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A carbon balance of Norway: terrestrial and aquatic carbon fluxes.

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## Abstract

Northern landscapes accumulate carbon in vegetation and soils while rivers transport significant amounts of land-derived carbon to coastal areas. Here, we quantify carbon sources and sinks in main ecosystems (forests, peatlands, mountains, agricultural areas, lakes) in Norway for 1990-2008, and compare riverine carbon transport with terrestrial carbon accumulation in Norway's four major discharge areas. Mean annual carbon accumulation ( $6.0 \pm 0.9$  Tg C;  $19 \text{ g C m}^{-2}$ ) in terrestrial ecosystems balanced 40% of national greenhouse gas emissions. The area-normalized terrestrial sink strength declined in the following order (in  $\text{g C m}^{-2} \text{ yr}^{-1}$ ): tree biomass ( $40 \pm 3$ ) >peatlands ( $19 \pm 15$ ) >forest soils ( $9 \pm 1$ ) >>lakes ( $2 \pm 1$ ) >mountains ( $0.5 \pm 0.3$ ), while agricultural soils were sources of carbon ( $-36 \pm 74$ ). The most precise estimate in the carbon balance was for tree biomass, because of the underlying forest inventory data. Poor data on land management and soil type in agricultural soils, and on (former) drainage and peatland type resulted in high uncertainty in carbon loss and uptake estimates in agricultural soils and peatlands, which impacted the uncertainty in total terrestrial carbon accumulation. Also, carbon losses from disturbance in organic soil types were poorly constrained. Riverine coastal inputs of land-derived organic carbon (OC) were  $1.0 \pm 0.1$  Tg C  $\text{yr}^{-1}$  ( $3.0 \text{ g C m}^{-2} \text{ yr}^{-1}$ ), with highest area-specific riverine export in western ( $4.5 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) and lowest ( $1.7 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) in subarctic Norway. In west and middle Norway, river OC export was approximately equal to carbon accumulation in soils and wetlands, while it was 50% of soil and wetland carbon accumulation in southeast and subarctic Norway. Lateral aquatic transport of carbon is not explicitly accounted for in forest soil carbon accumulation estimates, although aquatic fluxes represent a climate-dependent carbon loss from soil carbon pools. The lack of methods that adequately account for lateral fluxes in carbon balances adds considerable uncertainty to soil carbon sink estimates. Climate warming and associated changes in precipitation may result in substantial alterations of terrestrial and aquatic carbon fluxes, with uncertain implications for the terrestrial carbon sink of northern landscapes.

**Keywords:** carbon balance; aquatic carbon transport; drainage basins; terrestrial carbon sink; forest biomass; forest soil model; river; peatland; lake; agriculture; uncertainty; boreal landscape; subarctic landscape

## Introduction

Terrestrial ecosystems play an important role in mitigating climate change by absorbing a substantial part of global fossil fuel emissions. The size and location of the terrestrial CO<sub>2</sub> sink are under debate while its future strength is uncertain (Schimel 2007). A global carbon balance showed that the land sink between 2000 and 2006 was 2.7 Pg C yr<sup>-1</sup> (Canadell et al. 2007). This was similar to the global carbon uptake in forest of 2.5 Pg C yr<sup>-1</sup> estimated by Pan et al. (2011), although Canadell et al. (2007) estimated the land sink as the residual of the balance of CO<sub>2</sub> emissions from fossil fuels and land use change, and atmospheric and oceanic CO<sub>2</sub> uptake. A more recent analysis suggests that carbon uptake in land and ocean is not diminishing, while mechanisms and locations responsible for carbon uptake need better identification (Ballantyne et al. 2012).

Very often, land and oceans are treated separately in analyses of (global) carbon budgets. Aquatic systems, if considered at all, have often been described as part of the terrestrial landscape rather than as conduits and active processors of carbon between land and ocean (Battin et al. 2009). Recent estimates of aquatic systems as channels for carbon processing and transport indicate that losses of land-derived carbon from surface waters from CO<sub>2</sub> evasion and sedimentation could be in the same order of magnitude as net carbon fluxes between atmosphere and land, i.e. 0.9 to 2.0 Pg C yr<sup>-1</sup> (Cole et al. 2007; Tranvik et al. 2009).

A recent estimate of the European carbon budget was corrected for lateral fluxes of carbon, including riverine transport and international transport of wood products, where the size of the lateral transport was similar to total carbon uptake in forests (Ciais et al. 2008). Riverine carbon export equalled approximately 50% of the soil carbon sink in European forest (Luysaert et al. 2010). The implications of a sizable export of aquatic carbon for the terrestrial carbon sink are not immediately obvious. Positive relations between precipitation and catchment dissolved organic carbon (DOC) export (Raïke et al. 2012), and between precipitation and soil carbon density (Post et al. 1982) are well-documented, and could imply that wetter climates promote both riverine carbon export and soil carbon accumulation. Soil carbon models usually do not explicitly take vertical and lateral transport of carbon into account but consider soil carbon accumulation primarily as a function of litter decomposition influenced by chemical composition and temperature (Liski et al. 2005; Sitch et al.

2003; White et al. 2000; Ågren et al. 2007b) although there are exceptions (Kleja et al. 2008; Michalzik et al. 2003).

Regional scale carbon balances where both terrestrial and aquatic carbon fluxes were estimated include the 3025 km<sup>2</sup> forested Öreälven catchment (Jonsson et al. 2007), the 4000 km<sup>2</sup> subarctic Lake Torneträsk catchment (Christensen et al. 2007) in northern Sweden, and the 6400 km<sup>2</sup> Northern Highlands Lake District in the northern US (Buffam et al. 2011). Here, terrestrially fixed carbon was estimated based on eddy covariance techniques that quantify net ecosystem exchange (NEE) of carbon, and thus do not differentiate between carbon uptake in soils and biomass. In such cases, the correction of net ecosystem carbon uptake with aquatic export is straightforward (Randerson et al. 2002), and the terrestrial carbon sink was reduced by 6 to 19% when aquatic carbon export was included. However, none of these studies quantified the soil carbon sink, and thus no insights in the possible role of aquatic carbon export for soil carbon sequestration were provided. Climate factors – temperature, precipitation - that drive soil carbon accumulation (Post et al. 1982) also drive lateral flows of carbon (Hope et al. 1994), and climatic effects on aquatic carbon export may counteract or balance climatic effects on soil carbon sequestration.

Regional carbon balances in northern landscapes are determined to a large extent by the presence of forest, but also peatlands, mountains, lake sediments and agricultural lands can contribute significantly to carbon uptake and losses at the regional scale (Kortelainen et al. 2004; Maljanen et al. 2010; Yu 2012). Here, we aim to estimate a carbon balance for Norway between 1990 and 2008, taking into account all major ecosystems (forests, peatlands, mountains, lakes, agricultural lands), and include all key terrestrial and aquatic carbon fluxes and their uncertainties. Secondly, we aim to evaluate the relative importance of terrestrial and aquatic carbon fluxes along climatic and productivity gradients under a uniform and consistent framework by comparing these in Norway's four main drainage areas. A comparison of terrestrial and aquatic fluxes will contribute to a better understanding of terrestrial and aquatic linkages in the carbon cycle and to further integration of aquatic carbon fluxes in estimations of terrestrial carbon accumulation.

## **Materials and methods**

### *Study area*

Mainland Norway (excluding the arctic islands Svalbard and Jan Mayen) has a surface area of 324,000 km<sup>2</sup>, where the main land cover types in declining order of area are mountains, forest, peatlands, surface waters and agricultural areas (Table 1, Figure 1). Less than 2% of the land area in Norway is developed, i.e. roads and buildings. Because of its elongation northwards and the mountainous areas in the south, Norway has strong climate and associated vegetation gradients from maritime mild temperate in the south (nemoral vegetation zone) and southwest to continental subarctic in inland valleys (boreal vegetation zone) to polar tundra above the treeline and subarctic climate furthest north (alpine vegetation zone) (Moen 1987). The four main drainage areas of Norway are Skagerrak in the southeast, the North Sea in the southwest, the Norwegian Sea in middle Norway, and the Barents Sea in the north.

### *Calculation method and uncertainty analysis*

For the terrestrial ecosystems, a carbon balance was calculated for the different land cover categories and summed to give the total (equation 1 in Table 3). For forests, carbon uptake was calculated by region and then summed to all forested area. Regions were delineated according to county, climate and data availability (see below). For all other land cover categories, carbon uptake was not differentiated according to region. Aquatic organic carbon (OC) fluxes were calculated according to drainage area and then summed for Norway. In the comparison of terrestrial and aquatic fluxes in each drainage basin, forest carbon fluxes were summed according to the drainage areas to which they belonged. Some drainage basins divided a forest region in two, and here the forest carbon fluxes attributed to each drainage basin by assuming area-normalized carbon uptake (Table 1).

Uncertainties in the carbon balance of Norway and its components were calculated in two steps. First, uncertainties in a specific carbon flux were calculated by considering sources of error in the individual variables included in the equations (Table 3). Second, these uncertainties were used to calculate total uncertainties in the carbon balance for forest, and for all of Norway. A normal distribution was attributed to each component as default, expressed as relative standard errors, except

where specified (see below). Each constituent of the carbon balance was either a product of variables and/or a sum of variables. Where constituents of the carbon balance had normal distributions, we used the following rules to calculate uncertainty in products or sums of variables, as recommended in IPCC guidelines for greenhouse gas inventories (IPCC 2006): Uncertainties in *products* were calculated as the root of the squared sum of *relative* uncertainties in the variables, while uncertainties in *sums* were calculated as the root of the squared sum of *absolute* uncertainties. For calculations of uncertainty with other error distributions, and for all of Norway, we used a Monte Carlo method with the Excel add-on Crystall Ball (Oracle Crystall Ball, Fusion Edition, release 11.1.2.0.00).

### *Forest biomass*

The method and data for the calculation of the forest carbon balance are described in (De Wit et al. 2006). In short, data from the National Forest Inventory (NFI) and municipal statistics of commercial round wood removals provide standing living biomass and harvested volume, respectively, which in turn are used to calculate litter inputs for a soil model.

Forested Norway was divided into eight regions taking into account differences in climate (mean annual temperature, input variable to the soil model) and data availability (Table 1). The forest carbon balance was calculated by subtracting carbon pools in 1990 from carbon pools in 2008 (Equation 2 in Table 3). Regions 1 to 6 are below the coniferous forest limit, with data collected in a uniform design, in three repeated samplings, for the period 1990 to 2008 (Tomter et al. 2010). In region 7 (northernmost county of Finnmark) and 8 (forest above the coniferous forest limit in region 1 to 6), data collection started in 2005. Living biomass (above- and belowground) in region 1 to 6 and 8 was calculated with single tree allometric equations for Norway spruce, Scots pine and deciduous trees (mostly birch) (Marklund 1988; Petersson & Ståhl 2006) (Equation 3 in Table 3). Biomass in region 7 was calculated by converting growing stock with biomass expansion factors (Lehtonen et al. 2004) (Equation 4 in Table 3). The growing stock in 2008 in region 7 was 15.0 million m<sup>3</sup>, distributed as 30% pine-dominated forest and 70% birch-dominated forest (S. Tomter, Norwegian Forest and Landscape Institute, pers. comm). Forest birch biomass in 1990 in region 7 and 8 was constructed using the estimated 11% increase in birch biomass growth between 1990 and 2008 in 50% of region 7

(Tommervik et al. 2009). Biomass in pine forest in 1990 in region 7 was calculated using 2006 biomass estimate, assuming a constant annual increment of 1.3% and natural mortality of 15% between 1990 and 2008 (S. Tomter, pers. comm). Biomass and annual increment in 1990 and 2008 in region 8 were estimated using the biomass estimate from 2006 (based on 4 years of the 5-year inventory cycle (2005-2008)), and assuming a constant annual increment between 1990 and 2008 while taking into account natural mortality (20% for coniferous, 25% for birch: S. Tomter, , pers. comm).

Ground vegetation biomass (bryophytes, lichens, herbs and grasses and dwarf shrubs) and litter production was estimated for each NFI plot using empirical models relating aboveground ground vegetation biomass to vegetation type and stand age (Muukkonen & Mäkipää 2006) (Equation 5 in Table 3). Belowground biomass was estimated as a fixed proportion of aboveground biomass and biomass turnover factors were associated with all above- and belowground biomass components (Peltoniemi et al. 2004).

For mountain forest ground vegetation biomass, a time series for 1990 to 2008 was constructed using the same procedure as for growing stock, assuming that the temporal development for ground vegetation biomass was similar as for stem volume. Because of missing NFI data in region 7, we used the relative temporal change in ground vegetation biomass in birch forest reported for 50% of region 7 (Tommervik et al. 2009).

Uncertainty in the variables in the equations for carbon pools were based on reported uncertainty where available and otherwise on expert judgement. Uncertainty in the conversion factors (CF) was calculated from the standard deviations in the conversion factors reported for each biomass component (Lehtonen et al. 2004; Marklund 1988). Uncertainty for the whole tree biomass was calculated by mass-weighting each biomass compartment to the whole tree, resulting in 2.2%, 1.7% and 3.0% for pine, spruce and birch respectively. Standard deviations in the CF for biomass components in ground vegetation were based on those reported for the ground vegetation model parameters (Muukkonen & Mäkipää 2006), resulting in 18%, 23% and 34% for pine, spruce and birch forest respectively. Uncertainty in forest and ground vegetation biomass in each region was weighted according to proportion of dominating vegetation type.

Uncertainty in measurements of diameter and height in individual trees in the Austrian NFI, which uses similar methods as the Norwegian NFI, was found to be 1% and 3% for coniferous trees, respectively, resulting in an uncertainty of 11% for volume of individual trees (Berger et al. 2014). The authors concluded that uncertainty in volume of individual trees were negligible for stock estimates of nationwide assessments. We set the uncertainty related to volume estimates for region 1 to 6, and for region 8 in 2008, at a maximum of 1%. We assume that these uncertainties were threefold larger (3%) for the 1990 input values in region 8, where measurements were not available. For region 7, biomass in 2008 was estimated from regional volume estimates where uncertainty is estimated to be ca 5% (S. Tomter, pers. comm). Similar to biomass in region 8 in 1990, we assume a threefold increase in uncertainty for the 1990 biomass in region 8. Uncertainty in stand age is substantially larger than in volume, but data on the uncertainty were not available. We assumed a 10% uncertainty in all cases except for 1990 and 2008 for region 7, and for 1990 in region 8 in 1990 where we set uncertainty at 25%.

#### *Forest soils*

The forest soil carbon sink in each region was estimated using the Yasso model (Liski et al. 2005), using annual litter flow and mean annual temperature as inputs. Yasso is designed to process data derived from forest inventories and simulates the forest soil carbon stock down to 1 m depth on a yearly time step (Liski et al. 2005). The balance between litter inputs and decomposition (the only process responsible for carbon loss from soil organic matter (SOM) in Yasso) drives soil carbon accumulation. Litter flow is divided in non-woody (foliage and fine roots), fine woody (branches, coarse roots, bark) and coarse woody (stem and stumps) litter. Three SOM compartments are simulated, i.e. undecomposed, quickly decomposable and slowly decomposable SOM. Decomposition and transition of OM from one OM compartment to the next is described by process rates.

Temperature sensitivity and litter quality dependency of process rates were calibrated on litter bag studies with widely varying litter quality and under varying climate. Process rates were calibrated to give a correct soil carbon pool for a forest stand in Sweden, where key ecosystem carbon pools and

fluxes were measured and used as input to Yasso (Liski et al. 2005). We used the standard parameters in Yasso for spruce, pine and birch litter.

Annual litter flows were calculated as the sum of litter from living biomass, ground vegetation, natural mortality and harvest residues. Turnover factors (species-specific, for each biomass compartment) for living biomass are given in De Wit et al. (2006). Natural mortality was estimated as a fixed percentage of annual increment (region 1 to 6: 6% and 10% , region 8: 20% and 25%, in coniferous and deciduous forest, respectively), as in De Wit et al. (2006). Unrecovered fellings were calculated as 6% and 10% of the volume of the commercial round wood removals of coniferous and deciduous trees, respectively, as in De Wit et al. (2006). Harvest residues were estimated by subtracting ‘biomass associated with fellings’ from biomass of stem and bark.

A steady state soil carbon pool in 1990 (i.e. litter inputs equal decomposition carbon losses) was not likely given the estimation of an active, non-steady state soil carbon pool for southeast Norway in 1990 in De Wit et al. (2006). This agrees with the reasoning from Liski et al. (2006) and Ågren et al. (2007b) where an increased growing stock is associated with increased litter input, which – given a constant climate – results in a positive SOM accumulation rate. We estimated the initial soil carbon pool by reducing the estimated steady state soil carbon pool in 1990, with the percentage difference in 1990 soil pool calculated using litter input time series starting in 1960. The litter input series was calculated from national NFI statistics, which document an increase in national growing stock since 1919 (Granhus et al. 2012) (see (Supplementary information (SI 1))). The 1990 soil carbon pools was calculated using the litter inputs time series starting in 1960, and a steady-state 1990 soil carbon pool was calculated using the 1990 litter inputs in the time series. The %-difference between the (non-steady state) soil carbon pool and the steady state soil in 1990 was assumed to indicate the non-steady state forest soil carbon pool in all regions, and was 79%, 72% and 60% in spruce-dominated, pine-dominated and birch-dominated forest, respectively.

The uncertainty of the soil carbon sink was related to litter flow inputs, decomposition rates and initialization. The uncertainties in these components are difficult to quantify but they are considerably higher than uncertainties in growing stock estimates, as these are based on systematic, large-scale measurements in the NFI. Thus, we choose to set high uncertainty intervals for the

components where little quantitative information was available. Uncertainty in harvest residues, natural losses and ground vegetation biomass (Peltoniemi et al. 2006) were set at 25%, 30% and 25% respectively. Uncertainty in litter from standing biomass was set at 25% (non-woody litter), 15% (fine woody litter) and 10% (coarse woody litter), in agreement with the associated increasing uncertainty in the allometric equations (Marklund 1988). By region, this resulted in an uncertainty of 11 to 20% in litter inputs. Uncertainty in decomposition rates was set at 10%, which is within uncertainty intervals given by Liski et al. (2005). The uncertainty related to the initialization was set at 25% (De Wit et al. 2006).

### *Peatlands*

Uptake of carbon in peatlands in Norway was calculated separately for drained and undisturbed peatlands. Undisturbed peatland were separated into boreal and subarctic bogs. Peatland carbon accumulation rates in undisturbed peatlands and carbon losses from disturbed peatlands were taken from literature and multiplied with area for their respective peatland type (Equation 6 in Table 3).

Peatland area and type have not been assessed in great detail in Norway. The Norwegian Forest Inventory supplies a number of 4.7% of treeless peatlands (>30 cm organic layer) while Moen et al. (2011) assessed that circa 8% of Norway is covered by peatlands (>30 cm organic layer), including cultivated and drained peatlands, forest on organic soils (>30 cm organic layer), and wooded mire (Table 2). The areas defined as 'peatlands' by Moen thus belong partly to other land cover types than the NFI classification of 'peatlands'. Circa 15-30% of all peatlands has been drained for cultivation and forest growth in the 20<sup>th</sup> century, most actively until the 1960s (Johansen 1997). This practice was less common in treeless peatlands than in forests, suggesting that drainage of treeless peatlands was at the lower end of the indicated interval of 15-30%. We use the lower end of the interval, i.e. 15%, to calculate area of drained peatlands (170 km<sup>2</sup>) in Norway except for Finnmark (subarctic Norway). In Finnmark, we assume that no draining occurred due to low population and land use pressures.

The dominating type of peatlands at lower elevation in Norway are bogs (acidic, and nutrient-poor, mostly rain-water fed, and deeper), while fens (more alkaline, fed by groundwater, shallower)

are more common at higher elevation and latitude (A. Moen, NTNU, pers.comm.). A field-survey based estimate for mean depth of Norwegian boreal peatlands is 1.7 m (A. Moen, NTNU, pers.comm), higher than the mean estimate of boreal and subarctic peatlands in Fennoscandia of 1.1 m, given by Gorham (1991). In southeast and middle Norway, the dominating peatlands are typical raised bogs, an ombrotrophic peatland type (Moen et al. 2011). Atlantic raised bogs (blanket bogs) are found at the westernmost coast of western and northern Norway. Their limited surface area does not justify a separate treatment in our approach. In northern Norway, arctic-alpine shallow fens dominate the peatlands, with relatively low contents of organic matter and considerable mixing with mineral parent material (Moen & Øien 2011).

To estimate carbon accumulation rates for Norwegian peatlands, we used published data on measured carbon balances from representative undisturbed boreal and subarctic peatlands (Table 4). Only a few full carbon balances for northern peatlands exist (i.e. Nilsson et al. (2008), Roulet et al. (2007), Olefeldt et al. (2012)) where the net ecosystem carbon balance (NECB) is calculated as the sum of net ecosystem exchange (NEE) corrected for CH<sub>4</sub> emissions and DOC export (Yu 2012). Several other studies (i.e. Sagerfors et al. (2008), Lund et al. (2007), Aurela et al. (2007), Aurela et al. (2009), Aurela et al. (2004) ) measured only NEE and we chose to estimate CH<sub>4</sub> emissions and DOC export for these ecosystems in order to extend the basis for a robust estimate of carbon accumulation rates for Norwegian peatlands. A separate rate was estimated for subarctic peatlands as these appear to be less productive and have lower carbon stores (Lund et al. 2010; Turunen et al. 2002). Methane emissions were estimated by attributing measured rates to those sites for which they were most representative. The DOC export was estimated by calculating discharge for each site by correcting precipitation for evapotranspiration, and multiplying discharge by a default DOC concentration (i.e. the ratio of DOC export per mm discharge from the studies with the full carbon balance). The ratios were attributed to those sites for which they were most representative, while the uncertainties in the rates were derived from the full carbon balances (see notes under Table 4).

For drained peatlands, a longer-term estimate of losses of 30 g C m<sup>-2</sup> yr<sup>-1</sup> was given by Armentano and Menges (1986), between the IPCC mean emission factors for boreal and temperate drained forest land of 39 and 26 g C m<sup>-2</sup> yr<sup>-1</sup>, respectively (IPCC 2014). We set the relative uncertainty

equal to the peat accumulation rate in undisturbed peatlands. Losses from cultivated peatlands are treated under the 'agricultural areas'.

### *Agricultural areas*

Carbon emissions from agricultural soils depend on soil and management type (Maljanen et al. 2010). 65% of all agricultural land in Norway is temporary or permanent grassland and the remainder is arable land (primarily cereal and oil seed crops, and potatoes). Approximately 70% of the grasslands is fully cultivated (including plowing) while the remainder is surface-cultivated (Rognstad & Steinset 2012). Agricultural areas in Norway have been classified into mineral and organic soil types, which cover 10.18 and 0.83 thousand km<sup>2</sup>, respectively (Grønlund et al. 2008b). Combined statistics on soil type and land use are not available. We assume that cultivation of arable crops (35% of all agricultural land) is restricted to mineral soil types and distribute the remaining 65% grasslands proportionally over the remaining mineral and organic soil types (Table 5).

Carbon emissions from cultivated soils are highly variable. We use the carbon emission factor ( $590 \pm 290 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) for cultivated boreal drained inland organic grassland soils in the IPCC Wetlands Supplement (IPCC 2014). Conversion from tillage to no-tillage management usually reduces carbon emission rates from agricultural soils (West & Post 2002). Paustian et al. (2000) showed an up to two times longer residence of SOM under no-till compared with intensive tillage. Based on this, we assume that carbon emissions from the surface-cultivated grasslands on organic soils are 50% of the carbon emissions from fully cultivated grassland soils. For mineral soils, we do not differentiate according to cultivation practice because of lacking land-use specific carbon emission factors. A model study by Andren et al. (2008) indicated that mineral soil types were close to balance in Swedish agriculture, and we set the carbon loss rate for mineral soils to zero. The uncertainty in the loss rate for mineral soils was assumed to be proportional to the uncertainty in the loss rates for organic soils, and was calculated as the ratio of mineral and organic soil density multiplied by the uncertainty in the loss rate for fully cultivated organic grassland soils (Table 5). Mineral and organic agricultural soil types in Norway have estimated mean soil carbon densities of 15 and 56 kg m<sup>-2</sup> (Grønlund et al. 2008b).

Mean annual change in soil carbon storage in cultivated soils was calculated by cultivation type and soil type and summed (Equation 7 in Table 3). Changes in biomass were not considered, as agricultural crops and grass cultivated in Norway are not considered long-term sinks of carbon.

### *Mountains*

Mountain areas were defined as high elevation areas with little or no vegetation, consisting of four NFI land cover types, i.e. other wooded land (OWL) (circa 10% of the total), bare rock and shallow soils, wooded mire and Calluna heath (Table 2). Few data are available for carbon pools and changes therein in mountainous regions in Norway. NFI statistics provided growing stock per region for OWL between 2005 and 2008, i.e. <0.5% (region 1-3, 6), ~1% (region 4, 5) and 5% (region 8) of forest growing stock. Increased vegetation cover in mountainous areas occurs as a consequence of reduced summer farming and grazing pressure (Bryn 2008), suggesting an increase in biomass. Tree biomass in mountainous regions were estimated on the NFI statistics shown above, while ground vegetation biomass was assumed to be similar to tree biomass (mosses, bushes and shrubs are a common form of mountain vegetation in the tundra ecotone, see for instance Tommervik et al. (2009)). Biomass increase was estimated assuming a similar %-increase as forest biomass in region 7 (northern Norway), i.e. 0.01%, with an uncertainty interval of 50% (Equation 8 in Table 2). Changes in soil organic matter were considered as too uncertain to allow a meaningful contribution to the calculated carbon balance.

### *Lake sedimentation*

No nation-wide data on lake carbon sediments and sedimentation rates exist for Norway. We applied a Finnish model for lake carbon sediment pools (Kortelainen et al. 2004), developed for Finnish lakes in the Nordic Lake survey database sampled in 1995 (Henriksen et al. 1998). Here, the lake sediment carbon pool is quantitatively related to lake area, % agricultural area, and concentrations of dissolved total iron and dissolved nitrate. The Nordic lake database includes lakes from Finland, Sweden and Norway; selected using stratified random sampling and thus considered representative for the Nordic countries. Data collection with regard to catchment, lake and water chemistry was uniform across the

survey. Finland and Norway have similar climate, vegetation and geology suggesting that the relations found for Finland may also apply to Norway. We used the model to estimate sediments in circa 1000 Norwegian lakes, resulting in a mean lake sediment carbon density of  $17.8 \pm 8.2 \text{ kg C m}^{-2}$ . The estimated annual lake carbon sedimentation rates was  $1.8 \text{ g C m}^{-2} \text{ lake yr}^{-1}$ , assuming a linear development of the lake sediment stocks since the last Ice Age (10 000 years ago). Uncertainty in lake sediment pools and sedimentation rates was set at 50%, i.e. roughly the standard deviation of the lake sediment pools (Equation 9 in Table 2).

### *Aquatic carbon fluxes*

Aquatic fluxes of carbon were separated into riverine transport of total organic carbon (TOC) and dissolved inorganic carbon (DIC), and in evasion of  $\text{CO}_2$  from lakes and rivers.

- *TOC transport*

Riverine transport of TOC were estimated based on water chemistry and discharge from 46 major river outlets in Norway, monitored under the RID (Riverine Inputs and Direct Discharges) programme (OSPAR 2013; Skarbøvik et al. 2013) (Table 1, Table 6, Figure 1). The monitored river catchments cover 48% of Norway. Three drainage areas extend into Sweden, Finland and Russia. Carbon fluxes were corrected for this by assuming constant areal export coefficients and constant relative uncertainty.

The availability of water chemistry and discharge depended on river size. In the 10 largest rivers, water was sampled at monthly intervals while discharge was measured (1999-2008). In 36 smaller rivers, water was sampled annually between 1999 and 2003 and quarterly between 2004 and 2008, while discharge was modelled with the spatially distributed version of the hydrological HBV-model (Beldring et al. 2003). Concentrations of TOC were assumed to be equal to dissolved organic carbon (DOC). Concentrations of phytoplankton in Norwegian rivers are generally considered to be low because of low nutrient levels (Skarbøvik et al. 2009). The particulate fraction is small – on average, DOC in the largest rivers constitutes >95% of TOC (Austnes, unpublished data). In other Nordic studies of surface waters, DOC is more than 90% of TOC (Kortelainen et al. 2006; Mattsson et al. 2005)

For each river, annual flow-weighted concentrations of TOC (FWC TOC) for the years 1999-2008 were calculated by dividing annual TOC export with annual discharge. Annual TOC export was summed from daily TOC export, calculated by multiplying daily discharge by daily TOC concentration. Daily TOC concentrations were linear interpolations of measured TOC. Mean annual FWC TOC and associated uncertainty was calculated for each river as the average and standard deviation of annual FWC TOC for 1999-2008. For each drainage area, a catchment area-weighted mean FWC TOC was calculated based on the individual rivers, and multiplied by mean annual discharge (1990-2008) to obtain riverine TOC export (1990-2008) for the entire drainage area (Equation 10 in Table 2). Uncertainty in river TOC export was calculated using the standard deviations of area-weighted mean FWC TOC and mean annual discharge. Total riverine TOC transport for Norway was obtained by summing per drainage area.

- *CO<sub>2</sub> evasion*

CO<sub>2</sub> evasion was estimated separately for lakes and rivers. For lakes, CO<sub>2</sub> evasion rates were calculated for the 1000 Norwegian lakes in the Nordic lake survey (Henriksen et al. 1998). The rates were calculated using the equation describing flux of CO<sub>2</sub> over lake surfaces given in Jonsson et al. (2007), with the gas exchange velocity (k) applied in Humborg et al. (2010) (2 cm hr<sup>-1</sup>), CO<sub>2water</sub> from the TOC-pCO<sub>2</sub> relationship (GLM model) for Norwegian lakes (Larsen et al. 2011) and Henry's law, and CO<sub>2eq</sub> calculated using Henry's law, a pCO<sub>2air</sub> of 360 µatm and a water temperature of 8°C. Details on the methodology is found in Cole and Caraco (1998). Estimating pCO<sub>2</sub> from DOC has been done elsewhere (Humborg et al. 2010; Rantakari & Kortelainen 2008; Sobek et al. 2003; Worrall & Burt 2005). Similar to Humborg et al. (2010), median CO<sub>2</sub> evasion rate in five lake size categories (0-0.1, 0.1-1, 1-10, 10-100 and >100) was calculated (30.9, 28.8, 27.2, 26.7 and 27.7 g C m<sup>-2</sup> yr<sup>-2</sup>, respectively) and multiplied by the total area for each lake category, to give total lake CO<sub>2</sub> evasion.

There was a lack of relevant data for a direct calculation of CO<sub>2</sub> evasion in Norwegian rivers, and we relied on Humborg et al. (2010), a comprehensive study on river CO<sub>2</sub> evasion from Sweden. The area-weighted mean river CO<sub>2</sub> evasion rate estimate for Sweden is 1698 g C m<sup>-2</sup> yr<sup>-2</sup>. This rate is probably lower in Norway because of lower forest cover and shallower soils in Norway than Sweden, and therefore a less abundant source of heterotrophic and autotrophic CO<sub>2</sub> production and –transport

to rivers. Therefore, we calculated the CO<sub>2</sub> evasion rate from Norwegian rivers (902 g C m<sup>-2</sup> yr<sup>-2</sup>) by multiplying the ratio of CO<sub>2</sub> evasion in Norwegian and Swedish lakes by the Swedish river CO<sub>2</sub> evasion rate, and multiplied the rate by river area to give total river CO<sub>2</sub> evasion. River area (1237 km<sup>2</sup>) was estimated as the difference between surface water area (Table 1) and total lake area (19162 km<sup>2</sup>). The uncertainty of the CO<sub>2</sub> evasion was estimated from the 10- and 90-percentiles for the lake evasion rates in each size category, which were area-weighted to give the percentiles for all lake sizes. The relative percentiles were applied to the overall CO<sub>2</sub> evasion to give the uncertainty range.

- *DIC transport*

No representative data for DIC or alkalinity in Norwegian rivers are available. The only land-representative water chemistry dataset with relevant parameters was the Norwegian lake dataset from the Nordic lake survey (Henriksen et al. 1998). DIC concentration was calculated from the sum of HCO<sub>3</sub><sup>-</sup>+CO<sub>3</sub><sup>2-</sup> (estimated from alkalinity and pH) and dissolved CO<sub>2</sub> (see method description under ‘CO<sub>2</sub> evasion’) (Jonsson et al. 2007). Lake DIC was multiplied by the catchment-lake-specific normal discharge (1961-1990) (Beldring et al. 2002) to give lake DIC fluxes in g C m<sup>-2</sup> yr<sup>-1</sup>. Multiplying the different lake DIC fluxes by the area of Norway gave a range of DIC export, of which the median was chosen as the DIC export for Norway. The DIC fluxes were calculated for 1990 to 2008 by multiplication by the ratio of 1990-2008 discharge and 1961-1990 normal discharge for Norway. The 10- and 90-percentile of the lake DIC export, adjusted for discharge in the same way, was used as uncertainty range.

The use of lake instead of river chemistry might introduce a bias to the DIC export estimate. In Sweden, river mouth and stream DIC was found to be systematically higher than lake DIC, which was attributed to increasing groundwater inputs of carbonates (Humborg et al. 2010). However, no systematic differences between stream order and DIC were found in headwaters in Sweden and Finland (Huotari et al. 2013; Olefeldt et al. 2013; Wallin et al. 2013). An opposite effect to DIC estimates might be the declining oversaturation of dissolved CO<sub>2</sub> with stream order. Without additional data, biases in the DIC export are difficult to evaluate.

## Results

### *Carbon balance of Norway*

The mean annual uptake of carbon in terrestrial ecosystems in Norway between 1990 and 2008 was  $6.0 \pm 0.9$  Tg C, which equalled 40% of Norway's mean annual greenhouse gas (GHG) emissions for the same period (Figure 2A). The summed riverine transport of OC and DIC was almost 25% of the terrestrial carbon uptake, or  $1.0 \pm 0.1$  and  $0.3$  ( $0.1-0.8$ ) Tg C yr<sup>-1</sup>, respectively. It is important to note that the net change in the terrestrial carbon pool size is not simply found by reducing the terrestrial carbon uptake with the riverine OC export. Links between terrestrial carbon sequestration and lateral aquatic carbon transport may be conceptually clear, but methodologically it is not straightforward to incorporate estimates of lateral aquatic carbon transport in terrestrial carbon accumulation estimates at a regional scale. We will return to this issue in the discussion. Evasion of CO<sub>2</sub> from surface waters was  $1.7$  ( $0.6 - 4.0$ ) Tg C yr<sup>-1</sup>, which includes CO<sub>2</sub> from in-lake processing of OC, from autotrophic and heterotrophic respiration on land and from weathering processes. The largest terrestrial carbon uptake was in forest biomass ( $4.9 \pm 0.4$  Tg C yr<sup>-1</sup>), followed by forest soils ( $1.1 \pm 0.2$  Tg C yr<sup>-1</sup>). Carbon uptake in peatlands and carbon losses from agricultural areas almost balanced each other ( $0.3 \pm 0.2$  and  $-0.4 \pm 0.8$  Tg C yr<sup>-1</sup>, respectively). Mountains and lakes were the smallest carbon sinks ( $<0.1$  Tg C yr<sup>-1</sup>).

On an area basis, the most effective carbon sinks were forest biomass ( $40 \pm 3$  g C m<sup>-2</sup> yr<sup>-1</sup>) and peatland soils ( $19 \pm 15$  g C m<sup>-2</sup> yr<sup>-1</sup>), while the agricultural soils lost carbon ( $-36 \pm 74$  g C m<sup>-2</sup> yr<sup>-1</sup>) (Figure 2B). The lowest rates of carbon accumulation were found in forest soils ( $9 \pm 1$  g C m<sup>-2</sup> yr<sup>-1</sup>), lake sediments ( $1.8 \pm 0.9$  g C m<sup>-2</sup> yr<sup>-1</sup>) and mountain vegetation biomass ( $0.5 \pm 0.3$  g C m<sup>-2</sup> yr<sup>-1</sup>).

The uncertainty in the total terrestrial carbon uptake was 16%, primarily related to the uncertainty in three components of the carbon balance, i.e. carbon uptake in tree biomass, peatlands and agricultural soils. The uncertainty in carbon loss rate was larger than the rate itself for agricultural soils (Table 5). The relative uncertainty was lowest in tree biomass and forest soils, followed by peatlands. Mountain biomass and lake sediments had similar relative uncertainty but because of their modestly sized sink, mountains and lakes hardly contributed to the uncertainty in carbon uptake at the national scale.

### *Forest carbon sink*

The uncertainty in the forest biomass sink for all of Norway was relatively small (8%) because of the high precision in the forest inventory data. Most of the uncertainty in the forest biomass was related to the allometric equations. The uncertainty at the regional level was higher than at the country level (Table 7). In region 7 and 8, this was primarily related to the relatively poor data quality. Uncertainty in allometric equations was highest for birch and lowest for spruce forest, which added to the regional differences in uncertainty in forest biomass. The mean annual tree biomass sink in our study was 4.90 Tg C yr<sup>-1</sup>, less than 0.1 Tg C yr<sup>-1</sup> higher than the reported mean annual change in tree biomass for the period 1990 to 2009 in Norway, i.e. 4.83 Tg C yr<sup>-1</sup>, in the GHG inventory report (Miljødirektoratet 2013). The inventory report had its own method for backcasting biomass in mountain forest and Finnmark in 1990 (region 7 and 8), which may account for the difference between our estimate and the GHG inventory estimate.

The forest biomass carbon sink declined strongly from south to north (Table 7). South Norway (region 1 to 4) and high latitude and mountain forest (regions 7 and 8) represented 76% and 7%, respectively, of the total forest biomass sink. Most of Norway's productive forest is in the southeast, as illustrated by the high tree volume density, forested area (Table 1) and annual increment (Table 7). On an area basis, biomass carbon uptake varied between 12 and 76 g C m<sup>-2</sup> yr<sup>-1</sup>, with the highest rate found in western Norway (region 4) and the lowest in high latitude and mountain forest. In western Norway, only 15% of annual increments were felled, whereas elsewhere in south Norway 38% to 54% of annual growth was harvested (Table 7). The regional biomass sinks (in g C m<sup>-2</sup> yr<sup>-1</sup>) were significantly and positively correlated with mean annual temperature (MAT) ( $r^2 = 0.88$ ;  $p < 0.005$ ) (Table 8). Thus, the regional variation in the biomass carbon sink related to climate and harvesting intensity.

Soil carbon accumulation rates were between 2.3 and 12 g C m<sup>-2</sup> yr<sup>-1</sup>, and strongly and positively correlated with the biomass sink ( $r^2 = 0.84$ ,  $p < 0.01$ ) and MAT ( $r^2 = 0.77$ ,  $p < 0.05$ ) (Table 8). For the national soil carbon sink, uncertainty was 15%, primarily related to initialisation of the soil model and secondly, to variations in litter inputs. Uncertainty in the regional soil sink varied around 30%, except for northern Norway, where the uncertainty was larger than the sink. The relatively poor

data quality for the tree biomass in this region cascades down to the soil sink, as tree data drive soil carbon dynamics in our scheme of calculation.

#### *Carbon uptake in peatlands, mountains, lakes and agricultural areas*

The carbon sinks and sources of peatlands, mountains, lakes and agricultural areas were based on a combination of published studies with relevance for Norwegian conditions combined with what was available of national data. The annual change in the peatland carbon pool was calculated for undisturbed boreal and arctic ( $0.29 \pm 0.22$  and  $0.06 \pm 0.04$  Tg C yr<sup>-1</sup>, respectively), and disturbed boreal peatlands ( $-0.05 \pm 0.04$  Tg C yr<sup>-1</sup>), giving a total of  $0.29 \pm 0.23$  Tg C yr<sup>-1</sup> ( $19.3 \pm 15.2$  g C m<sup>-2</sup> yr<sup>-1</sup>). The uncertainty in the carbon sink for peatlands was related to variation in the carbon accumulation rates of the three full carbon balances for boreal and subarctic peatlands. Norway does not report on unmanaged wetlands in its national GHG inventories (Miljødirektoratet 2013).

The lake carbon sink in the sediments was modest ( $<0.1$  Tg C yr<sup>-1</sup>), calculated using an estimate of the Holocene lake sedimentation rate and large uncertainty, which was a reflection of spatial variation in lake sediment pools estimates. Mountainous Norway was a small carbon sink ( $0.07$  Tg C yr<sup>-1</sup>), related to increased biomass on wooded mires. Mountains are an inhomogeneous type of landscape with generally little vegetation and shallow soils, except for wooded mires. The reported change in biomass pools on wooded mires in 2011 in the National GHG Inventory Report was  $0.02$  Tg C (Miljødirektoratet 2013). Estimates for 1990 to 2008 were not available. Agricultural areas, by contrast, were a large but highly uncertain source of carbon to the atmosphere ( $-0.40 \pm 0.80$  Tg C<sup>-1</sup>). The main reason for the net losses from agricultural areas was subsidence of cultivated organic soils from cultivation. The uncertainty interval opened for the possibility that agricultural areas in Norway gain carbon, which was primarily related to the large uncertainty in the carbon balance of mineral soils. The national inventory report for GHG emissions between 1990 and 2008 estimated a mean annual loss from agricultural land (cropland and grassland) of  $0.57$  Tg C, primarily related to organic soils (Miljødirektoratet 2010), and the estimate was lowered to  $0.48$  Tg C in a subsequent inventory report, related to improved data quality (Miljødirektoratet 2013).

### *Aquatic organic and inorganic carbon fluxes*

Riverine transport of TOC was lowest in the Barents Sea ( $0.1 \text{ Tg C yr}^{-1}$ ) and varied between 0.2 and  $0.4 \text{ Tg C yr}^{-1}$  in the other drainage areas (Table 6). Area-normalized TOC export was highest in western Norway ( $4.5 \text{ g C m}^{-2} \text{ yr}^{-1}$ ), which was associated with highest discharge ( $2400 \text{ mm yr}^{-1}$ ) while TOC concentrations were lower than elsewhere in Norway. The Barents Sea drainage area had the lowest area-specific TOC export ( $1.7 \text{ g C m}^{-2} \text{ yr}^{-1}$ ), and here mean annual discharge was below  $500 \text{ mm yr}^{-1}$ . Estimates of TOC export per drainage basin had uncertainty intervals between 10% and 19%, related to interannual variations in discharge and TOC concentrations, and to variations in TOC between rivers.

Rivers contributed more to surface water  $\text{CO}_2$  evasion than lakes ( $1.1$  and  $0.5 \text{ Tg C yr}^{-1}$ , respectively), which is explained by the considerably higher river  $\text{CO}_2$  evasion rates from rivers ( $902$  ( $341$ - $2177$ )  $\text{g C m}^{-2} \text{ river yr}^{-1}$ ; lakes  $28$  ( $11$ - $68$ )  $\text{g C m}^{-2} \text{ lake yr}^{-1}$ ), which more than compensates for the relatively low area covered by rivers (6% of lake area). Riverine DIC transport ( $0.3 \text{ Tg C yr}^{-1}$ ) equalled almost 20% of the  $\text{CO}_2$  evasion.

Possibly, the sum of DIC export and  $\text{CO}_2$  evasion is overestimated because of double-counting dissolved  $\text{CO}_2$ , as DIC and  $\text{CO}_2$  evasion both rely on  $\text{pCO}_2$  in Norwegian lakes. All DIC that derives from supersaturated dissolved  $\text{CO}_2$  is assumed to be exported to the coast, while some supersaturated dissolved  $\text{CO}_2$  evades to the atmosphere. If  $\text{CO}_2$  oversaturation is disregarded in the calculation of coastal DIC inputs, by assuming equilibrium between atmospheric and dissolved  $\text{CO}_2$  at the river mouth, the estimate of DIC export is reduced by 35% to  $0.19 \text{ Tg C yr}^{-1}$ . However, it is unlikely that all excess dissolved  $\text{CO}_2$  is lost along the aquatic conduit. Moreover, groundwater is an increasingly important source of DIC from headwaters to coast, but hard to account for quantitatively. The possibility of double-counting cannot be resolved with the current data. The relatively poor suitability of the data for calculation of these estimates resulted in the widest uncertainty intervals of all the aquatic fluxes.

### *Carbon fluxes per drainage area*

Area-normalized terrestrial carbon uptake (in all ecosystems except agriculture) was largest in southeast Norway and declined towards west, middle and subarctic Norway (Figure 1). This pattern

was primarily related to a decline in carbon accumulation in biomass. Carbon sequestration in soils and peatlands varied between the drainage areas, because of a considerable proportion of peatlands in middle and subarctic Norway (Table 1), and because of a higher carbon sequestration rate in peatlands than in forest soils (Figure 2B). In subarctic Norway, carbon accumulation in peatlands dominated over carbon accumulation in forest soils. Riverine transport of OC varied more between drainage areas ( $1.7$  to  $4.5 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) than accumulation of carbon in soils ( $3.7$  to  $6.1 \text{ g C m}^{-2} \text{ yr}^{-1}$ ). The riverine OC flux equalled 10% of the terrestrial carbon uptake in southeast Norway and 19% to 23% in the other drainage basins (Figure 3). In subarctic Norway, about half of what was stored in biomass annually was transported as OC to the Barents Sea. For the other drainage areas, this percentage varied between 13% and 25%. In west Norway, the riverine carbon flux exceeded the combined accumulation of carbon in peatlands and forest soils, and was elsewhere 46% to 77% of combined forest soil and peatland accumulation.

## Discussion

### *Carbon accumulation in boreal landscapes - forests*

Boreal landscapes in Norway are important sinks for atmospheric CO<sub>2</sub>: uptake in biomass and soils was equal to circa 40% of anthropogenic greenhouse gas emissions (in CO<sub>2</sub> equivalents) in Norway between 1990 and 2008 (Miljødirektoratet 2010). Globally, the land carbon sink – not included emissions from land use change – amounts to 30% of CO<sub>2</sub> emissions from fossil fuel and cement (Le Quéré et al. 2013).

In Norway, forests comprise the largest carbon sink, as well as in Sweden and Finland. Combined annual forest carbon uptake in the Nordic countries (this study, Ågren et al. (2007b) and Liski et al. (2006)) around the start of the 21<sup>st</sup> century was 21 Tg C, corresponding to circa 0.3% of global carbon emissions from fossil fuels and cement production (Canadell et al. 2007). Expressed on an area basis, forest biomass in Norway accumulated 40 g C m<sup>-2</sup> yr<sup>-1</sup> (1990-2008) (this study). In Sweden, a comparable estimate is 23 (1926-2006) (Ågren et al. 2007b), and in Finland 28 (1990-1999) (Liski et al. 2006) g C m<sup>-2</sup> yr<sup>-1</sup>. The soil carbon sink in these studies is 23%, 35% and 39% of the biomass sink, respectively. Luysaert et al. (2010) calculated a biomass and soil carbon sink in European forests between 1990 and 2005 of 54 and 22 g C m<sup>-2</sup> yr<sup>-1</sup>, respectively. Luysaert et al.'s estimate of the biomass sink was primarily based on forest inventory data, just like the Fennoscandian studies, and is therefore expected to be of similar certainty. The present rates of biomass increase in Scandinavia are largely a legacy of reduced logging intensity and the age-structure of the forest (Anton-Fernandez & Astrup 2012), suggesting that future growth rates may decline (Liski et al. 2006; Luysaert et al. 2010). Old forests can still be strong carbon sinks, but less effective than younger, middle-age forests (Luysaert et al. 2010; Luysaert et al. 2008).

Interestingly, the soil carbon sink for Europe is considerably larger than the national forest soil sink estimates for Fennoscandia, suggesting that present rates of soil carbon accumulation of temperate forests exceed those of boreal forests. However, soil carbon pools in boreal forests are higher than in temperate forests (Lal 2005; Post et al. 1982), implying lower Holocene soil carbon accumulation rates in temperate than in boreal forests. Luysaert et al. (2010) calculated the soil carbon sink with a simple soil model (Nabuurs et al. 2003), somewhat comparable to the Yasso model

(Liski et al. 2005) and the Q-model (Ågren et al. 2007b) used in the Fennoscandian studies. These models describe soil carbon accumulation as driven by litter decomposition and dependent on litter quality, with fixed (Nabuurs) or temperature-dependent (Yasso, Q-model) decay rates. Soil carbon accumulation rates in European forests might be higher than in Fennoscandian forests, possibly due to higher levels of nitrogen deposition in Europe (de Vries et al. 2009). Nitrogen deposition, however, is not included as a driver of soil carbon accumulation in the aforementioned models. None of the models has detailed descriptions of soil-forming processes, probably because they were developed for processing data derived from forest inventories, with calibration of process rates based on litter bag studies (Hyvonen & Ågren 2001; Liski et al. 2003; Liski et al. 2005). Thus, soil carbon accumulation in these models was simply defined as the balance between litter production and heterotrophic respiration of litter and SOM, where litter quality and temperature-dependent decay rates are central features.

Our approach for calculating the soil carbon sink hinges on the assumption that vegetation dynamics are the dominant driver of soil carbon sequestration (Liski et al. 2006), an assumption which is also used in global vegetation models, i.e. Sitch et al. (2008). Using temperature as a climatic driver of soil carbon sequestration, however, is a gross simplification of well-understood climatic effects on soil carbon cycling. For instance, Post (1982) suggests that precipitation is a strong positive driver of soil carbon accumulation in biomes. Within northern and temperate climates, soil organic matter accumulation is strongly and positively related to precipitation (Callesen et al. 2003; Michalzik et al. 2001; Michalzik et al. 2003) in addition to temperature, adsorption processes and organic matter quality (Lundstrom et al. 2000). Whether the net effect of increased forest growth and higher temperatures is more soil carbon storage is under debate (Davidson & Janssens 2006; Jandl et al. 2007; Kammer et al. 2009). Possible biases in the forest carbon soil sink estimates for Europe and Fennoscandia, related to the overly simplified soil models, are hard to evaluate, as few other estimates for soil sinks at regional scales are available.

*Carbon accumulation in boreal landscapes - mountains, peatlands, agricultural areas, lakes*

Our estimates of ecosystem carbon sinks indicate that the other dominating ecosystems in Norway are far less effective carbon accumulators than forests. Mountainous Norway sequesters little carbon, despite covering most of Norway. The most likely process for increasing carbon stores in the mountains is birch forest expansion related to reduced summer farming and grazing pressure (Bryn 2008; Speed et al. 2014), however, carbon pools in mountain forest and tundra vegetation are low compared with forest. De Wit et al. (2014) concluded that mountain forest expansion has limited potential to increase the terrestrial carbon sink in Norway.

The net carbon accumulation in peatlands is the result of accumulation in undisturbed peatlands and losses of carbon from drained peatlands. The estimated overall carbon accumulation rate ( $19 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) is somewhat lower than the long-term ( $29 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) and recent ( $23 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) carbon accumulation rate in northern peatlands (Gorham 1991). A synthesis of eddy covariance carbon flux studies at five northern peatland sites indicated a much higher carbon accumulation rate during the last decade ( $32 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) than during the last 7000 years ( $11 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) (Yu 2012). Some of the peatland flux studies in Yu's study were from bogs in oceanic climates with longer growing seasons (Ireland, Scotland), which could account for the relatively high carbon accumulation rates. Our estimate appears to be in reasonable agreement with other studies on peatland carbon accumulation.

Agricultural soils are a significant, but highly uncertain source of atmospheric carbon. Subsidence of cultivated organic soils was the main driver of the agricultural carbon source, based on an IPCC emission factor of  $570 \text{ g C m}^{-2} \text{ yr}^{-1}$  which is close to emission factors estimated for Norwegian cultivated peat soils (i.e., 800, 860 and  $600 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) (Grønlund et al. 2008a). Agricultural, cultivated organic soils cover 3% of Norway, and their importance in the national carbon balance is disproportionate to their size. Other studies of greenhouse gas emissions from northern agricultural soils also emphasize carbon losses from organic soils (Kasimir-Klemetsson et al. 1997; Maljanen et al. 2010).

The estimate for the lake carbon sink in Norway is modest compared with global estimates of sedimentation in lakes (Cole et al. 2007). Lake carbon sedimentation was insignificant compared with

transport and mineralization of terrestrial organic carbon in a large catchment in Northern Sweden (Jonsson et al. 2007), similar to our study. We used the mean Holocene carbon of  $1.8 \text{ g C m}^{-2} \text{ lake area yr}^{-1}$  as an estimate of lake carbon accumulation rates, with a variation between  $0.2$  and  $8.5 \text{ g C m}^{-2} \text{ yr}^{-1}$ . This range is wider than measured rates of lake carbon sedimentation in boreal regions (i.e.  $1.0$  to  $5.7 \text{ g C m}^{-2} \text{ lake area yr}^{-1}$ ) (Algesten et al. 2004). Paleolimnological studies of Norwegian lakes document substantial variation in lake sedimentation over time (Balascio & Bradley 2012). Still, even a tripling of the lake carbon sink will not turn it into a significant factor in the carbon balance of Norway. It seems reasonable to conclude that lake sedimentation is a process of minor importance for recent carbon accumulation in northern landscapes, although in a longer-term perspective boreal lakes sequester significant amounts of carbon (Kortelainen et al. 2004).

#### *Riverine carbon export from boreal landscapes*

The river OC export estimate for Norway ( $3.0 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) is firmly grounded in monitoring data, similar to the forest biomass carbon uptake, and therefore considered relatively certain and unlikely to be strongly biased. It agrees with other estimates of riverine OC export of OC from northern landscapes, such as from Finland to the Baltic Sea ( $3.5 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) (Raike et al. 2012), while Swedish coastal inputs are  $2.7 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Humborg et al. 2010). Riverine OC transport to Arctic seas varied between  $0.8$  and  $2.3 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Holmes et al. 2012), on average  $1.6 \text{ g C m}^{-2} \text{ yr}^{-1}$ , almost equal to riverine OC export in subarctic Norway ( $1.7 \text{ g C m}^{-2} \text{ yr}^{-1}$ ). Ciais et al. (2008) estimated riverine OC export from northern Europe ( $>50^\circ\text{N}$ ) to  $2.9 \text{ g C m}^{-2} \text{ yr}^{-1}$ . All estimates of riverine OC export from large drainage areas in boreal and arctic regions fall within a narrow range, roughly  $1$  to  $5 \text{ g C m}^{-2} \text{ yr}^{-1}$ .

Riverine inorganic carbon export is more uncertain than the OC export. The mean DIC export of  $1.0 \text{ g C m}^{-2} \text{ yr}^{-1}$  and its uncertainty interval ( $0.4$ - $2.5 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) falls in the range of DIC export reported for Northern landscapes elsewhere: Lake Pääjärvi in southern Finland ( $1.0 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Huotari et al. 2013)), the Krycklan catchment in northern Sweden ( $0.4 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Wallin et al. 2013)), the Öreälven catchment in northern Sweden ( $0.9 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Jonsson et al. 2007)) and for all of Sweden ( $1.6 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Humborg et al. 2010)). Riverine IC export from northern Europe ( $2.2 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Ciais et al. 2008)) also falls within the uncertainty range, although this region includes areas

with more limestone than what is found in Norway. Clair et al. (1994) observed a wide range of DIC export from large Canadian rivers ( $0.04\text{--}4.19\text{ g C m}^{-2}\text{ yr}^{-1}$ ), attributed to differences in sources of IC, i.e. bedrock and associated weathering rates, and autotrophic and heterotrophic respiration.

The lake  $\text{CO}_2$  evasion rate ( $28\text{ g C m}^{-2}\text{ lake yr}^{-1}$ ) is similar to the estimates for large catchments in mid-northern Sweden ( $28\text{ g C m}^{-2}\text{ lake yr}^{-1}$  (Algesten et al. 2004)), but lower than in the Öreälven catchment ( $63\text{ g C m}^{-2}\text{ lake yr}^{-1}$  (Jonsson et al. 2007)) and the estimate for Sweden ( $53\text{ g C m}^{-2}\text{ lake yr}^{-1}$  (Humborg et al. 2010)). The latter are within the uncertainty range of the Norwegian estimate ( $11\text{--}68\text{ g C m}^{-2}\text{ lake yr}^{-1}$ ). Also for river  $\text{CO}_2$  evasion rate, the results from other studies fall within or overlap with the uncertainty range ( $902\text{ (}341\text{--}2177\text{) g C m}^{-2}\text{ river yr}^{-1}$ ):  $471\text{ g C m}^{-2}\text{ yr}^{-1}$  in Jonsson et al. (2007),  $1690\text{ g C m}^{-2}\text{ river yr}^{-1}$  in Huotari et al. (2013) and  $1455\text{--}6411\text{ g C m}^{-2}\text{ river yr}^{-1}$  in (Wallin et al. 2013). Algesten et al. (2004) applied the same evasion rate to rivers and lakes, resulting in a much lower rate ( $47\text{ g C m}^{-2}\text{ river yr}^{-1}$ ).

Cole et al. (2007) estimated that circa 50% of all headwater land-derived carbon inputs on a global scale are lost on its way from headwater to coast, either through  $\text{CO}_2$  evasion or by sediment storage. The sum of  $\text{CO}_2$  evasion and sediment storage for Norway is  $2.0\text{ Tg C yr}^{-1}$ , slightly higher than the total OC inputs to the coast, i.e.  $1.7\text{ Tg C yr}^{-1}$ . However, given the large uncertainty in these numbers, our estimates agree with Cole et al. (2007). This implies that headwater OC export in Norway might be higher than coastal OC inputs ( $6\text{ g C m}^{-2}\text{ yr}^{-1}$  or  $2\text{ Tg C yr}^{-1}$ ). Reported headwater TOC export from boreal landscapes presents a wide range, from  $<2$  to  $>50\text{ g C m}^{-2}\text{ yr}^{-1}$ , with median exports of  $7.6$  and  $9.6\text{ g C m}^{-2}\text{ yr}^{-1}$  for North America and Europe, respectively (Hope et al. 1994). Headwater catchments in Northern Sweden and eastern Finland exported  $1.5$  to  $10\text{ g C m}^{-2}\text{ yr}^{-1}$  (Ågren et al. 2007a), and  $2.3$  and  $15\text{ g C m}^{-2}\text{ yr}^{-1}$  (Rantakari et al. 2010), respectively. Buffam et al. (2011) estimated that forested and wetland catchments exported  $4$  and  $11\text{ g C m}^{-2}\text{ yr}^{-1}$ , respectively.

Headwater DOC concentrations have shown wide-spread increases in northern lakes and rivers, including in Fennoscandia (De Wit et al. 2007; Erlandsson et al. 2008; Monteith et al. 2007; Vuorenmaa et al. 2006). Given the strong relation between discharge and DOC export (Clair et al. 2013; Gielen et al. 2011; Haaland et al. 2008; Raike et al. 2012), the positive trends in headwater DOC, and observed and predicted increases in discharge in the Nordic countries due to climate

warming (Wilson et al. 2010), a future increase in headwater catchment DOC aquatic export appears likely, with possible impacts on soil carbon sequestration in forests soils and peatlands.

Coastal margin sediments are the main recipient of land-derived organic matter, but the fate of deposited terrestrial organic matter is poorly understood (Borges et al. 2005; Hedges et al. 1997). Degradation of land-derived organic matter in lakes and rivers, and further transformations in coastal areas, can lead to highly refractory organic matter, with potentially long residence times in coastal sediments and deeper oceans (Dittmar & Kattner 2003; Raymond & Bauer 2001). This is especially true for arctic oceans, as there are very few removal mechanisms for organic matter (Dittmar & Kattner 2003), suggesting a long-term sink for atmospheric carbon from land-derived organic carbon.

#### *Integration of terrestrial and aquatic carbon fluxes*

A key question with regard to the role of riverine OC transport in the terrestrial cycle relates to the source of OC in rivers. If the OC in rivers is recently mobilized, formerly stable soil organic matter, aquatic OC export would reduce soil carbon stores and bring the terrestrial carbon pool from one (semi-) steady state to the next. If not, river OC transport represents a flux of carbon from soils in steady state with the carbon flux from vegetation to soils and is a fixed proportion of terrestrial productivity. If lateral aquatic carbon fluxes impact present rates of terrestrial carbon accumulation, it may not be adequately accounted for in terrestrial carbon balances (Cole et al. 2007; Luysaert et al. 2010).

In the carbon balance for European forest (Luysaert et al. 2010), river OC export equals circa 50% of the soil carbon sink. The estimated river OC export for Norway (this study), Sweden (Humborg et al. 2010) and Finland (Raïke et al. 2012) is 32% to 37% of the national forest soil carbon sinks. Luysaert et al. (2010) state explicitly that their methods were not conclusive with regard to the necessity of correcting the soil carbon sink with riverine OC transport, and therefore no correction was done.

Net Ecosystem Production (NEP) can be determined as the balance of all major carbon fluxes in and out of the ecosystem: gross primary production (GPP), ecosystem respiration (Reco) (autotrophic (Ra) and heterotrophic (Rh)) and lateral transport including riverine carbon transport

(Randerson et al. 2002). This approach is common in single-site carbon balances in peatlands (Yu 2012) and forests (Gielen et al. 2011), but few regional carbon balances follow this concept.

Three carbon balances for several thousand km<sup>2</sup> catchments have been reported based on upscaled eddy covariance measurements of vertical CO<sub>2</sub> fluxes, to give Net Ecosystem Exchange (NEE), from which the lateral riverine carbon flux could be subtracted in order to quantify the terrestrial sink or NEP.

The first was made by Jonsson et al. (2007) at the 3000 km<sup>2</sup> Öreälven river basin in boreal Sweden. Here, headwater aquatic export of TOC was 8.6 g C m<sup>-2</sup> yr<sup>-1</sup> and made up 6% of headwater catchment NEE (139 g C m<sup>-2</sup> yr<sup>-1</sup>). For the entire river basin, the ratio of TOC export to NEE was 3%, as river basin TOC export was reduced to 3.6 g C m<sup>-2</sup> yr<sup>-1</sup> because of in-stream and in-lake processes. The second was conducted by Christensen et al. (2007) at the 4000 km<sup>2</sup> Lake Torneträsk river basin in subarctic Sweden. Aquatic DOC export was 2 g C m<sup>-2</sup> yr<sup>-1</sup> and comprised 19% of NEE (10.6 g C m<sup>-2</sup> yr<sup>-1</sup>). The third was carried by Buffam et al. (2011) at the 6400 km<sup>2</sup> Northern Highlands Lake (NHL) District in the northern US. Here, riverine organic carbon export (5.3 g C m<sup>-2</sup> yr<sup>-1</sup>) was 3% of catchment NEE (175 g C m<sup>-2</sup> yr<sup>-1</sup>). The NHL district and the Öreälven catchment included large areas of productive forest, driving the relatively high NEE. For a single forest stand, Gielen et al. (2011) found that DOC export from a pine forest was 11% of NEP (91 g C m<sup>-2</sup> yr<sup>-1</sup>), where NEP was estimated as the balance of all major carbon fluxes. None of these carbon balances supplied a separate estimate of the soil carbon sink. Thus, an evaluation of the relative importance of DOC export for catchment soil carbon accumulation is not possible. A review of five full carbon balances in northern peatlands showed that DOC export was on average 40% of NEP (Yu 2012).

At the landscape scale, the simplicity of defining NEP based on theoretical fluxes contrasts with the complexity of measuring GPP and Reco (Luysaert et al. 2009) and upscaling of point measurements of NEE. In our approach, we estimated NEP as the change in ecosystem carbon pools in biomass and soils, similar to Luysaert et al. (2010). Using a consistent approach across four climatically contrasting drainage basins, we calculated that riverine OC export ranged from 10% to 23% of drainage basin NEP, and 46% to 113% of soil carbon accumulation (summed for forests and peatlands). If we assume that an unbiased estimate of NEP with regard to lateral carbon fluxes is

obtained by simply subtracting riverine OC export from NEP, drainage basin NEP is reduced by between 10% and 23%. This is lower than the DOC flux correction of NEP in peatlands (Yu 2012), similar to Lake Torneträsk in northern Sweden) (Christensen et al. 2007), and much higher than the NHL District in northern US (Buffam et al. 2011) and Öreälven catchment (Jonsson et al. 2007). NEP would be reduced even more if we had used headwater OC export, instead of coastal OC inputs. As river OC originates from soils, we might correct the soil carbon sink by subtracting riverine OC fluxes. This results in a circa 50% reduction of the soil sink in southeast and subarctic Norway, and a switch of the soil in western Norway from sink to source of carbon. The latter appears to be an unreasonable result, from which it may be concluded that either 1) NEP should not be corrected by subtracting riverine OC fluxes, 2) the estimate for the soil sink is too low, or 3) the soil sink should be at least equal to the riverine OC flux to compensate for lateral losses of OC. The latter point might be considered as a way to contribute to validation of regional scale soil carbon sink estimates. For this, better estimates of headwater OC export would be extremely useful. For better quantification and understanding of the role of northern landscapes in the carbon cycle, there is a clear need for validation of soil sink estimates and tools to investigate the role of lateral carbon fluxes in soil carbon sequestration.

#### *The role of management for landscape carbon accumulation*

Land use and management set a strong mark on the global carbon cycle due to greenhouse gas emissions from deforestation (Bala et al. 2007), peatland drainage, burning and planting (Frolking et al. 2011) and agriculture (Schulze et al. 2009). The current increase in carbon pools in forests in the northern hemisphere may be largely a legacy of former land use (Goodale et al. 2002), although additional factors such as nitrogen deposition (Thomas et al. 2010) and climate warming (Boisvenue & Running 2006) also are likely to contribute.

Greenhouse gas balances in cultivated peatlands in the Nordic countries are strongly dependent on site characteristics and land-use practices (Maljanen et al. 2010). Drainage for cultivation and forestry has turned peatlands into significant sources of CO<sub>2</sub>. In our carbon balance, annual losses of carbon from cultivated organic soils in agricultural areas and from disturbed peatlands

were 0.40 and 0.05 Tg C, respectively, exceeding carbon accumulation in undisturbed peatlands (0.29 Tg C). Undisturbed peatlands could become significant sources of atmospheric CO<sub>2</sub> under higher temperatures (Dorrepaal et al. 2009) and drought (Mettrop et al. 2014). However, the threat from land use to destabilization of peatland carbon stores in boreal landscapes appears larger. Between 15 and 30% of Norwegian peatlands may have been drained for cultivation and forestry until the 1960s (Johansen 1997; Maljanen et al. 2010), which is likely to have led to large losses of carbon. Little is known about the current carbon sink or source strength of these drained, forested peatlands in Norway, but other studies suggest that formerly drained peatlands continue to be carbon sources for decades (Armentano & Menges 1986). For cultivated organic soils in Norway, there are measurements of subsidence rates and CO<sub>2</sub> effluxes (Grønlund et al. 2008a) but to what extent these rates are representative for various combinations of soil type and management is not clear. Quantifying greenhouse gas emissions taking into a combination of management system and soil type such as done by Andren et al. (2008) would improve the reliability of the carbon balance in Norwegian agricultural soils. Without improved geographic data and understanding of effects of past on current land use on carbon-rich soils, especially those under agricultural land use, peatlands will continue to represent a large source of uncertainty in the national carbon balance.

## **Conclusions**

Terrestrial carbon accumulation and riverine transport of land-derived carbon in northern landscapes are significant compared with anthropogenic emissions of CO<sub>2</sub>. Terrestrial carbon uptake in Norway was largest in the south. Riverine carbon fluxes were similar in size compared with changes in soil carbon pools in forests and peatlands. Where accumulation of carbon in forest biomass and riverine fluxes of organic carbon are relatively well-constrained because of their empirical basis in monitoring databases, accumulation and losses of soil carbon continue to create considerable uncertainty in landscape carbon balances. This is related to inadequately validated tools for estimation of the forest soil carbon sink, and to the role of land use and management in agricultural and peatland areas. Future drivers of terrestrial carbon stores are climate and land use, which are expected to impact the ecosystems in northern landscapes differently. Integration of lateral and vertical carbon fluxes

deserves more attention, especially in cold and wet boreal landscapes of low productivity, for a better understanding and quantification of the terrestrial carbon cycle.

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Figure 1 Norway – drainage basins with mean annual area-normalized fluxes of carbon in  $\text{g C m}^{-2} \text{ yr}^{-1}$ .

Vertical arrows terrestrial fluxes, horizontal arrows show aquatic fluxes of organic carbon.

B=biomass, S=soils and sediments. Included ecosystems are forest, lakes, mountains and peatlands.

Figure 2 Carbon balance of Norway for 1990 to 2008 in  $\text{Tg C yr}^{-1}$  (panel A) and area-normalized per ecosystem in  $\text{g C m}^{-2} \text{ yr}^{-1}$  (panel B). Greenhouse gas (GHG) emissions are mean emissions from Norway in  $\text{CO}_2\text{-C}$  equivalents (Miljødirektoratet 2010)

Figure 3 TOC export in % of terrestrial sink, biomass sink, forest and peatland sink, and forest soil sink for each drainage basin and summed for Norway

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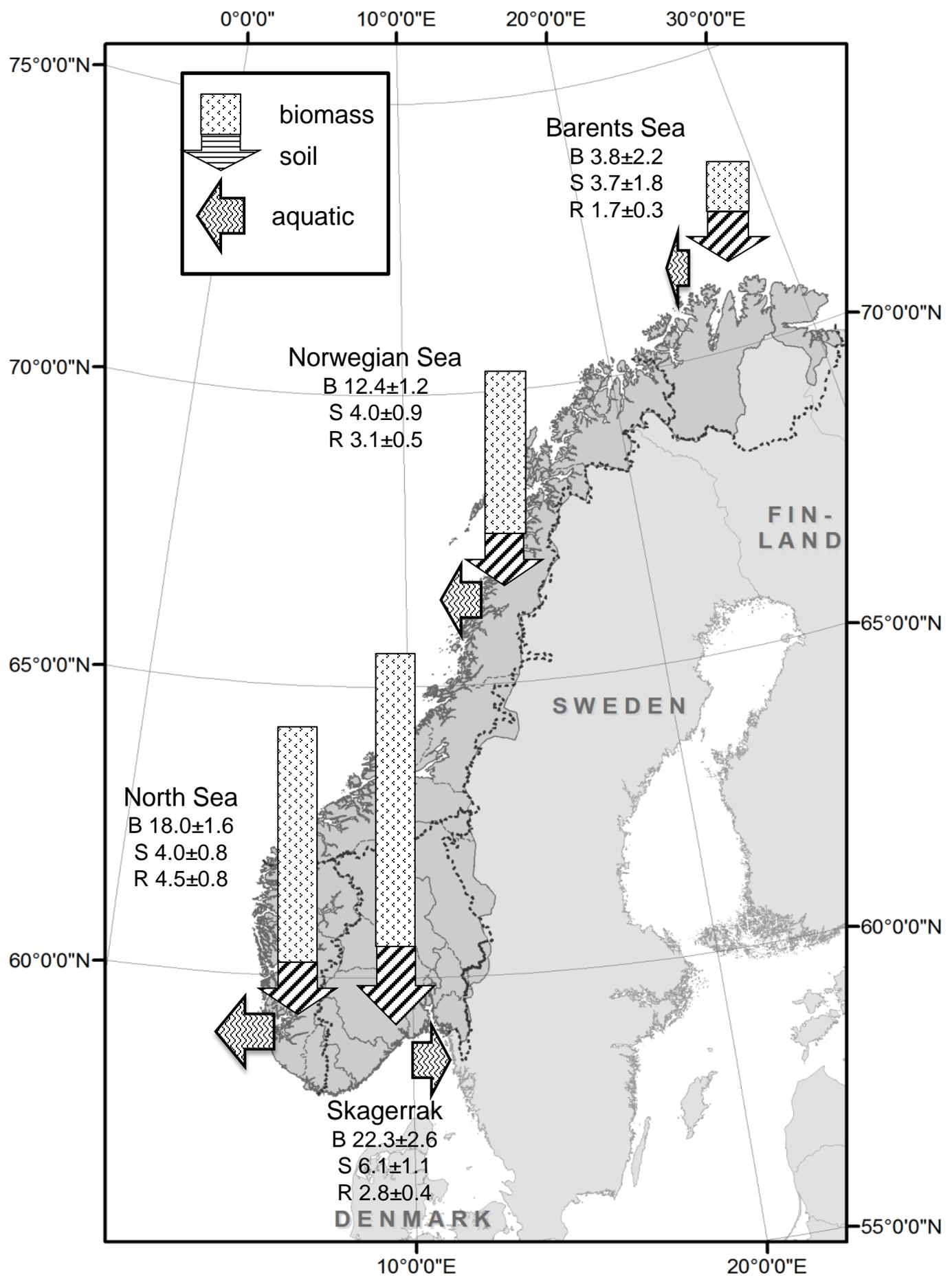
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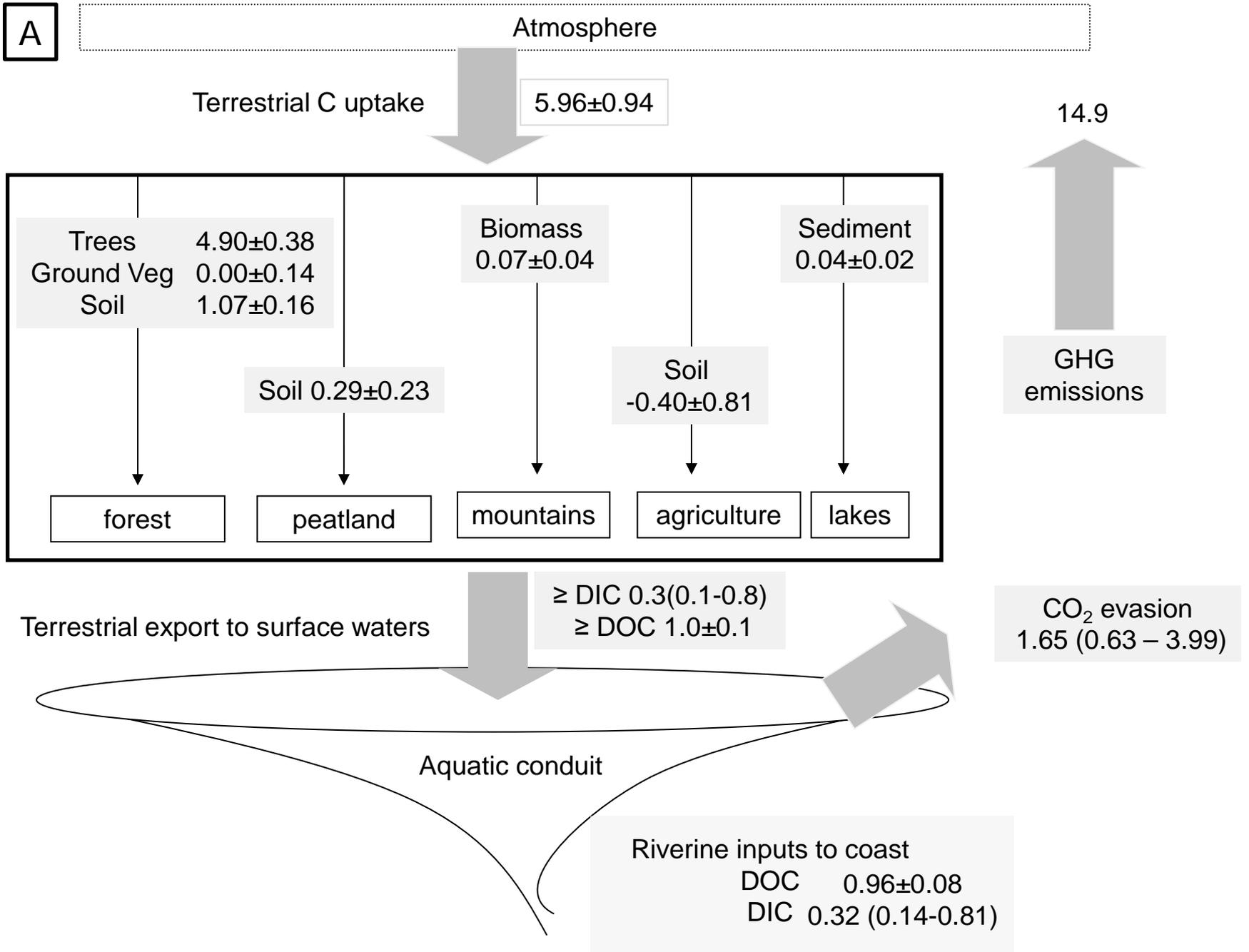
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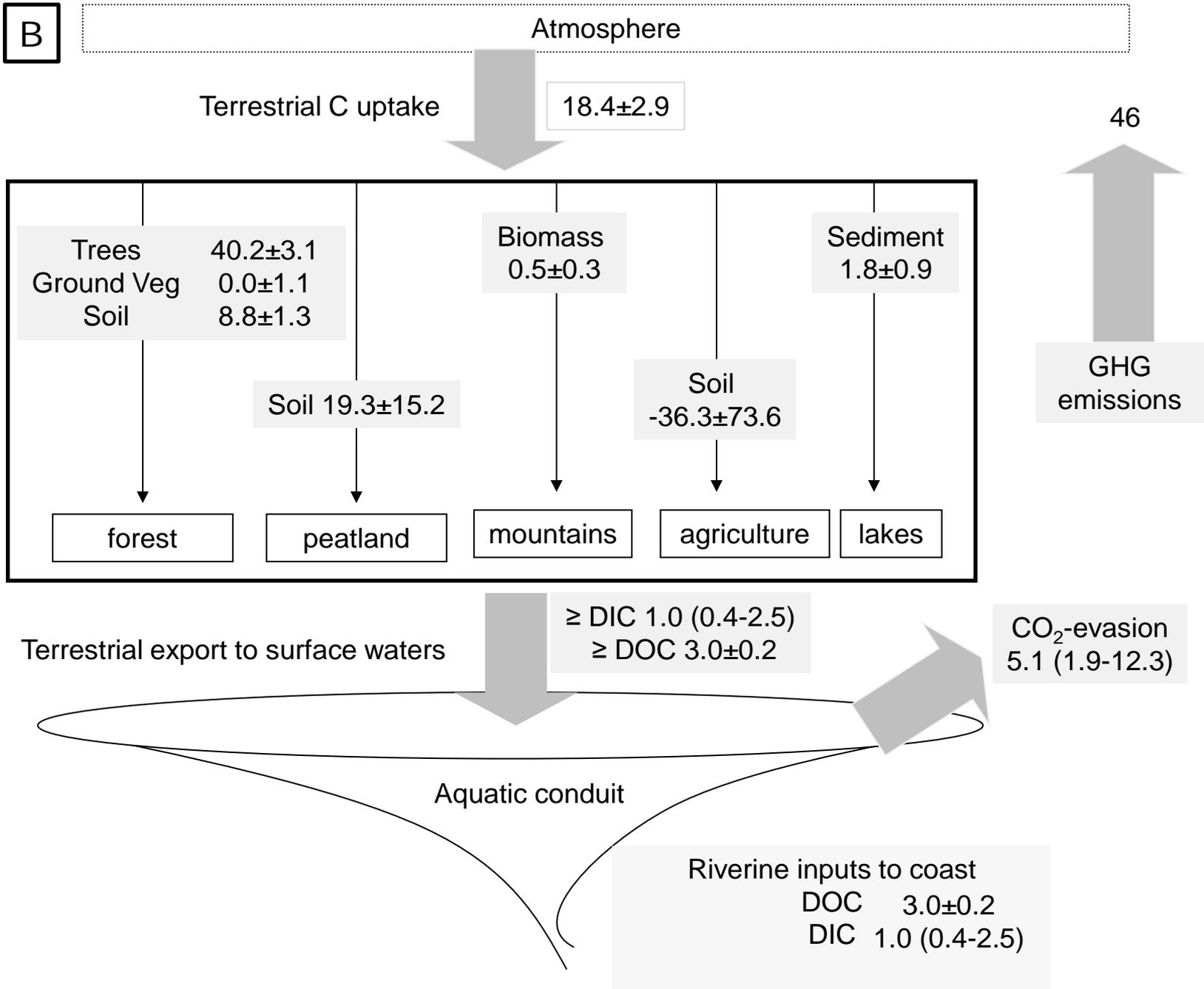
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A



B



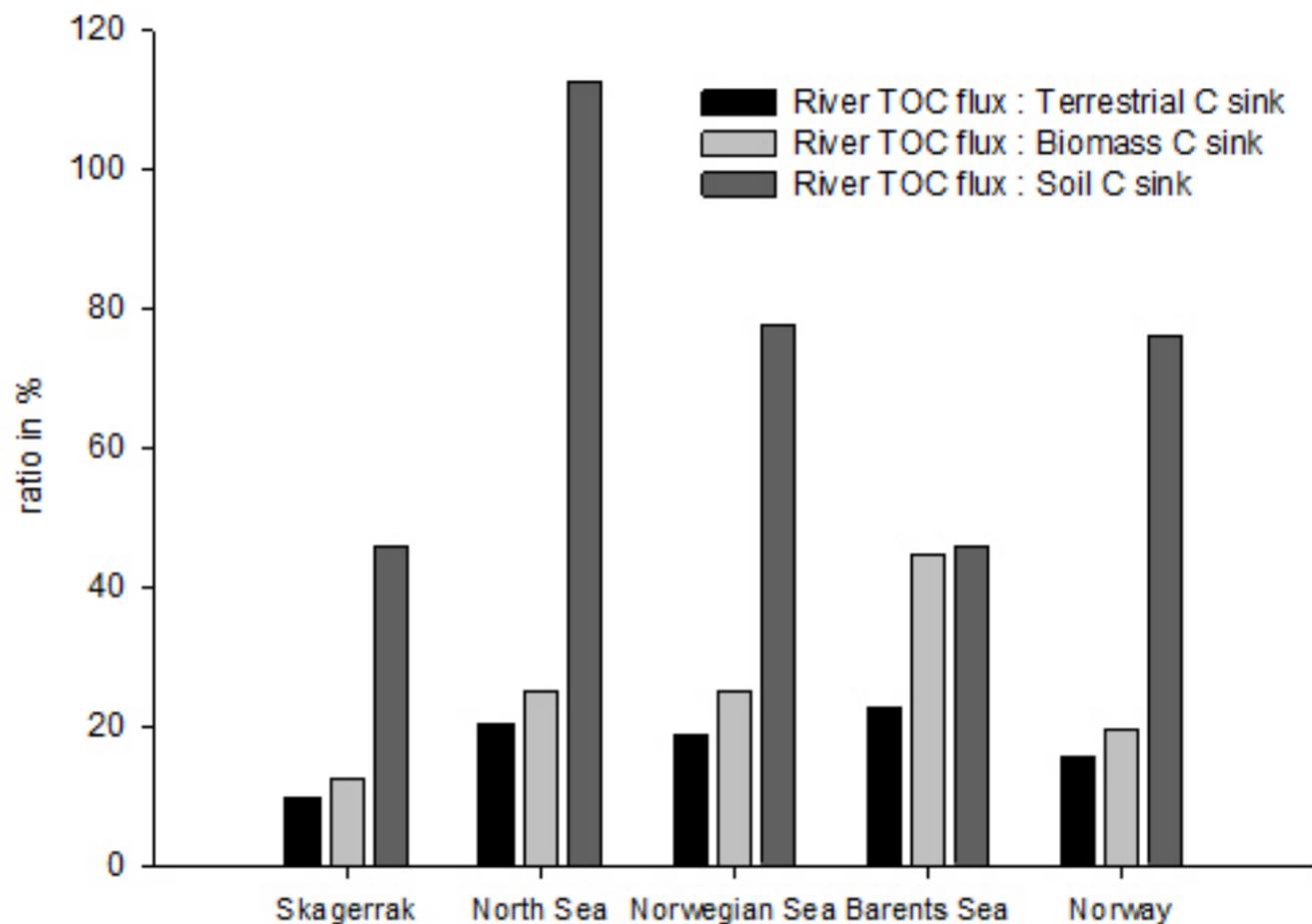


Table 1 Description of drainage areas and regions in Norway. Details on the land cover categories are given in Table 3.

Table 2 Description of land cover categories based on statistics from the Norwegian Forest Inventory

Table 3 Equations used in the carbon balance for Norway.

Table 4 Peatland carbon balance studies and estimates of peatland carbon accumulation rates for common Norwegian peatland types.

Table 5 Carbon balance for agricultural areas

Table 6 Key characteristics of river monitoring in four main drainage areas of Norway, and riverine carbon fluxes for the period 1990 to 2008.

Table 7 Mean annual forest carbon uptake in eight regions in Norway between 1990 and 2008.

Table 8 Multivariate correlations of forest carbon fluxes and forest and climate characteristics for eight regions. Bold and *italic* fonts indicate that pairwise correlations were significant at the 0.01 and 0.05 level, respectively. All forest fluxes and pools were area-normalized.

Table 1 Description of drainage areas and regions in Norway. Details on the land cover categories are given in Table 3.

Drainage area name	NFI Region Nr	County	Area 10 <sup>6</sup> ha	MAT <sup>1</sup> °C	MA P <sup>1</sup> mm	forest	Peat-lands	Moun-tains	OWL	Open water	culti vated	deve- loped	Nr of NFI plots n	Tree volume m <sup>3</sup> ha <sup>-1</sup>	Spruce <sup>15</sup> Pine <sup>15</sup> Birch <sup>15</sup>		
															vol% forest type (in 2008)		
Skager-rak <sup>2</sup>	1 <sup>6</sup>	1 to 4 <sup>8</sup>	2.98	3.1	754	73.2	3.0	0.5	2.3	6.8	9.4	9.2	2821	116	50	37	13
	2 <sup>6</sup>	5 to 7 <sup>9</sup>	2.38	2.5	777	73.1	3.8	0.9	2.2	6.7	8.6	8.1	2225	111	56	27	17
	3 <sup>6</sup>	8 to 10 <sup>10</sup>	2.10	4.8	1260	73.3	3.8	3.3	3.2	9.3	3.2	2.5	2020	108	33	44	24
North Sea <sup>3</sup>	4 <sup>6</sup>	11 to 15 <sup>11</sup>	2.60	5.9	2008	51.6	3.8	14.4	6.3	6.5	12.7	7.7	1834	95	29	36	35
Norwe- gian Sea <sup>4</sup>	5 <sup>6</sup>	16, 17 <sup>12</sup>	2.37	3.7	1200	62.3	9.3	5.2	5.7	8.6	6.5	6.2	2074	75	59	21	20
	6 <sup>6</sup>	18, 19 <sup>13</sup>	2.54	3.1	1290	60.7	6.5	12.6	6.2	6.6	4.9	4.0	2069	45	26	11	62
Barents Sea	7 <sup>6,7</sup>	20 <sup>14</sup>	4.86	-0.9	582	21.2	7.7	54.1	10.5.	6.1	0.2	0.2	1153	19	0	30	70
unspeci- fied <sup>5</sup>	8 <sup>7</sup>	all but 20 <sup>14</sup>	12.55	0.4	1366	9.0	3.2	79.0	3.6	5.1	0.1	0.0	440	25	4	7	89
		all	32.38	1.8	1175	37.6	4.7	42.6	3.4	6.3	3.6	1.8					

1 Mean annual temperature (MAT) and mean annual precipitation (MAP) was available for each NFI plot, derived from a nationwide 1x1 km<sup>2</sup> grid of monthly meteorological data from the Norwegian meteorological institute. MAT and MAP (1990-2008) per region was calculated by averaging MAT for all NFI plots that were included in a region

1 Land cover is derived from the National Forest Inventory (NFI) 2004-2008, based on a systematic grid of geo-referenced fixed-area permanent sample plots, with a grid of 3x3 km density below the coniferous forest limit, 3x9 km in the mountain birch area and 9x9 km the northernmost county Finnmark.

2 NFI regions 1 to 3, except Vest-Agder county (0.9 Mha)

3 NFI region 4 and Vest-Agder, except Møre og Romsdal county (1.5 Mha)

4 NFI regions 5 and 6 and Møre og Romsdal county

5 The mountain region was all of Norway above the coniferous forest limit, and attributed to drainage area by assuming homogeneous area-weighted carbon fluxes.

6 Below the coniferous forest limit.

7 Above the coniferous forest limit

8 Østfold, Akershus, Oslo, Hedmark.

9 Oppland, Buskerud, Vestfold counties

10 Telemark, Aust-Agder, Vest-Agder counties

11 Rogaland, Hordaland, Sogn og Fjordane, Møre og Romsdal (province nr 13 was merged with nr 12).

12 Nord- and Sør-Trøndelag county

13 Nordland and Troms county

14 Finnmark county

15 Forest dominated by spruce, pine and birch.

Table 2 Description of land cover categories based on statistics from the Norwegian Forest Inventory

Area category	Name	Definition	
		Crown cover	Description
Forest	Productive forest	>10%	Potential yield (stemwood incl bark) >1 m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup>
	Unproductive forest	>10%	Potential yield (stemwood incl bark) <1 m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup>
Peatlands	Peat	<10%	Peatland without tree cover or with less than 10% vegetated cover (shrubs, bushes)
Lakes	Lake and rivers	-	Water bodies
Mountains	Other wooded land	5-10%	Mineral soil type. Low productivity: trees with potential to reach 5 m height; alternatively, cover of shrubs, bushes, trees >10%
	Wooded mire	5-10%	Organic soil type. Productivity as for other wooded land
	Tundra, bare rock	<10%-	Bare rocks, shallow soil with or without vegetated cover (shrubs, bushes) less than 10% during any time of the year.
Agricultural	Calluna heath	n.d.	Dominance of calluna heath
	Grazing land	-	Grazing land, not regularly cultivated
	Arable land	-	Arable land, regularly cultivated
Developed	Other areas	-	Dominated by roads, asphalt, buildings and other constructed materials

Table 3 Equations used in the carbon balance for Norway.

Equation

1	Terrestrial carbon balance <sub>Norway</sub> = $\sum$ carbon uptake (forest + peatlands + mountains + agricultural areas + lakes)
2	Forest carbon balance = $\sum$ (forest carbon pool <sub>2008</sub> – forest carbon pool <sub>1990</sub> ) <sub>pool</sub> <sup>1</sup>
3	Carbon pool tree biomass <sub>region</sub> <sup>2</sup> = $\sum$ (d, h <sup>3</sup> * CF <sup>4</sup> <sub>biomass components</sub> <sup>5</sup> ) <sub>tree species</sub> <sup>6</sup>
4	Carbon pool tree biomass <sub>region</sub> <sup>2</sup> = $\sum$ (volume * CF (BEF) <sup>7</sup> <sub>biomass components</sub> <sup>5</sup> ) <sub>tree species</sub> <sup>6</sup>
5	Ground vegetation biomass <sub>region</sub> <sup>2</sup> = $\sum$ (stand age * CF <sup>2</sup> <sub>biomass components</sub> <sup>5</sup> ) <sub>tree species</sub> <sup>6</sup>
6	Peatland carbon balance = $\sum$ carbon accumulation rate * area <sub>peatland type</sub> <sup>8</sup>
7	Carbon balance agricultural areas = $\sum$ carbon accumulation rate <sub>cultivation type, soil type</sub> <sup>9</sup> * area <sub>cultivation type, soil type</sub> <sup>9</sup>
8	Mountain carbon balance = $\sum$ carbon accumulation rate * area
9	Lake carbon balance <sub>Norway</sub> = $\sum$ carbon sedimentation rate * area
10	Aquatic TOC export <sub>Norway</sub> = $\sum$ TOC concentration * discharge <sub>drainage area</sub> <sup>10</sup>

<sup>1</sup> pool: biomass, ground vegetation, soil. <sup>2</sup> NFI region 1 to 8. <sup>3</sup> d, diameter, h, height <sup>4</sup> CF, conversion factor. <sup>5</sup> Stems, stubs, branches, foliage, roots.

<sup>6</sup> Dominating tree species: spruce, pine and birch. <sup>7</sup> BEF, biomass expansion factor. <sup>8</sup> Undisturbed boreal and subarctic peatlands; disturbed peatlands <sup>9</sup> Arable land on mineral soil types; fully cultivated and surface-cultivated organic and mineral soil types. <sup>10</sup> Norway's four major drainage areas.

Table 4 Peatland carbon balance studies and estimates of peatland carbon accumulation rates for common Norwegian peatland types.

Study <sup>1</sup>	Climate <sup>2</sup>	Peatland <sup>3</sup>	Country	Period (n yrs)	Name	Latitude (N)	Longitude	MAT	MAP	Q <sup>4,5</sup>	C balance	NECB <sup>4</sup>	NEE <sup>4</sup>	CH <sub>4</sub> <sup>4,6</sup>	DOC <sup>4,7</sup>	DOC/Q				
								(oC)	mm	mm		g C m <sup>-2</sup> yr <sup>-1</sup>	Stdev	g C m <sup>-2</sup> yr <sup>-1</sup>	Stdev	g C m <sup>-2</sup> yr <sup>-1</sup>	stdev	g C m <sup>-2</sup> yr <sup>-1</sup>	stdev	g C m <sup>-2</sup> mm <sup>-1</sup> yr <sup>-1</sup>
1	B	OMF	Sweden	2004-2005(2)	Degero Stormyr	64°11.10	19°13.30E	1.2	685	448	full	23.5	3.4	52	2	-8.2	2.1	-13.0	1.4	0.029
2	B	OB	Canada	1998-2004(7)	Mer Bleue	45.41°N	75.48°W	6	943	391	full	21.5	39	40	41	-3.7	0.5	-14.9	3.1	0.038
3	SA	PPM	Sweden	2008-2009(2)	Stordalen	68.37	19.05E	0	336	227	full	44.5	16.3	50	17	-2.0		-3.2	0.6	0.014
4	B	OMF	Sweden	2001-2003(3)	Degero Stormyr	64°11.10	19°13.30E	1.2	453	296	estimate	36.8		55	7	-8		-9.9		
5	B, T	B	Sweden	2005 (1)	Fajemyr	56°15	13°33E	6.2	700	290	estimate	5.7		21	6	-6		-9.7		
6	B	SF	Finland	2006-2008(3)	Lompolojankka	67°89.532	24°12.55E	-1.4	484	317	estimate	27.3		44	38	-6		-10.6		
7	SA	OB	Finland	1997-2002(5)	Kaamanen	69.14	27.3E	0.2	471	308	estimate	15.2		22	20	-2		-4.3		
8	B	SF	Finland	2004 (1)	Not given	61.83	24.19E	4.2	713	466	estimate	48.9		71	0	-6		-15.6		
									all		Mean <sup>8</sup>	254	19.7 <sup>9</sup>	40.9	18.8 <sup>9</sup>	-4.6	0.6 <sup>9</sup>	-10.2	1.7 <sup>9</sup>	
									B	OB	mean	29.6	23.0 <sup>9</sup>	51.5	23.7 <sup>9</sup>	-6.5	0.8 <sup>9</sup>	-14.5	2.4 <sup>9</sup>	
									SA-PPM	OB	mean	23.5	18.2 <sup>9</sup>	29.6	13.6 <sup>9</sup>	-2.0	0.3 <sup>9</sup>	-4.0	0.7 <sup>9</sup>	
									SA	OB	mean	15.2	11.7 <sup>9</sup>	21.5	9.9 <sup>9</sup>	-2.0	0.3 <sup>9</sup>	-4.3	0.7 <sup>9</sup>	

1 references S1; Nilsson ea 2008; S2, Roulet ea 2007; S3: Olefeldt ea 2012; S4: Sagerfoss ea 2007; S5 Lund ea 2007; S6: Aurela ea 2007; S7: Aurela ea 2009; S8: Aurela ea 2004.

2 B, boreal; SA, subarctic, T, temperate

3 O, oligotrophic; M, minerogenic; F, fen; b, bog; PPM, permafrost-palsamire; SF, sedge fen.

4 estimates in italics.

5 discharge estimated as MAP - EP: in S4, 6, 7, 8 EP is proportional to S1; in S5, EP is proportional to S2.

6 CH<sub>4</sub> emissions: S4= S1; S5,6,8: mean of S1+S2; S7 = S3.

7 estimated DOC export (g C m<sup>-2</sup> yr<sup>-1</sup>) = ratio of DOC export and discharge (g C m<sup>-2</sup> yr<sup>-1</sup> mm<sup>-1</sup>) x discharge (mm). S4, from S1; S5,6,8, from mean S1,2; S7, from S3

8 mean is weighted on number of years in each study.

9 stdev, standard deviation, is estimated as average of the relative standard deviations from study 1-3 multiplied by the estimated mean.

Table 5 Carbon balance for agricultural areas

Land use	% area	area (million ha)		Emission factor g C m <sup>-2</sup> yr <sup>-1</sup>		Carbon balance Tg C yr <sup>-1</sup>		
		M soils	O soils	M soils	O soils	M soils	O soils	all
arable land	35	0.36	0	0 (78)	n.r.	0.00 (0.28)	n.r.	0.00 (0.28)
grassland, fully cultivated	45	0.46	0.06	0 (78)	570 (290)	0.00 (0.36)	0.33 (0.17)	0.33 (0.39)
grassland, surface-cultivated	20	0.21	0.03	0 (78)	285 (145)	0.00 (0.16)	0.07 (0.04)	0.07 (0.16)
		1.02	0.08			0.00 (0.80)	0.40 (0.17)	0.40 (0.81)

Table 6 Key characteristics of river monitoring in four main drainage areas of Norway, and riverine carbon fluxes for the period 1990 to 2008.

Drainage area	Area in Norway	total area	Monitored		Discharge <sup>1</sup>	TOC <sup>2</sup>	TOC flux <sup>3</sup>		DIC flux	CO <sub>2</sub> evasion
			area	Nr of monitored rivers			Tg C yr <sup>-1</sup>	g C/m <sup>2</sup> / yr		
	10 <sup>6</sup> ha	10 <sup>6</sup> ha	%	n	mm yr <sup>-1</sup>	mg L <sup>-1</sup>	Tg C yr <sup>-1</sup>	g C/m <sup>2</sup> / yr		Tg C yr <sup>-1</sup>
Skagerrak	10.70	10.94	82	10	720 (101)	3.8 (0.2)	0.29 (0.04)	2.8 (0.4)		
North Sea	4.75	4.75	26	18	2395 (419)	1.9 (0.1)	0.21 (0.04)	4.5 (0.8)		
Norwegian Sea	11.88	12.23	30	15	1312 (164)	2.4 (0.2)	0.37 (0.06)	3.1 (0.5)		
Barents Sea	4.95	7.52	55	3	477 (46)	3.6 (0.5)	0.10 (0.01)	1.7 (0.3)		
Norway	32.27	35.45	51	46			0.96 (0.08)	3.0 (0.3)	0.32 (0.14-0.81)	1.65 (0.63 – 3.99)

1 Discharge expressed as mean annual discharge (1990-2008) and standard deviation. 2 Flow-weighted, area-weighted mean (1999-2008) and standard deviation 3 TOC flux and calculated from discharge and TOC with combined standard deviation

Table 7 Mean annual forest carbon uptake in eight regions in Norway between 1990 and 2008.

		unit	year	Region 1 East	Region 2 East	Region 3 East	Region 4 West	Region 5 Middle	Region 6 North	Region 7 Finnmark	Region 8 Mountains	Norway
region	Forested area	Mha		2.18	1.74	1.54	1.34	1.47	1.54	1.03	1.13	12.18
	MAT <sup>1</sup>	°C		3.1	2.5	4.8	5.9	3.7	3.1	-0.9	0.4	
biomass	tree biomass	Tg C	2008	98.7 (2.7)	80.3 (2.2)	68.5 (1.8)	56.1 (1.5)	50.3 (1.4)	34.4 (0.9)	10.6 (0.8)	14.7 (1.1)	415.9 (4.7)
	GV <sup>2</sup> biomass	"		3.6 (2.3)	2.4 (1.9)	2.6 (2.4)	1.9 (1.3)	2.3 (1.6)	1.5 (0.4)	2.0 (1.9)	0.5 (0.0)	16.8 (4.8)
	tree biomass	kg C m <sup>-2</sup>		4.53	4.61	4.44	4.18	3.41	2.23	1.03	1.30	3.40
	tree sink	Tg C yr <sup>-1</sup>	1990-2008	1.10 (0.19)	0.67 (0.16)	0.96 (0.13)	0.99 (0.10)	0.40 (0.10)	0.46 (0.06)	0.13 (0.08)	0.19 (0.13)	4.90 (0.38)
	ground veg sink	"		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00 (0.14)
	biomass sink	g C m <sup>-2</sup> yr <sup>-1</sup>		50	38	62	74	27	30	12	17	40
annual increment		Mm <sup>3</sup> yr <sup>-1</sup>	1990-2008	7.1	5.0	3.7	3.3	2.5	1.6	0.2	0.7	23.9
fellings		"		3.9	2.7	1.4	0.5	1.1	0.3	0.0	0.0	10.0
		Tg C yr <sup>-1</sup>		1.6	1.1	0.6	0.2	0.5	0.1	0.0	0.0	4.1
litter flow	tree + GV	Tg Cyr <sup>-1</sup>	1990-2008	4.4 (1.0)	3.4 (0.7)	2.9 (0.6)	2.2 (0.5)	2.7 (0.6)	1.6 (0.3)	0.6 (0.1)	0.6 (0.1)	18.5 (1.6)
	mortality	"		0.2 (0.1)	0.2 (0.1)	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)	0.0 (0.0)	0.1 (0.0)	0.9 (0.1)
	harvest residues	"		0.8 (0.2)	0.6 (0.2)	0.3 (0.1)	0.1 (0.0)	0.2 (0.1)	0.1 (0.0)	0.0 (0.0)	0.0 (0.0)	2.1 (0.3)
	all	"		5.5	4.2	3.4	2.5	3.0	1.7	0.6	0.7	21.5
	all	kg C m <sup>-2</sup> yr <sup>-1</sup>		0.25	0.24	0.22	0.18	0.20	0.11	0.06	0.06	0.18
soil	sink	Tg C	1990-2008	0.24 (0.07)	0.16 (0.05)	0.17 (0.05)	0.16 (0.05)	0.11 (0.03)	0.11 (0.03)	0.02 (0.03)	0.10 (0.03)	1.07 (0.12)
	sink	g C m <sup>-2</sup> yr <sup>-1</sup>		11	9.5	11	12	7.2	7.1	2.3	8.5	8.8

1 Mean annual temperature. 2 Ground vegetation

Table 8 Multivariate correlations of forest carbon fluxes and forest and climate characteristics for eight regions. **Bold** and *italic* fonts indicate that pairwise correlations were significant at the 0.01 and 0.05 level, respectively. All forest fluxes and pools were area-normalized.

	Tree sink	Soil sink	MAT <sup>1</sup>	MAP <sup>2</sup>	Tree biomass	Litter flux	Ann. Incr <sup>3</sup>
Tree sink	1						
Soil sink	<b>0.84</b>	1					
MAT <sup>1</sup>	<b>0.88</b>	<i>0.77</i>	1				
MAP <sup>2</sup>	0.54	0.51	0.65	1			
Tree biomass	<i>0.80</i>	<i>0.80</i>	<i>0.78</i>	0.13	1		
Litter flux	0.66	0.69	0.68	-0.05	<b>0.97</b>	1	
Ann. Incr <sup>3</sup>	0.61	<i>0.72</i>	0.51	-0.16	<b>0.88</b>	<b>0.91</b>	1

<sup>1</sup> mean annual temperature. <sup>2</sup> mean annual precipitation. <sup>3</sup> annual increment.