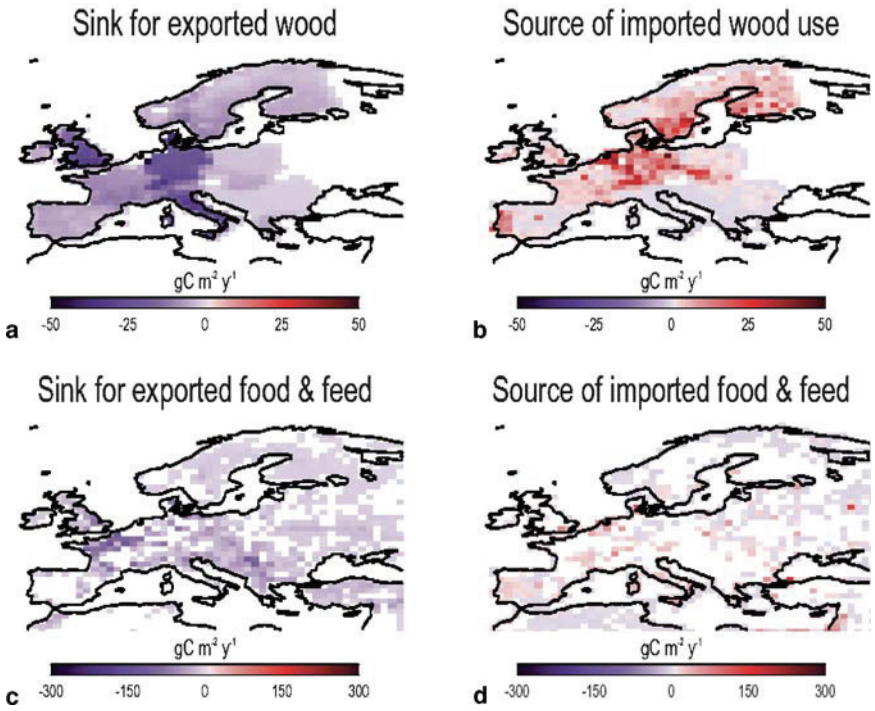

Fig. 16.3 Spatial patterns of trade-induced CO_2 fluxes with the atmosphere. Sources of CO_2 are positive and sinks of CO_2 are negative. **A** and **B** Sinks and sources of CO_2 associated to harvest, trade and consumption of crop products. **C** and **D** Same for forest products CO_2 fluxes (*See Color Plate* 10).

Finally, the release of consumed food is assumed to have the geographic distribution of human population, neglecting transport of organic carbon into dejections to sewage water and rivers.

16.2.2 Forest Products

We also analyzed wood and forest products carbon displacement. In the analysis, we include coniferous and nonconiferous industrial roundwood, sawn wood, wood panels, and paper listed in the FAO (2004) database. Wood harvest data in volume units are converted to mass of carbon by using a mean wood density of 0.5, and a 0.45 carbon fraction in dry biomass. The FAO (2004) statistics indicate that Sweden and Finland export more wood carbon than they import, thus being net sinks of atmospheric CO_2. Portugal and the Czech Republic are also net sinks, but of smaller magnitude. All other countries are CO_2 sources. The largest sources are Italy, Spain, the Netherlands, and the UK. When comparing crop and forest product lateral

carbon pumps, it is striking to see that countries which export food products generally also export wood products (except Nordic countries). Conversely, countries which import food products (e.g., Mediterranean regions) import forest products as well.

To map the geographic distribution of CO_2 fluxes associated to forest product trade, we distributed the FAO (2004) country-level data using NPP fields from Lafont et al. (2002) and a forest cover map (CORINE Land cover 2000) at $1° \times 1°$ resolution. The results are given in Fig. 16.2. The decomposition or combustion of forest products, releasing CO_2, is determined by population density. This assumes that landfills are part of the population density. There are large uncertainties around these maps. First, the forests grid points with the largest NPP locally do not necessarily have the largest harvest, although one analysis (Myneni et al. 2001) shows a significant correlation between Normalized Difference Vegetation Index (NDVI) and biomass stocks in European countries. Furthermore, the areas emitting CO_2 by wood product decay may differ in their geographic location from the population density (e.g., depending on regional practice for using wood as a construction material).

16.3 Reduced Carbon Compounds Atmospheric Transport and Chemistry

Ecosystems and anthropogenic activities emit non-CO_2 reactive carbon compounds (RCCs). The RCCs are reduced species which include CO, CH_4, biogenic volatile organic compounds (BVOCs, such as isoprene, terpene), and anthropogenic volatile organic compounds (VOCs). If the objective of a study is to determine the *CO_2 budget* of Europe by inverse modeling of CO_2 concentration data, then the RCC emissions can rightfully be ignored. On the contrary, if the objective is to determine the *carbon budget* of Europe, the RCC fluxes must be added to the CO_2 fluxes (Eq. 16.1).

In the atmosphere, the RCCs are oxidized with various lifetimes. From ~9 years for CH_4 and few months for CO, the lifetime of RCCs drops to a mere few hours in the case of terpenes. The oxidation sequence of RCCs' species can be complex, but their main end product is a volume source of CO_2 in the atmosphere. The surface emission of RCC is small compared to gross ecosystem fluxes, but significant compared to net CO_2 fluxes. The global biogenic organic carbon emission to the atmosphere was estimated to amount to ~1% of gross primary production globally (Kesselmeier 2005).

Because the lifetime of atmospheric RCCs with respect to their chemical sink in the atmosphere can easily exceed typical atmospheric transport time scales, the carbon contained into RCCs is displaced away by atmospheric transport and eventually released as CO_2. Globally, if there is no perturbation of that branch of the carbon cycle, the atmospheric cycle RCC compounds should be carbon neutral.

To quantify how much carbon is displaced by atmospheric transport of RCCs, we made a European inventory of these compounds. Table 16.1 shows that the total

Table 16.1 Component budget of atmospheric RCCs 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 positive and sinks negative

RCC emissions over Europe (TgC year^{-1})	
Methane	60.0
CO	82.0
BVOCs	27.0
Other VOCs	15.5
Total	184.5
CO_2 production from RCC atmospheric oxidation over Europe (TgC year^{-1})	
Boundary layer	25.7
Free troposphere	19.3
Total	45.3
Carbon deposition in Europe (GtC year^{-1})	
Surface dry deposition	12.0
Wet deposition	9.6
Total C deposited	21.6

RCC reactive carbon compound, *BVOC* biogenic volatile organic compound, *VOC* volatile organic compound

RCC emission over Europe is 185 TgC year^{-1}. In this total, the biogenic source of 87 TgC year^{-1} must be matched by a CO_2 photosynthetic sink of equal magnitude.

The RCC emitted to the atmosphere react into CO_2. We estimated the atmospheric oxidation rates using a 3-D chemistry transport model (Folberth et al. 2005; Hauglustaine et al. 2004). The model explicitly accounts for two major oxidation channels of RCC into CO_2: (1) the oxidation of CO produced either by combustions, or by oxidation of CH_4 and VOCs, (2) the reaction of peroxy-radicals yielding CO_2. A third and minor channel is the direct ozonolysis of alkenoid compounds, which also produces CO_2. The total chemical CO_2 production in the volume of the atmosphere over Europe is given in Table 16.2. The modeled production of "photochemical" CO_2 in the European air shed was found to equal 45 TgC year^{-1}, among which 26 TgC year^{-1} in the boundary layer (PBL) (Fig 16.4.). If "Europe" is defined as the continent and its PBL, then the net carbon loss is 45 − 26 = 19 TgC year^{-1} (Table 16.3).

Opposing these CO_2 losses, a sink of carbon of 22 TgC year^{-1} is caused by dry deposition and wet scavenging of RCC over the continent (Table 16.3). The net effect of the RCC cycle on the European continent carbon balance (Europe = continent + its PBL; source ≥ 0 flux) is given by

$$\text{Net carbon budget} = \text{RCC anthropogenic emissions} - \text{photochemical } CO_2 \text{ in PBL} - \text{deposition sink} \quad (16.2)$$

This assumes that the biogenic RCC emissions are neutralized by a CO_2 photosynthetic sink of equal magnitude everywhere. Equation (16.2) gives a net carbon loss of 76 TgC year^{-1}, available as CO_2 for long-range transport outside the European domain.

Table 16.2 Summary of the lateral transport fluxes and associated atmospheric CO_2 flux for the European continent. The European continent includes its boundary layer and its inner estuary regions. Sources to the atmosphere are counted positive and sinks negative (all units in TgC year^{-1})

	Estimated flux	Quality index of the estimate
Crop and forest products trade		
Crop and forest product import and use	110	+++
Crop and forest product export	−81	+++
Total CO_2 flux[b]	29	+++
Total carbon flux[b]	29	++
Atmospheric RCCs		
RCC total emissions (1)	185	++
RCC emissions of biogenic origin (2)[a]	87	++
CO_2 source from RCC oxidized in boundary layer (3)	26	++
Carbon sink from wet + dry deposition of RCC (4)	−22	+
Total net CO_2 flux = (3) − (2)	−61	+
Total net carbon flux[a] = (1) − (4) − (2)	76	++
River carbon fluxes[d]		
CO_2 outgassing in river systems	90	++
Carbon burial in lakes, dams, and estuarine sediments	33	++
Export to estuaries	53	+++
CO_2 outgassing in estuaries	10–20	+
CO_2 uptake by coastal seas	−68	+++
Total net carbon flux including coastal seas[c]	−113	+
Total net CO_2 flux including coastal seas[c]	−60 to −50	+
Total net CO_2 flux	−160 to −150	+
Total net carbon flux	−76	+

RCC reactive carbon compound

[a]Assumes that 100% of RCC biogenic sources originates from photosynthetic uptake of atmospheric CO_2

[b]Assumes that consumption of crop and forest products produces 100% of CO_2 released to the atmosphere

[c]Assumes that 90% of the DIC transport is a carbon sink is of atmospheric origin equal to −160 TgC year^{-1} (see text), and accounting for the atmospheric share only of carbon flux exported

[d]Established for 8.16 Mkm^2, including Barentz and Black Sea river catchments

16.4 Rivers and Estuaries Carbon Transport

River systems (streams, lakes, river main stems, and 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. Export to the ocean and burial in sediments is a net sink of atmospheric carbon, whereas degassing in aquatic systems is a source (Fig. 16.1).

Rivers and freshwater systems transport carbon originating from land ecosystems to estuaries under dissolved and particulate organic forms [DOC and particulate

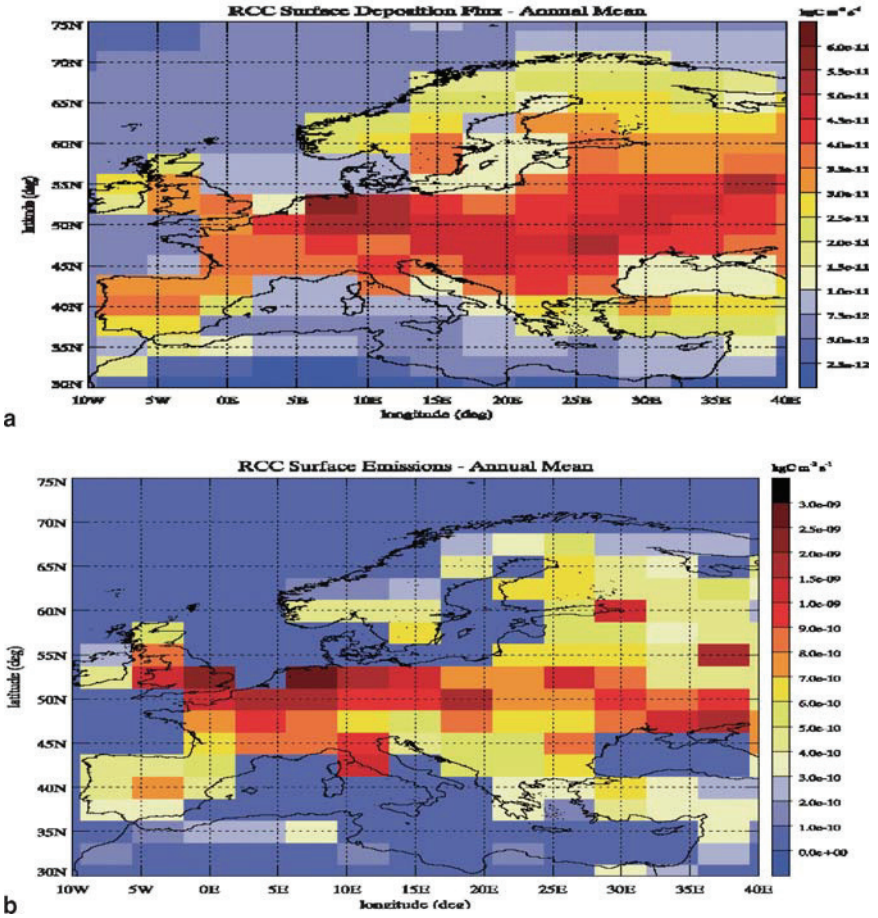

Fig. 16.4 **A** Spatial patterns of the surface deposition (sink) of carbon from reduced carbon compounds. **B** Patterns of reduced carbon compounds emissions to the atmosphere from antropogenic and biospheric sources (*See Color Plate* 11).

organic carbon (POC)] and under inorganic forms [DIC, particulate inorganic carbon (PIC), and CO_2]. Sources and sinks of river carbon in natural conditions are schematized in Fig. 16.1. Sources include: (1) wetlands and peatbog drains (Fig. 16.5A; A), (2) soil leaching and erosion (B), and (3) chemical weathering of soil minerals (C and D). This form of carbon is originally taken up from the atmospheric reservoir via photosynthesis (as followed by $CO_2 + H_2O \rightarrow C_{org} + O_2$), carbonate rock weathering ($CO_2 + H_2O + MCO_3 \rightarrow 2HCO_3^- + M^{2+}$), and by silicate rock weathering via the reaction ($2CO_2 + H_2O + MSiO_3 \rightarrow 2HCO_3^- + M^{2+} + SiO_2$). During weathering of noncarbonated rocks, 100% of river DIC originates from the atmosphere. In contrast, during weathering of carbonated sedimentary rocks, which

Table 16.3 Fluxes of carbon in TgC year^{-1} and origins of net river carbon reaching the continental shelf after estuarine filters (Abril and Meybeck, in preparation). Irrigation not taken into account

	Drainage area (10^3 km^2)	Water flow (km^3 year^{-1})	River carbon (TgC year^{-1})	Carbon yield (gC m^{-2} year^{-1})	%DOC	%POC	%DIC[a]
Northern Europe	2,528	806	13.6	5.4	54.3	4.4	41.1
Temperate Europe	4,699	1,188	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	8,163	2,355	48.3	5.9	29.1	8.3	62.6

DOC dissolved organic carbon, *POC* particulate organic carbon, *DIC* dissolved inorganic carbon

[a] In percent of total carbon of atmospheric origin

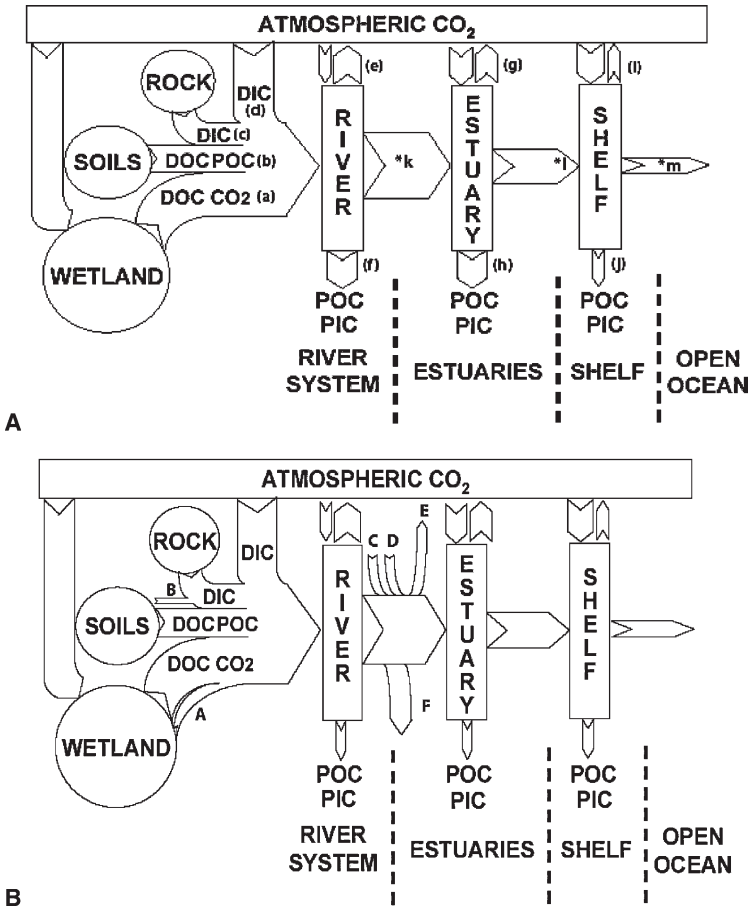

Fig. 16.5 Schematic transport of river carbon along the aquatic continuum. **A** Under natural conditions. **B** With multiple human impacts. See text for indications.

results in important fluxes of DIC, usually as bicarbonates, half of the DIC is taken up from the atmosphere, and half derives from fossil carbonates stored in rocks over 10 millions to 100 millions years. Thus, carbonated sedimentary rocks represent an important source of DIC, usually in the form of bicarbonates. Therefore, the nature and ages of river carbon species is very different (Meybeck 1993, 2005). The PIC is derived from the mechanical erosion. While being transported downstream to the coast, it is gradually trapped in lowlands, floodplains, lakes, estuaries, and on the continental shelf [Fig. 16.1. F_A, F_B, I, and J; Fig. 16.5A (f) and (h)]. This relocation of the rock PIC generally does not affect the CO_2 cycle. Under the specific climate and ecological conditions (such as, arid conditions, high river pH), some DIC may precipitate as calcite and can thus be stored in soils and in sediment "traps" on their way from headwaters to the coastal areas.

Factors controlling the river export of atmospheric carbon, that is, DOC + POC + atmospheric derived DIC, are first river runoff, then rock type (occurrence of carbonate rocks), and finally the presence of wetlands. Large lakes are also efficient filters of dissolved carbon fluxes (Fig. 16.1). A preliminary comparison of river carbon fluxes in Northern, Central, and Southern Europe shows major regional contrasts. Northern European catchments are characterized by high DOC export (most POC is trapped in lakes, which cover 5–20% of these river basins), derived from wetlands and peatbogs, the age of which probably ranges from 100 to 6,000 years. In Southern catchments, DIC is the dominant form of river carbon and nearly half of it originates from carbonate rock dissolution with carbon aged of 10–100 million years, the other half from contemporary soil and atmospheric CO_2. Central Europe catchments are intermediate, with carbon fluxes depending on river runoff and rock type. From mass-balance considerations, we estimated that the river transport of DIC corresponds to an ecosystem CO_2 sink of 160 TgC $year^{-1}$ (see Table 16.3 and below).

Direct human pressures on river catchments may greatly modify carbon fluxes, transfers, and sinks (Fig. 16.5B). The exploitation of peatbogs generally increases DOC contents in headwaters (Fig. 16.1, D; Fig. 16.5B, A). Increased soil erosion and agricultural practices may result in soil POC inputs. Untreated organic waste water (Fig. 16.1, H; Fig. 16.5B, C) and eutrophication (Fig. 16.5B, D) of river and lakes are additional sources of very labile DOC and POC. It must be noted that the ages of these carbon species are also highly variable and range from a few days for river algal carbon to a thousand of years in the case of, for example, peat DOC. The CO_2 evasion (outgassing) from river, lakes, and reservoirs greatly depends on the reactivity of this organic carbon carried by rivers. During the 1970s, when rivers were accepting large quantities of untreated urban and industrial waste waters, river respiration (R) was exceeding river production (P) related to eutrophication: net CO_2 evasion was observed as in the Rhine River (Kempe 1984). Present conditions are changing because of waste treatment and the same river may have multiple changes of P/R ratio from headwaters to estuary as is the case for the Scheldt and Seine Rivers.

In addition to new carbon input to river system, river damming and irrigation control net river 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 and the irrigation residues do not balance these fluxes. In Southern Europe, most river water flows to the ocean have been decreased, up to 90% (as for the Nile), although this impact on net river fluxes to the Mediterranean Sea or the Portuguese Coast is unknown as the last gauging and water quality stations are located upstream of the major water withdrawal for deltas irrigation (e.g., Ebro, Rhone, Axios, Nile) (Ludwig et al. 2003).

Continental aquatic surfaces including streams, lakes, river main stems, and floodplains and estuaries are sources of CO_2 to the atmosphere (Sobek et al. 2003). Except for a few cases occurring seasonally, CO_2 supersaturation episodes in the water prevail in streams (Hope et al. 2001; Billett et al. 2004), lakes (Cole et al. 1994), rivers (Kempe 1982; Jones and Mulholland 1998; Abril et al. 2000; Cole and Caraco 2001), and estuaries (Frankignoulle et al. 1998; Abril and Borges 2004). The high CO_2 concentrations in continental waters can have two distinct origins and are either produced on land by soil respiration, followed by surface runoff and riparian transport, or result from the oxidation of terrestrial organic carbon in the aquatic system itself, by microbial respiration and photochemistry (Graneli 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 versus DOC relationship (Fig. 16.6), as a result of anthropogenic (mainly domestic) loads, that increase the DOC, followed by aquatic respiration, that increases the pCO_2 (Neal et al. 1998; Abril et al. 2000). By contrast, boreal headwaters in Scottish peatlands show much lower pCO_2 in comparison with a very high DOC. This is due to the soil origin of the CO_2 and its rapid evasion to the atmosphere in these fast flowing headwaters (Hope et al. 2001; Billett 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. 16.6). In such case, atmospheric carbon is fixed by aquatic primary production and further transported laterally as organic carbon downstream to the estuary. The Loire River, for instance, transports large quantities of algal carbon during summer, but these are totally mineralized in the estuarine turbidity maximum (Meybeck et al. 1988), leading to hypoxia and high CO_2 degassing in the estuary (Abril et al. 2004). Along the river basin continuum, estuaries, particularly when macrotidal, behave as "hotspots" for CO_2 degassing, owing to the quantity of organic carbon they receive from the land as well as to the long residence time of waters and suspended sediments (Frankignoulle et al. 1998; Abril et al. 2002; Abril and Borges 2004). Gas transfer velocities in continental waters also vary in a wide range, and are controlled by the wind stress (lakes, estuaries, to a lesser extend rivers) and by the land topography, water flow, and bottom roughness (streams, rivers, estuaries) (Wanninkhof et al. 1990; Borges et al. 2004). The relative scarcity of CO_2 data in continental waters, relative to the high spatial and temporal variations, renders a bottom-up estimate at the European scale rather uncertain. In addition, surface areas of some ecosystems are also accompanied by significant uncertainties and the highest CO_2 flux rates occur in ecosystems with the

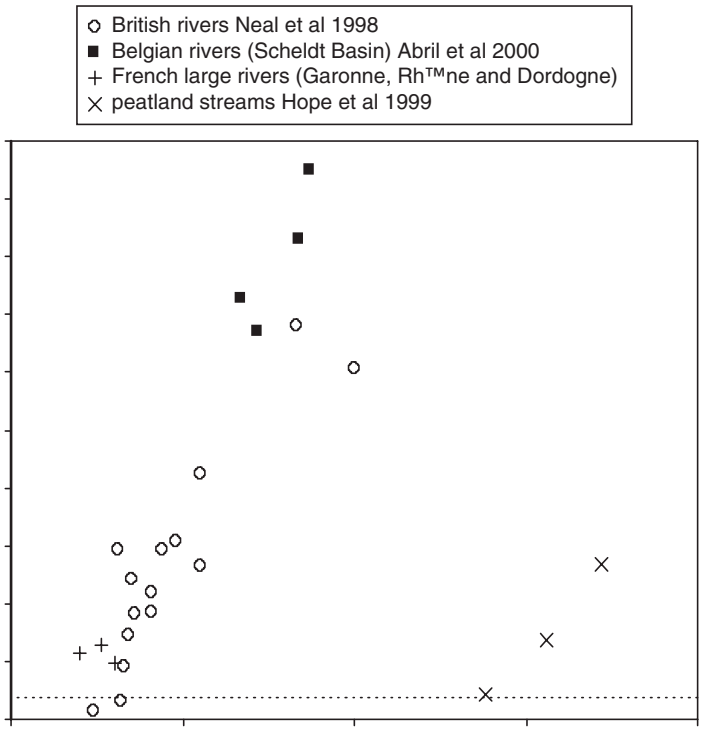

Fig. 16.6 Relationship between pCO_2 and dissolved organic carbon (DOC) in selected European river systems. British lowland rivers from Neal et al. (1998); Belgian lowland rivers (Scheldt watershed) from Abril et al. (2000); large French rivers from Abril and Commarieu (Unpublished) (Garonne and Dordogne) and from Aucour et al. (1999) (Rhône); and Scottish upland peat streams from Hope et al. (2001).

smallest surface areas, such as estuaries and rivers. For DOC, POC, and atmospheric-derived DIC, the lateral transport of carbon to the coastal zone by rivers has been compiled using the main European rivers database (Meybeck and Ragu 1996) and then extrapolated for the European seas catchment ($8.16\,Mkm^2$) on the basis of runoff, landcover, and rock types similarities. Southern, Central, and Northern Europe can be differentiated (Table 16.3) showing marked diversity in export rates and carbon species. Estuarine filters are included in this estimate (Abril and Meybeck, in preparation) taking into account the carbon species fate.

Table 16.2 summarizes carbon fluxes through the European river system on an order-of-magnitude basis and compares river carbon lateral transport with CO_2 outgassing. CO_2 fluxes from each subecosystems (peatland streams, lakes, rivers, and estuaries) are based on a compilation of published pCO_2 distributions, on typical gas transfer velocities, and on available information on surface areas of subecosystems (Abril and Meybeck, in preparation). Because the river transport as summarized in Table 16.3 is based on nontidal river sampling and is calculated for the entrance of

Table 16.4 Sensitivity of lateral carbon fluxes to global change

	River atmospheric carbon[a]			
Global change	Natural C fluxes to ocean	Anthropogenic C fluxes to ocean	C storage on land	CO_2 evasion from water mirror
CO_2 increase	x			x
Warming	x			x
Sea level rise			x	
Runoff increase	xx			
Direct human impacts				
Waste management		xx		xx
Eutrophication		x		x
Damming			xxx	xx
Irrigation			xxx	
channelization			x	
Land use change	x to xx			

[a] From headwaters to estuary included

estuaries, we have distinguished the CO_2 degassing in freshwaters from those in estuaries. Although European rivers transport 53 TgC year^{-1} to estuaries, they emit 90 TgC year^{-1}of CO_2 to the atmosphere. A majority of this CO_2 outgassing is occurring at northern latitudes. Owing to their large surface area (183,000 km^2) and despite their lower CO_2 flux density, lakes contribute up to 35% of the total CO_2 outgassing from European freshwaters (lakes, reservoirs, rivers, and their floodplains but excluding wetlands and estuaries). The CO_2 degassing from European estuaries has been previously estimated to 30–60 TgC year^{-1} by Frankignoulle et al. (1998). This range is probably an overestimate for two reasons: (1) the surface area of European estuaries (112×10^3 km^2) was uncertain and much higher than indicated by recent estimates of 36×10^3 km^2 compiled in the Global Lakes and Wetlands Database (GLWD) (2) the investigated estuaries are in the majority macrotidal, where net heterotrophy and CO_2 degassing are favored (Abril and Borges 2004; Borges et al. 2006). Little or no CO_2 data are available in fjords, fjärds, deltas, and coastal lagoons. Applying the available CO_2 fluxes to the surface area of coastal wetlands from the GLWD results in an estuarine CO_2 source to the atmosphere of 10–20 TgC year^{-1}, which is much closer to the organic carbon transport by European rivers before the estuarine filter of 20 TgC year^{-1}reported in Table 16.3. We estimated that 90% of the DIC transported by rivers is of atmospheric origin, that is the DIC transport is matched by a CO_2 sink in ecosystems. The net carbon balance of the continent is given in Table 16.4.

$$\begin{aligned}\text{Net carbon budget} = {} & \text{Ecosystem } CO_2 \text{ sink forming river} \\ & \text{DIC} - \text{Net flux to estuaries} + \\ & CO_2 \text{ outgassing from estuaries} + \\ & CO_2 \text{ outgassing by freshwaters}\end{aligned} \tag{16.3}$$

16.5 Carbon Dioxide Fluxes in Coastal Seas

Coastal seas not only receive nutrient and organic matter inputs from estuaries but also exchange water and matter with the open ocean across marginal slopes. In European coastal seas, the gross water fluxes across marginal slopes are about 250–2,000 times more intense than that of the respective freshwater discharge; water flux exchanges between open ocean and adjacent coastal seas are 80–520 times higher than that of the respective freshwater discharge (Huthnance 2006). The overall flow 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 because of 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, respectively, than 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, but the inputs of DOC and DIC from the English Channel are 3 and 13 times higher, respectively, than the inputs of the same species from estuaries (Thomas et al. 2005).

Unlike macrotidal estuaries that emit CO_2 to the atmosphere throughout the year, coastal seas usually exhibit a distinct seasonal cycle of air–sea CO_2 exchange, shifting from a source to the atmosphere to a sink from the atmosphere. This shift to a large extent is related to the variation in biological activity. The direction and the intensity of the air–sea fluxes of CO_2 are predominantly controlled by the net ecosystem production (NEP), as exemplified in Fig. 16.6 for the Southern Bight of the North Sea (SBNS). The SBNS acts as a sink of atmospheric CO_2 in April and May during the phytoplankton blooms, and as a source of CO_2 to the atmosphere during the rest of the year due to the degradation of organic matter. Overall, the SBNS is a sink of atmospheric CO_2 because of the seasonal decoupling of organic matter production and degradation, with a probable export of organic matter to the adjacent areas in relation to the short exchange time of the water mass in this area (on average 70 days).

Note that besides NEP, air–sea CO_2 fluxes in coastal seas are also modulated by other factors such as additional biogeochemical processes (e.g., $CaCO_3$ precipitation/dissolution), purely thermodynamic effects (temperature change, salinity change, Revelle factor), exchange of water with adjacent aquatic systems, the residence time of the water mass within the system, and the decoupling of organic carbon production and degradation across the water column in relation to the physical conditions of the system (e.g., Borges 2005; Borges et al. 2005, 2006).

Figure 16.7 shows the annually integrated air–sea CO_2 fluxes for various European coastal seas. A significant spatial heterogeneity is clearly apparent. Seasonal patterns also differ from one coastal sea to another (not shown in the figure) as discussed in detail by Borges (2005) and Borges et al. (2005, 2006).

Overall, the European coastal seas are a sink of atmospheric CO_2 of about 68 TgC $year^{-1}$. The air–sea CO_2 fluxes over European coastal seas are also significantly

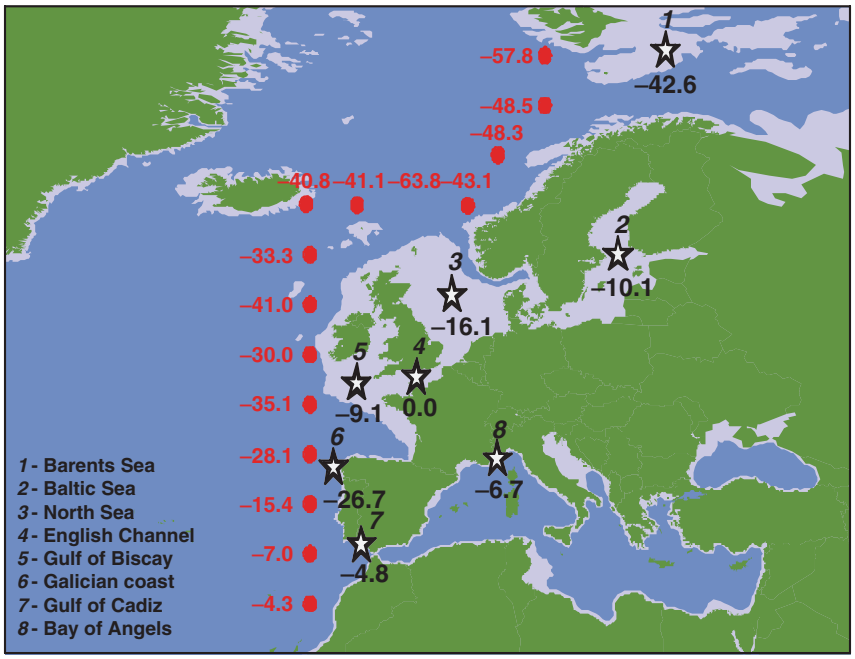

Fig. 16.7 Compilation of annually integrated air–sea CO_2 (gC m^{-2} $year^{-1}$) fluxes in European coastal seas (stars and black numbers) (adapted from Borges et al. 2006) and adjacent open ocean grid nodes from the Takahashi et al. (2002) climatology (red circles and numbers) (*See Color Plate* 12).

different from those in the adjacent open ocean grid nodes in the Takahashi et al. (2002) climatology (Fig. 16.7). The latter is commonly used in atmospheric CO_2 inversion models which probably will lead to a significant but yet unquantified 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, the Gulf of Biscay and the North Sea.

16.6 Conclusions and Outlook

In summary, the carbon budget of a continent is more complex than just the sum of photosynthesis and respiration. A number of processes pump carbon away from ecosystems after its fixation by photosynthesis. The carbon displaced by lateral pumps can travel over long distances, but eventually gets oxidized and released back to the atmosphere in the form of CO_2, thus closing the cycle. Lateral transport of carbon occurs within Europe, resulting in local and regional imbalances between CO_2 sources and CO_2 sinks. It also occurs across the borders of the European continent, resulting in a CO_2 sink inside Europe which is balanced by a source outside

the continental boundaries. This makes inverse modeling more difficult, since ignoring lateral CO_2 fluxes may bias inversion results. Consequently, the comparison of approaches measuring CO_2 fluxes (inversion modeling and eddy covariance) with those measuring carbon fluxes (soil and forest biomass inventories) must account for lateral fluxes.

At the local scale, the imbalance in the CO_2 flux, created by carbon lateral transport, can be very large, especially in cultivated areas and harvested forests. However, when considered at the continental level, food and wood trade result only in a very small net source of CO_2 to the atmosphere. We also found that a large source of carbon is released to the atmosphere in the form of RCC (183 TgC $year^{-1}$), but its impact on the net carbon balance is complex, involving the rapid oxidation of RCC into CO_2 within the boundary layer itself and the deposition of RCC at the surface. Overall, we estimated that the cycle of RCC causes a net carbon loss of 76 TgC $year^{-1}$.

Rivers altogether transport a large carbon of atmospheric origin, that is an ecosystem CO_2 sink of 160 TgC $year^{-1}$. En route to the oceans, part of this river carbon is outgassed to the atmosphere; part is sequestered in lakes, dams, and estuarine sediments, with the rest being delivered to inner estuaries where a large fraction is outgassed. In total, the river geologic carbon cycle causes a net carbon sink of 113 TgC $year^{-1}$ at the continental level.

Coastal seas were considered because they are subject to important lateral transport (their CO_2 budget largely depends on lateral fluxes), and because coarse resolution inversions' results encompass coastal seas in their estimates. The sink for atmospheric CO_2 in coastal seas of 68 TgC $year^{-1}$ is comparable in magnitude to the terrestrial carbon fluxes. The air–sea CO_2 fluxes in European coastal seas are significantly different from those in the adjacent open waters. The latter are commonly used as a prior in atmospheric CO_2 inversion models, leading to a yet unquantified bias in the output from these models.

In conclusion, the fluxes transported by wood and food trade, RCC cycle, and river geological cycle are significant. Altogether, the displaced carbon pump amounts to roughly 20% of the NPP of the European continent. The contribution of these fluxes to the continental carbon balance is not negligible either, amounting to a CO_2 sink of 165–155 TgC $year^{-1}$ and to a net carbon sink of 81 TgC $year^{-1}$.

River lateral carbon fluxes have not been considered on the environmental agenda of European countries. For improving estimates of these fluxes, what is needed is regional statistics of wood and food harvest and consumption. It is also needed measurements of RCC fluxes from representative ecosystems. For rivers, data sources are limited to bicarbonates, as a component of ionic analysis, and recently total organic carbon, as an indicator of "organic pollution" in some rivers. It is now necessary to create a European network for river carbon sources fluxes and sinks from headwaters to the continental shelf including DOC, POC, DIC, and CO_2. So far, most of the carbon budgets have been realized in macrotidal estuaries of Western Europe. Other estuarine types must be considered in order to improve our knowledge of net carbon fluxes to the European continental shelf.

References

Abril G. and Borges A.V. (2004). Carbon dioxide and methane emissions from estuaries. In Greenhouse Gas Emissions: Fluxes and Processes. Hydroelectric Reservoirs and Natural Environments. A. Tremblay, L. Varfalvy, C. Roehm and M. Garneau (Eds.), Environmental Science Series, Springer-Verlag, Berlin, Heidelberg, New York. 187–207.

Abril G., Etcheber H., Borges A.V., and Frankignoulle M. (2000). Excess atmospheric carbon dioxide transported by rivers into the Scheldt Estuary. Comptes Rendus de l'Académie des Sciences. Série IIA 330: 761–768.

Abril G., Nogueira M., Etcheber H., Cabeçadas G., Lemaire E., and Brogueira M.J. (2002). Behaviour of organic carbon in nine contrasting European estuaries. Estuarine, Coastal and Shelf Science. 54: 241–262.

Anthoni P., Freibauer A., Kolle O., and Schulze E.-D. (2004). Winter wheat carbon exchange in Thuringia, Germany. Agricultural and Forest Meteorology. 121: 55–67.

Aucour M.-A., Sheppard S.M.F., Guyomar O., and Wattelet J. (1999). Use of ^{13}C to trace origin and cycling of inorganic carbon in the Rhône river system. Chemical Geology. 159: 87–105.

Aumont O., Orr J.C., Monfray P., Ludwig W., Amiotte-Suchet P., and Probst J.L. (2001). Riverine-driven interhemispheric transport of carbon. Global Biogeochemical Cycle. 15: 393–405.

Billett M.F., Palmer S.M., Hope D., Deacon C., Storeton-West R., Hargreaves K.J., Flechard C., and Fowler D. (2004). Linking land-atmosphere-stream carbon fluxes. Global Biogeochemical Cycles. 18(1): 1–12.

Borges A.V., Delille B., Schiettecatte L.S., Gazeau F., Abril A., and Frankignoulle M. (2004). Gas transfer velocities of CO_2 in three European estuaries (Randers Fjord, Scheldt and Thames). Limnology and Oceanography. 49(5): 1630–1641.

Borges A.V. (2005). Do we have enough pieces of the jigsaw to integrate CO_2 fluxes in the Coastal Ocean ? Estuaries. 28(1): 3–27.

Borges A.V., Delille B., and Frankignoulle M. (2005). Budgeting sinks and sources of CO_2 in the coastal ocean: Diversity of ecosystems counts. Geophysical Research Letters. 32: L14601 (doi:10.1029/2005GL023053).

Borges A.V., Schiettecatte L.S., Abril G., Delille B., and Gazeau F. (2006). Carbon dioxide in European coastal waters. Estuarine Coastal and Shelf Science. 70: 375–387.

Ciais P., Bousquet P., Freibauer A., and Naegler T. (2006). On the horizontal displacement of carbon associated to agriculture and how it impacts atmospheric CO_2 gradients. Global Biogeochemical Cycles, in revisions.

Cole J.J. and Caraco N.F. (2001). Carbon in catchments: Connecting terrestrial carbon losses with aquatic metabolism. Marine and Freshwater Research. 52: 101–110.

Cole J.J., Caraco N.F., Kling G.W., and Kratz T.W. (1994). Carbon dioxide supersaturation in the surface waters of lakes. Science. 265: 1568–1570.

CORINE Land cover (2000). EEA online publications: http://reports.eea.eu.int/COR0- landcover/en., edited.

Enting, I. G., and Mansbridge J. V.: Latitudinal Distribution of Sources and Sinks of CO2 - Results of an Inversion Study, Tellus, 43B, 156–170, 1991.

FAO (2004). Food and Agriculture Organization database, in http://faostat.fao.org/faostat/collections?subset = agriculture, edited.

Folberth G., Hauglustaine D., Ciais P., and Lathière J. (2005). On the role of atmospheric chemistry in the global CO_2 budget. Geophysical Research Letters. doi:10.1029.

Frankignoulle M., Abril G., Borges A., Bourge I., Canon C., Delille B., Libert E., and Théate J.M. (1998). Carbon dioxide emission from European estuaries. Science. 282: 434–436.

Gazeau F., Gattuso J.-P., Middelburg J.J., Brion N., Schiettecatte L.-S., Frankignoulle M., and Borges A.V. (2005). Planktonic and whole system metabolism in a nutrient-rich estuary (the Scheldt Estuary). Estuaries. 28(6): 868–883.

Graneli W., Lindell M., and Tranvik L. (1996). Photo-oxidative production of dissolved inorganic carbon in lakes of different humic content. Limnology and Oceanography. 41: 698–706.

Grosbois C., Négrel P., Fouillac C., and Grimaud D. (2000). Dissolved load of the Loire River: Chemical and isotopic characterization. Chemical Geology. 170: 179–201.

Hauglustaine D.A., Hourdin F., Jourdain L., Filiberti M.A., Walters S., Lamarque J.F., and Holland E.A. (2004). Interactive chemistry in the laboratoire de météorologie dynamique general circulation model: Description and background tropospheric chemistry evaluation. Journal of Geophysical Research. 109.

Hope D., Palmer S., Billet M., and Dawson J.J.C. (2001). Carbon dioxide and methane evasion from a temperate peatland stream. Limnology and Oceanography. 46: 847–857.

Huthnance J.M. (2006). North-East Atlantic margins. In Carbon and Nutrient Fluxes in Global Continental Margins. Atkinson L., Liu K.K., Quinones R., and Talaue-McManus L. (Eds.), Springer, New York.

Imhoff M.L., Bounoua L., Ricketts T., Loucks C., Harriss R., and Lawrence W.T. (2004). Global patterns in human consumption of net primary production. Nature. 429: 870–873.

Janssens I.A., et al. (2003). Europe's terrestrial biosphere absorbs 7 to 12% of European Anthropogenic emissions. Science. 300: 1538–1542.

Janssens I.A., et al. (2005). The carbon budget of terrestrial ecosystems at country-scale—A European case study. Biogeosciences. 2: 15–26.

Jones J.B. and Mulholland P.J. (1998). Carbon dioxide variation in a hardwood forest stream: An integrative measure of whole catchment soil respiration. Ecosystems. 1: 183–196.

Kempe S. (1982). Long term record of CO_2 pressure fluctuations in freshwaters. Mitteilungen aus dem Geologish-Paläontologishen Institut der Universität Hamburg. 52: 91–332.

Kempe S. (1984). Sinks of the anthropogenically enhanced carbon cycle in surface fresh waters. Journal of Geophysical Research. 89: 4657–4676.

Kesselmeier J. (2005). Volatile organic carbon compound emissions in relation to plant carbon fixation and the terrestrial carbon budget, Global Biogeochemical Cycles. 16: 11.

Lafont S., Kergoat L., Dedieu G., Chevillard A., Karstens U., and Kolle O. (2002). Spatial and temporal variability of land CO_2 fluxes estimated with remote sensing and analysis data over western Eurasia. Tellus. 54B: 820–833.

Ludwig W., Meybeck M., and Abousamra F. (2003). Riverine transport of water, sediments and pollutants to the Mediterranean Sea. Medit. Action Technical Report Series #141, UNEP/MAP Athens, 111 pp.

Meybeck M. (1993). Riverine transport of atmospheric carbon: Sources, global typology and budget. Water, Air Soil Pollution, 70: 443–464.

Meybeck M. (2005). Global distribution and behaviour of carbon species in world rivers. In Soil Erosion and Carbon dynamics. Roose E., Lal R., Feller C., Barthès B., Stewart B.A. (Eds.), Advances in Soil Science Series, CRC Boca Raton, FL, 209–238.

Meybeck M. and Ragu A. (1996). River discharges to the oceans. An assessment of suspended solids, major ions, and nutrients. Environment Information and Assessment Report. UNEP, Nairobi, 250 pp.

Meybeck M., Cauwet G., Dessery S., Somville M., Gouleau D., and Billen G. (1988). Nutrients (Organic C, P, N, Si) in the eutrophic river Loire and its estuary. East Coast Shelf Science. 27: 595–624.

Myneni R., Dong J., Tucker C., Kaufmann R.K., Kauppi P.E., Uski J., Zhou L., Alexeyev V., and Hughes M.K. (2001). A large carbon sink in the woody biomass of Northern forests. PNAS. 9: 14784–14789.

Neal C., House W.A., Jarvie H.P., and Eatherall A. (1998). The significance of dissolved carbon dioxide in major rivers entering the North Sea. The Science of the total Environment. 210/211: 187–203.

Pacala S. W., et al. (2001). Consistent land- and atmosphere-based U.S. carbon sink estimates. Science. 292: 2316–2320.

Peylin P., Bousquet P., LeQuéré C., Sitch S., Friedlingstein P., McKinley G.A., Gruber N., Rayner P., and Ciais P. (2005). Multiple constraints on regional CO_2 fluxes variations over land and oceans. Global Biogeochemical Cycles. 19: GB1011, doi:10.1029/2003GB002214.

Ramankutty N. and Foley J. (1998). Characterizing patterns of global land use: An analysis of global croplands data. Global Biogeochemical Cycles. 12: 667–685.

Sarmiento J.L. and Sundquist E.T. (1992). Revised budget for the oceanic uptake of anthropogenic carbon dioxide. Nature. 356: 589–593.

Schiettecatte, L.-S., Thomas, H., Bozec, Y., and Borges, A.V. (2007). High temporal coverage of carbon dioxide measurements in the Southern Bight of the North Sea., Marine Chemistry, submitted.

Sobek S., Algesten G., Bergstrom A.-K., Jansson M., Tranvik L.J. (2003). The catchment and climate regulation of pCO2 in boreal lakes. Global Change Biology, 9: 630–41.

Takahashi T., Sutherland S.C., Sweeney C., Poisson A., Metzl N., Tilbrook B., Bates N.R., Wanninkhof R., Feely R.A., Sabine C., Olafsson J., and Nojiri Y. (2002). Global sea-air CO_2 flux based on climatological surface ocean pCO_2, and seasonal biological and temperature effects. Deep-Sea Research. II 49(9–10): 1601–1622.

Tans P.P., Fung I.Y., and Enting I.G. (1995). Storage versus flux budgets: The terrestrial uptake of CO_2 during the 1980s. In Biotic Feedbacks in the Global System. Woodwell G.M. and Mackensie F.T. (Eds.), Oxford University Press, New York. 351–366.

Thomas H., Bozec Y., De Baar H.J.W., Elkalay K., Frankignoulle M., Schiettecatte L.-S., and Borges A.V. (2005). The carbon budget of the North Sea. Biogeosciences. 2(1): 87–96.

Tranvik L. (2005). Terrestrial dissolved organic matter—A huge but not unlimited subsidy to aquatic ecosystems. ASLO summer meeting, Santiago de Compostella. 19–24 June 2005.

Vörösmarty C.J., Meybeck M., Fekete B., Sharma K., Green P., and Syvitski J. (2003). Anthropogenic sediment retention: Major global-scale impact from the population of registered impoundments. Global Planetary Changes. 39: 169–190.

Wanninkhof R., Mulholland P.J., and Elwood J.W. (1990). Gas exchange rates for a first order stream determined with deliberate and natural tracers. Water Resources Research 26: 1621–1630.