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The European CO_2, CO, CH_4 and N_2O balance between 2001 and 2005

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Abstract

Globally, terrestrial ecosystems have absorbed about 30 % of anthropogenic emissions over the period 2000–2007 and inter-hemispheric gradients indicate that a significant fraction of terrestrial carbon sequestration must be north of the Equator. We present a compilation of the CO_2, CO, CH_4 and N_2O balance of Europe following a dual constraint approach in which (1) a land-based balance derived mainly from ecosystem carbon inventories and (2) a land-based balance derived from flux measurements are confronted with (3) the atmospheric-based balance derived from inversion informed by measurements of atmospheric GHG concentrations. Good agreement between the GHG balances based on fluxes (1249 ± 545 Tg C in CO_2-eq y^{-1}), inventories (1299 ± 200 Tg C in CO_2-eq y^{-1}) and inversions (1210 ± 405 Tg C in CO_2-eq y^{-1}) increases our confidence that current European GHG balances are accurate. However, the uncertainty remains large and largely lacks formal estimates. Given that European net land-atmosphere balances are determined by a few dominant fluxes, the uncertainty of these key components needs to be formally estimated before efforts could be made to reduce the overall uncertainty. The dual-constraint approach confirmed that the European land surface, including inland waters and urban areas, is a net source for CO_2, CO, CH_4 and N_2O. However, for all ecosystems except croplands, C uptake exceeds C release and us such 210 ± 70 Tg C y^{-1} from fossil fuel burning is removed from the atmosphere and sequestered in both terrestrial and inland aquatic ecosystems. If the C cost for ecosystem management is taken into account, the net uptake of ecosystems was estimated to decrease by 45 % but still indicates substantial C-sequestration. Also, when the balance is extended from CO_2 towards the main GHGs, C-uptake by terrestrial and aquatic ecosystems is compensated for by emissions of GHGs. As such the European ecosystems are unlikely to contribute to mitigating the effects of climate change.

1 Introduction

Globally, terrestrial ecosystems have absorbed about 30 % of anthropogenic emissions over the period 2000–2007 (Canadell et al., 2007; Le Quéré et al., 2009). The fact that the inter-hemispheric gradient of CO_2, $\delta^{13}C$, and O_2 in the atmosphere is smaller than predicted from fossil fuel emissions alone (Ciais et al., 1995; Keeling et al., 1995; Tans et al., 1990) suggests that a significant fraction of terrestrial carbon sequestration must be north of the Equator. Using vertical profiles of atmospheric CO_2 concentrations as a constraint in atmospheric inversions, Stephens et al. (2007) inferred that the magnitude of the total northern land uptake ranges between −900 and −2100 Tg C yr^{-1}. This range was confirmed through atmospheric inversions (−1100 to −2500 Tg C yr^{-1}) and land-based accounting (−1400 and −2000 Tg C yr^{-1}) (Ciais et al., 2010a). By assuming that carbon uptake is evenly distributed across the land surface, we obtain a threshold value against which the actual uptake can be compared. Under the assumption of a uniform uptake, the European continent, as defined in this synthesis (5×10^6 km^2; see below), would absorb about 5 % or equivalently −45 to −105 Tg C yr^{-1}.

Early estimates indicated that carbon uptake (−135 to −205 Tg C yr^{-1}) (Janssens et al., 2003) of the European ecosystems extending to the Ural Mountains (9×10^6 km^2) was indeed close to the average Northern Hemisphere sink i.e. −90 to −210 Tg C yr^{-1} for 9×10^6 km^2. More recent estimates, found evidence for a stronger carbon sink of about −270 Tg C yr^{-1} (Schulze et al., 2009) for the same region. However these new estimates also suggest that the climate mitigation effect of this uptake is being compromised by emissions of other greenhouse gases, leaving little or no greenhouse gas mitigation potential for the European continent. Due to differences in methodology and data products the aforementioned sink estimates cannot be compared against each other and should therefore not be used in support of the hypothesis of an increasing C sink in Europe. The more recent estimates (Schulze et al., 2009) should be simply considered as an update of the earlier estimates (Janssens et al., 2003) because the new estimates made use of new and probably more realistic cropland models (Ciais et

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al., 2010c), revised estimates of forest heterotrophic respiration (Luyssaert et al.,2007, 2010), incorporated Russian forest inventories (Shvidenko and Nilsson, 2002; Shvidenko et al., 2001) to account for differences in forest management and productivity between EU-25 and Eastern Europe, and accounted for soil carbon losses and gains following land-use change (UNFCCC, 2011).

When estimating the GHG balance of Europe, one has to deal with the small-scale variability of the landscape and of emission sources and simultaneously cover the entire geographic extent of the continent. No single technique spans the range in temporal and spatial scales required to produce reliable regional-scale GHG balances. Nevertheless, we believe the problem can be tackled by using an integrated suite of data and models, based on the philosophy that the continental GHG balance must be estimated by at least two independent approaches, one coming down from a larger scale, and one coming up from a smaller scale.

We present a new compilation of the GHG balance of Europe as defined in Sect. 2.1 following this dual constraint approach in which (1) a land-based balance derived mainly from ecosystem carbon inventories and (2) a land-based balance derived partly from eddy-covariance measurements are confronted with (3) the atmospheric-based balance derived from inversion informed by measurements of atmospheric GHG concentrations.

This work builds on earlier compilations by Janssens et al. (2003), Schulze et al. (2009, 2010) and Ciais et al. (2010a) but (1) formalizes the accounting framework, (2) better separates the data sources which resulted in two independent rather than a single land-based estimate, (3) increases the number of data products and as such presents a more realistic bias estimate and (4) achieves a higher spatial and temporal consistency of the sink strength through accurate accounting and reporting of the spatial and temporal extent of the estimates.

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2 Methods and material

2.1 Spatial and temporal extent of this study

The area under study (Fig. 1) was limited to Europe defined as the landmass containing the EU-27 plus Albania, Bosnia and Herzegovina, Croatia, Iceland, Kosovo, Macedonia, Norway, Serbia and Montenegro and Switzerland. A geographical rather than a political definition was followed, therefore, overseas territories (e.g. French Guyana) and distant islands (e.g. Spitsbergen, Canary Islands) where excluded from the carbon and GHG budgets whenever possible. It is often not clear whether the fluxes and stock changes from these islands are included in the data products underlying the carbon and GHG budgets. However, this resulted in minor inconsistencies in the spatial extent of the region under study. Also, it is often unclear whether the data for Serbia and Montenegro include Kosovo or not. We assumed they did not and whenever needed applied a bias correction for Kosovo. For each data product, the known anomalies in the spatial extent are indicated in Table 1.

Geographical Europe typically extends as far as the Ural Mountains and thus includes Belarus, Ukraine, the Caucasian republics and part of Russia. Under the RECAPP initiative these states are subject of a separate synthesis included in this series (Dolman et al., 2012).

Where data availability permitted, carbon and GHG budgets were estimated for two arbitrary time periods i.e. 1996–2000 and 2001–2005. However, especially for the flux-based and inventory-based approaches the time period of several fluxes and stock changes was limited to a period shorter than the study period or ill-defined when based on a compilation of data with different time frames. Table 1 indicates anomalies in the temporal extent.

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2.2 Accounting framework for GHG budgets

An accounting framework was developed to infer the C-flux between terrestrial ecosystems and the atmosphere (Fig. 2). The framework is based on a mass balance approach and given that for Europe most of the components have been independently estimated, different accounting schemes may be used to estimate the variable of interest i.e. the net land-atmosphere exchange. In this study we applied three, largely independent, accounting schemes based on: (1) atmospheric inversions, (2) land-based flux measurements and (3) land-based carbon inventories.

In the inversion approach the net land-atmosphere exchange is calculated through optimizing a prior land-atmosphere flux where the prior is adjusted to match the observed atmospheric CO_2, CO, CH_4 or N_2O concentrations. Following the notation introduced in Fig. 2 and Table 1 this can be formalized for CO_2 as:

$$\text{Net land} - \text{atmosphere flux} = 14\text{a} \tag{1}$$

Where, flux 14a (Fig. 2) represents the change in atmospheric CO_2 as derived from the inversions. In the land-based approaches the change in C stock can be estimated from flux-based estimates the different components of the budget or alternatively, some of the fluxes can be estimated from repeated C-inventories. These approaches are respectively formalized as:

$$\text{Net land} - \text{atmosphere flux} = 7\text{e} + 1\text{a} + 1\text{b} + 2\text{a} + 2\text{b} + 2\text{d} + 2\text{e} + 2\text{f} + 2\text{g} + 2\text{h} + 3\text{e} + 7\text{a} + 4\text{a} + 4\text{b} + 5\text{a} + 6\text{b} + 6\text{c} + 6\text{a} \tag{2}$$

Where 2a + 2b (notation explained in Table 1 and Fig. 2) was derived from eddy-covariance measurements. Following the principle of mass conservation, every individual component flux can be calculated based on the sum of the observed stock change and incoming and outgoing fluxes. Stock changes for fresh water ecosystems (9j), land ecosystems (9a to 9i), biological products (10a, 10b and 11) and non-CO_2

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C-gasses (14a$'$ and 14a$''$) have been estimated allowing us to calculate the following component fluxes of Eq. (2):

$$1a + 1b = 1c + 1b' - 2c - 6a - 6d - 7f - 9j \quad (3)$$

$$2a + 2b + 2d + 2e + 2f + 2g + 2h = 2c + 2d' + 2d''' + 2i + 2kl + 2m + 3a + 3b + 7c + 7d - 7g - 9a - 9b - 9c - 9d - 9e - 9f - 9g - 9i \quad (4)$$

$$3e = -10a - 10b - 11 - 3b + 3c - 3d + 3e' \quad (5)$$

$$7a = -1b' - 2d' - 2d''' - 2i - 2kl - 2m - 3e' - 4a' - 4a'' - 4b' - 4b'' - 5a' - 5a'' - 6b' + 7b - 7c - 14a' - 14a'' \quad (6)$$

Substitution of Eqs. (3) to (6) in Eq. (1) results into the following expression for the inventory-based net land-atmosphere flux:

$$\text{Net land} - \text{atmosphere flux} = 7e + (1c + 1b' - 2c - 6a - 6d - 7f - 9j) + (2c + 2d' + 2d''' (+2i + 2kl + 2m + 3a + 3b + 7c + 7d - 7g - 9a - 9b - 9c - 9d - 9e - 9f - 9g - 9i) + (-10a - 10b - 11 - 3b + 3c - 3d + 3e') + (-1b' - 2d' - 2d''' - 2i - 2kl - 2m - 3e' - 4a' - 4a'' - 4b' - 4b'' - 5a' - 5a'' - 6b' + 7b - 7c - 14a' - 14a'') + 4a + 4b + 5a + 6b + 6c + 6a \quad (7a)$$

or following elimination of terms

$$\text{Net land} - \text{atmosphere flux} = 1c + 3a + 3c - 3d + 4a - 4a' - 4a'' + 4b - 4b' - 4b'' + 5a - 5a' - 5a'' + 6b - 6b' + 6c - 6d + 7b + 7d + 7e - 7f - 7g - 9a - 9b - 9c - 9d - 9e - 9f - 9g - 9i - 9j - 10a - 10b - 11 - 14a' - 14a'' \quad (7b)$$

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Given that several inversions used land surface models to derive the prior fluxes and their errors are and that these models are often calibrated and validated against different subsets of eddy-covariance data (see for example Bousquet et al., 2010), many inversion-based and flux-based accounting schemes are not entirely independent. However, the assumptions and subsequent post-processing of the eddy-covariance observations differed substantially resulting in quasi-independent schemes. Also CO_2 inversion and inventory-based schemes share their data sources for fossil fuel emissions and are therefore not entirely independent for this study.

The same mass balance approach can be applied to estimate the C and GHG sink in ecosystems and biological product pools. Also these sinks could be estimates following three quasi-independent approaches: inversion-based, flux-based and inventory-based. Following the notation introduced in Fig. 2 and Table 1 this can be formalized for C as:

$$\text{Inversion}-\text{based C}-\text{sink} = 14a + 14a' + 14a'' - 7e - 4a - 4a' - 4a'' - 4b - 4b' - 4b'' - 5a - 5a' - 5a'' + 6a - 6b - 6c \quad (8)$$

$$\text{Flux}-\text{based C}-\text{sink} = (-2c - 7f + 1a + 1b + 1b' + 1c + 6a - 6d)(2ab + 2c + 2d + 2d' + 2d'' + 2e + 2f + 2g + 2h + 2i + 2k + 2l + 3a + 3b + 7c + 7d - 7g) + (-3b + 3d + 3c + 3e + 3e' + 2m) \quad (9)$$

$$\text{Inventory - based C - sink} = 9a + 9b + 9c + 9d + 9e + 9f + 9g + 9i + 9j + 10a + 10b + 11 \quad (10)$$

2.3 Balance closure

The mass balance approach introduced in Sect. 2.2 supports internal consistency checks. Stock-based changes in carbon content of inland aquatic ecosystems, land ecosystems, biological products and atmospheric pools obtained from inventories or inversions were confronted with their flux-based equivalents. This approach is formalized for in Eq. (3) for inland aquatic ecosystems, Eq. (4) for land ecosystems, Eq. (5) for the biological product pool and Eq. (6) for the atmospheric pool of non-CO2 gasses.

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2.4 Boundaries of the GHG budget

The GHG budget is determined by three boundaries: the spatial, the temporal and the accounting boundary. In this study we used a single spatial boundary (see Sect. 2.1) and two temporal boundaries (see Sect. 2.1). The accounting boundary describes the components that are included in the budget (Fig. 2). However, each of the included components has its own spatial boundaries (e.g. depth to which soil carbon is measured in inventory studies) and its own accounting boundaries. Given that these boundaries are often method-dependent, we choose to specify them in the supplementary material describing the data products (see supplementary material).

2.5 Data products

All data products used in this study are described in the supplementary material providing details on the underlying observations, processing done by the data owner, uncertainty estimates and post-processing in this study in addition to literature references.

2.6 Uncertainty estimates and error propagation

For data products that were subject of a formal uncertainty analysis, these uncertainty estimates were propagated in the balance computations. However, for the vast majority of the data products, no formal uncertainty analysis was available, for those products we assumed a normal uncertainty distribution with 95 % uncertainty interval amounting to 100 % of the flux estimate (thus 1 standard deviation is 50 % of the flux estimate). This imposed uncertainty was also propagated in the balance computations.

In addition to the uncertainty we quantified the spatial and temporal heterogeneity of the data product for the region (Table 1). Spatial heterogeneity was defined as the between-country heterogeneity of the annual flux of the first year of the sampling period. The country level was the smallest common unit across the different data products. Temporal heterogeneity was calculated as the interannual variability of the

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aggregated flux of the region under study. The heterogeneity estimates are simply reported but not used in any of the uncertainty estimates.

For flux components with a single uncertainty component, the probability distribution was assumed to be normal with mean and standard deviation equal to the reported values. The probability distribution of the uncertainty of the CO_2, CO, CH_4 and N_2O inversions is often reported by two components. The first component describes a quasi uniform range of likely model outputs and is derived from sensitivity analyses (Table 1). The second component describes a normally distributed uncertainty and is due to the set-up of the inversion model and is typically obtained through the Bayesian approach. Within an inversion these components depend on each other and the former should be contained in the latter, if the latter is well-defined. We used the uncertainty that resulted in the widest uncertainty intervals.

Probability distributions were fully accounted for in the balance sheets by means of simulations based on Monte Carlo techniques. Within each realization of the 6000 Monte Carlo simulations that were performed, (sub)totals were computed from randomly selected realizations of the component fluxes. Mean and standard deviations of the (sub)totals were taken from their probability distribution based on 6000 realizations.

2.7 Life cycle analysis

We performed a basic country-based life cycle analysis of the CO_2 cost of land management including the following processes: (a) agricultural activities (ploughing, harrowing, cultivation and planting), (b) production and application of fertilizer, (c) production and application of herbicide (glyphosate), (d) thinning, harvesting and planting of forest, (e) transport of roundwood and (f) transport of fire wood. Emission factors were retrieved from Ecoinvent database (Frischknecht et al., 2007). Fertilizer and herbicide consumption are respectively based on European Fertilizer Association on fertilizer consumption in the EU between 2006 and 2007 (EFMA, 2007). Wood harvest comes from the FAO (2008). Although the time frames of these data are not exactly in line with the time frame of the study, this inconsistency was though to be of minor importance given the assumptions made in the life cycle analysis.

For cropland the following assumptions were made: each cropland is ploughed, harrowed, planted, cultivated, fertilized, sprayed and harvested annually. Grassland is ploughed and harrowed every 10 yr and cultivated and fertilized every year. In the absence of specific data, the CO_2 cost of fertilizer production was distributed over crop and grassland assuming that grasslands received half the dose of croplands. One percent of the forest land was harvested and planted and 10 % was thinned each year. The harvested wood was transported over a distance of 80 km if used as industrial roundwood. Fire wood was transported over a distance of 40 km.

3 Results and discussion

3.1 Inversion-derived net land-atmosphere GHG fluxes

A subset of inversions, optimized for Europe was selected to compile the European CO_2, CH_4, CO and N_2O budgets (Tables 1 and 2). Despite the effort in harmonizing the spatial, and temporal extent, the different inversions resulted in largely different estimates of the land-atmosphere flux ranging from 654 $Tg\,C\,y^{-1}$ to 1239 $Tg\,C\,y^{-1}$ for CO_2 (Chevallier et al., 2010; Peters et al., 2010; Peylin et al., 2005; Rödenbeck et al., 2003). For N_2O the two available inversions converged within 25 % from each other. Although at first this looks very encouraging it should be noticed that both inversions largely used the same observations (Corazza et al., 2011; Thompson et al., 2011) so that the difference between the inversions is most likely due to differences in atmospheric transport and the definitions for prior uncertainties. For CH_4 (Bousquet et al., 2006) and CO (Fortems-Cheiney et al., 2011) just a single inversion was used and therefore inter-model variability could not be estimated. Further, inversions provide only a top-down estimate for regions constrained by the observations. For N_2O the constrained region was smaller than the region under study (Corazza et al., 2011).

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The land-atmosphere flux of GHG's determines to a large extent the rate of accumulation of GHG's in the atmosphere and its interannual variability modulates the year-to-year growth-rate of GHG's and is thus of special interest to the climate system. Also interannual variability hints at the sensitivity of the land surface to climate variability and therefore in hindsight about future land surface responses to climate change. The interannual variability of Europe was studied by simultaneously considering two characteristics: (1) the absolute value of the land-atmosphere flux $\mu_j(\mu_i(|\,\mathrm{Flux}_{ij}|))$ and (2) the mean interannual variability of the land-atmosphere flux $\mu_j(\sigma_i(|\,\mathrm{Flux}_{ij}|))$. Where i indicates the pixel and j indicates the data product. The first characteristic identifies regions where the land-atmosphere flux is potentially important for the climate system whereas the second characteristic identifies regions where the interannual variability is expected to be large. Combining both characteristics in a single variable (Fig. 3) allows the regions to be distinguished that contribute most to the year-to-year variability in atmospheric CO_2 concentration.

For both periods (1996–2000 and 2001–2005), the net land-atmosphere flux in Scandinavia is a small contributor and the central region appears as an important contributor to the interannual variability in atmospheric CO_2 concentration over Europe. A similar latitudinal pattern in interannual variability was observed for deciduous forests but contradicted for evergreen forest based on observations from 39 northern-hemisphere eddy-covariance sites located at latitudes ranging from 29^{o}N to 64° N (Yuan et al., 2009). A comparison between two deciduous and one evergreen site suggests that deciduous forests may contribute disproportionately to variability in atmospheric CO_2 concentrations within the northern hemisphere (Welp et al., 2007). Given the higher abundance of deciduous forests in central and southern compared to northern Europe, this finding may help to explain the observed spatial pattern (Fig. 3) in interannual variability. However, it should be noted that the observed higher variability for deciduous trees compared to evergreen is pre-mature given that only three sites were investigated (Welp et al., 2007).

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Rather than being an ecosystem property, the interannual variability in ecosystem productivity may be due to differences in weather patterns between central and northern Europe. Such a difference could for example be determined by the North Atlantic Oscillation (NAO) (Hoerling et al., 2001). In some years, the NAO pushes the Mediterranean climate southward resulting in wet weather in the central and Mediterranean Europe, other years the NAO allows a more northern occurrence of the Mediterranean climate resulting in dry weather in central Europe (Hurrell, 1995). Differences in the spatial extent of the summer and winter NAO (Linderholm et al., 2009) may contribute to the observed north-south trend in interannual variability of the land-atmosphere CO_2 flux.

The inversion-derived interannual variability over Europe is sensitive to the lack of observational constraint on fluxes and imperfect knowledge of the prior flux estimates. Atmospheric inversions are forced to achieve mass balance closure. The inversions may achieve mass balance closure by simply attributing the residual fluxes to the least constrained regions. In Europe, the tall tower network that is used to constraint the inversions is less dense in northern, southern and eastern compared to central Europe (Ramonet et al., 2010). Contrary to our observations, this set-up of the inversions is expected assigning the residual fluxes and thus the highest variability to northern and southern Europe. However, in line with the set-up of the inversions, the inversions assigned a high variability to eastern Europe (EST, LVA, LTU and POL), a region poorly constrained by measurements. Therefore, the observed pattern in Eastern Europe could reflect the state of the art in inversion rather than a biological phenomenon.

3.2 Eddy-covariance and inventory-based net land-atmosphere GHG fluxes

3.2.1 Land-use and surface area

The study region has surface area of 5×10^6 km^2 of which all except Switzerland is being accounted for in the CORINE database. The dominant land cover is forest (35 %) followed by cropland (25 %) and grassland (18 %). Estimates for forest area differ at

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most 12 % for the EU-25 when FAO and CORINE are compared. This difference is likely explained by CORINE classifying part of the harvested forest as semi-natural vegetation. While different sources (i.e. CORINE versus FAO) agree on the importance of forest and cropland (estimates differ at most 6 % for the EU-25), such convergence is absent for grazing land with estimates diverging by more than 20 % for the EU-25, which contains the best documented nations of Europe. This uncertainty is caused by whether the classification of grazing land includes only permanent grasslands (e.g. permanent pastures) which are intensively and continuously managed (i.e. mowing or grazing) or also natural or semi-natural vegetation that is extensively grazed.

Where the CORINE land cover classes account for wetlands it is important to distinguish between marshes and peatland and more specifically between disturbed and undisturbed peatland. For GHG budgets, distinguishing between these management types is essential because the undisturbed peatland typically acts as a GHG-sink whereas the disturbed peatland under cropland and forests often act as a GHG-source because of enhanced decomposition following harvest, ploughing and or drainage. The areas for different land uses on peatland have been taken from Joosten (2010). Although not explicitly reported by Joosten (2010), for this study, the areas were assumed constant between 1996 and 2005.

3.2.2 Eddy covariance based net land-atmosphere flux

The current eddy-covariance tower network is equipped to record the CO_2 exchange between land and atmosphere (this fluxes is also known as NEE in the sense of Chapin et al., 2005). Although an eddy-covariance based CH_4 network is emerging, at present only very few sites report other greenhouse gas fluxes than CO_2, therefore, our eddy-covariance based estimates are limited to CO_2 exchange.

At the site scale, the scale for which eddy-covariance measurements are available, CO_2 is exchanged with neighbouring sites (i.e. lateral CO_2 transport, harvest and trade), the underlying soil matrix and the overlying atmosphere. The typical eddy-covariance tower set-up records only small scale vertical exchange between

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ecosystem and atmosphere. Consequently, NEE estimates need to be corrected for lateral transport and leaching from the soil matrix to obtain the ecosystem carbon sink. Accounting is further complicated by the fact that (Korner, 2003): (1) C, CH_4 and CO_2 are exported to neighbouring ecosystems that are not part of the eddy-covariance network i.e. inland water and product pools (Fig. 2). Therefore, lateral fluxes and the CO_2 exchange between these ecosystems and the atmosphere also need to be accounted for. (2) For forests and grasslands the network is biased towards uniform established ecosystems, hence, newly established ecosystems following land-use change need to be separately accounted for. (3) Eddy-covariance measurements are not made during fires to prevent the equipment from being damaged; fires emissions thus need to be separately accounted for. (4) No eddy-covariance network exists over urban and industrial areas, therefore, fossil fuel emissions need to be separately accounted for. (5) The eddy-covariance is not globally representative but given its density over Europe, this is likely a minor issue for estimating mean fluxes over the study region (Sulkava et al., 2011). Equation (2) and Fig. 2 show how issues 1 to 4 were accounted for in this study.

Despite being well documented that annual NEE poorly correlates to climate and is more likely driven by site disturbance such as harvest, grazing, thinning, fire, ploughing, etc. (Luyssaert et al., 2007), for a given site, NEE fluxes at high temporal resolutions (i.e. hourly to monthly) are (partly) driven by meteorology (Baldocchi, 2008; Law et al., 2002). Jung et al. (2011) and Papale et al. (2003) used this observation to upscale eddy-covariance measurement to the region. Nevertheless, these authors caution for the lack of spatially explicit disturbance data in their upscaling approach and the substantial uncertainty of their data products (Jung et al., 2009, 2011).

For the region and period under consideration both eddy-covariance-based estimates (Table 1), using the same data but different statistical methods, converged at $-965\,\mathrm{Tg\,C\,y^{-1}}$ within 10 % (one standard deviation). Not surprisingly the estimates indicate that the European land surface consistently takes up CO_2 from the atmosphere. Interannual variability was estimated at 70 % (one standard deviation) and was tightly

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related to meteorology. Although the spatial variability in NEE is thought to be driven by disturbances, the relationship between the temporal variability in NEE and meteorology may be real (Baldocchi, 2008; Law et al., 2002). Nevertheless, the strength of this relationship is most likely an artefact of the fact that the upscaling makes use of remotely sensed fpar and meteorological data (Jung et al., 2011). Following accounting for fluxes not measured by the eddy-covariance technique (Eq. 2), the net land-atmosphere flux was estimated at 943 ±540 Tg C y^{-1} between 2001 and 2005. Several of the flux estimates were temporally unresolved, hence, the interannual variability of the net land-atmosphere flux could not be estimated.

3.2.3 Inventory based net land-atmosphere flux

Alternatively, net land-atmosphere fluxes of CO_2, CH_4 and CO can be estimated from repeated C-inventories often in conjunction with deterministic models (i.e. Tupek et al., 2010; see also supplementary material) and flux measurements to complete the inventory measurements (see Methods and material). This approach has been formalized in Eq. (7). Although this appears as the most straightforward of the three applied approaches to estimate the net land-atmosphere flux, the representativeness of the European estimates may be hampered by data scarcity (see supplementary material). For example, changes in soil carbon for the entire territory are based on a rather limited number of sampling plots for croplands (Ciais et al., 2010c) and grasslands (Lettens et al., 2005; Goidts and Wesemael, 2007; Soussana et al., 2004; Bellamy et al., 2005) and are based on deterministic modelling for forests (Luyssaert et al., 2010; Tupek et al., 2010). Further, spatially explicit estimates are none existent for several potential hotspots such as drained peatlands, reservoirs and areas under land-use change, for example, it remains unclear what happens with soil carbon following urbanisation.

Assuming that the regions that were inventoried are representative for the spatial domain under study, the European net land-atmosphere flux was estimated at $993 \pm 190\ \text{Tg C y}^{-1}$ between 2001 and 2005 (Table 2). A similar approach was used to estimate the net land-atmosphere fluxes for CH_4, CO and N_2O. The land surface

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is a source for CH_4 and CO of respectively 23 ± 5 and 21 ± 5 Tg C y^{-1}. For N_2O the land-atmosphere flux is estimated at 125 ± 35 Tg C in CO_2-eq y^{-1} or 1 Tg N y^{-1}. Several of the flux estimates required to estimate the net land-atmosphere flux of CO_2, CH_4, CO and N_2O were temporally unresolved, hence, the interannual variability was not estimated.

3.3 Uncertainty and consistency of the net land-atmosphere GHG fluxes

Inversion based accounting adjusts a prior set of fluxes for the net ecosystem-atmosphere exchange with a given uncertainty to better match the observed atmospheric concentrations of the species under study within their uncertainty. Recent inversions come with a formal uncertainty analysis (Table 1). However, the vast majority of the data products other than inversions have not been subjected to formal uncertainty analysis. For these products we assumed a Gaussian uncertainty distribution with 95 % uncertainty interval amounting to 100 % of the flux estimate (thus 1 standard deviation is 50 % of the flux estimate).

The uncertainty of the eddy-covariance and inventory based estimate of the net land-atmosphere flux was estimated from the uncertainty of its components and is thus determined by the assumed uncertainty of 50 %. Despite the shared assumption, the uncertainty of the inventory-based estimate was estimated to be almost one third of that of the flux-based estimate (Table 2). This difference is due to the difference in the magnitude of the fluxes that are used in the balance calculations (i.e. Eq. 2 vs. Eq. 7). Given our assumption, the largest component flux comes with the largest uncertainty. Consequently, the total uncertainty is determined by the uncertainty of the upscaled NEE (2ab; Table 1) in the flux-based approach whereas the uncertainty of the inventory-based approach is determined by the uncertainties of fossil fuel burning (5a; Table 1) and the changes in forest carbon (9e; Table 1) . Improved uncertainty estimates require formal uncertainty analyses for the upscaled NEE and changes in forest carbon.

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The mass balance approach introduced in Sect. 2 supports internal consistency checks. Stock-based changes in carbon content of the aquatic, terrestrial, product and atmospheric pool obtained from inventories or inversions were confronted with their flux-based equivalents (Fig. 2). This approach is formalized for CO_2 in Eqs. (3) to (6) and the balance closure has been reported in Table 3. Balance closure between the stock-based and flux-based estimates is not significantly different from zero mainly because of the wide uncertainty intervals. The current estimates and their uncertainties lack statistical evidence to justify introducing a 'closure gap'. Hence, our estimates for these components were considered consistent. Consistency is expected to further improve if atmospheric transport to adjacent regions would be accounted for (7b, 7d and 7e in Table 1).

However, when the land sink is used as reference, the statistics-based consistency seems not justified for the biological product pool (i.e. all harvested biomass and subsequent products such as food, fodder, wood, paper, ...) which shows an inconsistency of 88 $Tg\,C\,y^{-1}$ between the stock-change and flux-based approach. This inconsistency represents about 40 % of the inventory-based change in carbon stock for the region under study (Table 3). This inconsistency may be due to the lack of dense harvest and herbivory observations for grasslands and croplands. The current budget relies on modelled data (see 3b, c and 3b, d in Table 1). Hence, it is expected that the internal consistency of the European C budget could largely improve by informing emissions estimates of biological product pools by measurements.

It should be noted that in this consistency check, two inaccurate fluxes could compensate each other resulting in an apparently high consistency. Consequently, the information content of our balance closure approach is limited as it does not identify which fluxes or stock-change estimates need to be further improved to improve the consistency and accuracy of the net land-atmosphere flux.

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3.4 GHG mitigation of European ecosystems

Sink estimates, based on Eqs. (8) to (10), show that the European ecosystems and biological product pools were a C-sink between −356 and −201 $Tg\,C\,y^{-1}$ between 2001 and 2005 (Table 4). Individual sink estimates come with large uncertainties ranging between 80 and 330 $Tg\,C\,y^{-1}$. However, the extreme high and low sink-strengths are in conflict with the inventory-based approach that has a much smaller uncertainty of 80 $Tg\,C\,y^{-1}$ and as such puts a tighter constraint on the estimated sink strength. Applying the Bayesian theorem, a sink of -210 ± 70 $Tg\,C\,y^{-1}$ was found to be consistent with our three independent data sources i.e. atmospheric measurements, observed stock-changes and measured fluxes.

This C-sink in European ecosystems and biological product pools is thought to be mainly driven by changes in atmospheric CO_2, climate, atmospheric N-deposition, land use (intensity) change and to a minor extent by changes in ozone concentration and diffuse versus direct light flux (Le Quéré et al., 2009). Proper understanding of the drivers, their interaction and their contributions to the current sink is a prerequisite to predict whether the current sink-strength will increase, decrease or persist in the future. Spatially explicit sink attribution at the European scale is beyond the capacity of experimental work and can only be achieved by well-validated model-based experiments. For example, model-based experiments could shed a light on the effect of large scale bio-energy production on the current sink-strength. Such modelling-experiments could extent the time period of data-driven studies (for example Hudiburg et al., 2011). However, model-based sink attribution is still in its infancy because currently no single large scale model can deal with all aforementioned factors. At present multiple model-based experiments have been performed with different models. Hence, the observed sink is attributed to just a limited number of drivers, likely overestimating the importance of the drivers the model accounts for.

JULES (Joint UK Land Environment Simulator), a land surface model integrating climate change and [CO_2], showed that [CO_2] increase had a higher impact on the

European C-sink than climate (Harrison et al., 2008b). Note that Europe was here defined as continental Europe. Warming was reported to emit C to the atmosphere. This C-source, however, was more than offset by the effect of increasing atmospheric [CO_2] resulting in a $-114\,Tg\,C\,y^{-1}$ sink between 1980–2005 (Harrison et al., 2008a). This modelling-experiment likely overestimates the effects of climate change and increasing [CO_2] because it accounted for land-use (intensity) change, N-deposition, increasing atmospheric ozone and diffuse vs. direct light.

Another model experiment performed with a version of the LPJ (Lund Potsdam Jena) land surface model) accounting for climate change, increasing atmospheric [CO_2] and land cover change, found an important effect of land use change over the EU-15 (Zaehle et al., 2007). During the 1990's, $3.3\,Tg\,C\,y^{-1}$ was lost to urbanization, $19.3\,Tg\,C\,y^{-1}$ to agricultural and $14.5\,Tg\,C\,y^{-1}$ to grasslands. Emission due to land cover change were offset by sequestration of $-59.1\,Tg\,C\,y^{-1}$ in forest and wood products resulting in a mean annual C-sink of $-29\,Tg\,C\,y^{-1}$ (Zaehle et al., 2007).

O-CN, a branch of ORCHIDEE (Organizing Carbon and Hydrology in Dynamic Ecosystems) integrating climate change, increasing atmospheric [CO_2] and the nitrogen cycle, shows that nitrogen deposition considerably alters the attribution of the C-sink to its drivers. Including nitrogen dynamics limited the global sink-strength by almost $0.4\,Pg\,C\,y^{-1}$ in the N-limited boreal regions, whereas N-deposition was reported to enhance the global terrestrial C-sink by 10 to 20 % (i.e. -0.2 to $-0.4\,Pg\,C\,y^{-1}$). Given that no N-effect was simulated for tropical regions, interactions with reactive nitrogen (Nr) substantially contribute to the C-sink in the temperate zone (Zaehle et al., 2010). A similar modelling-experiment using a slightly different version of O-CN that also accounts for the effects of land cover change .(Zaehle et al., 2011) resulted in a net forest uptake rate due to Nr deposition of $23.5 \pm 8.5\,Tg\,C\,y^{-1}$ (mean and standard deviation of the temporal heterogeneity for the years 1996–2005), In addition, the Nr effect on unmanaged grasslands accounts for a further sink of $2.8\,Tg\,C\,y^{-1}$. The simulations with O-CN suggest that Nr deposition has played only a minor role in terrestrial C cycling prior to the 1950s, after which the effect increased to the mid 1980s. The effect has

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thereafter remained relatively constant with some inter-annual variations related mainly to the interactions of Nr availability with climatic variability (Zaehle et al., 2011).

A comparison of BIOME-BGC (Global Biome model – Biogeochemical Cycles), JULES, ORCHIDEE and O-CN suggested a continuous increase in carbon storage from 85 Tg C y^{-1} in 1980s to 108 Tg C y^{-1} in 1990s, and to 114 Tg C y^{-1} in 2000–2007 (Churkina et al., 2010). These estimates are for continental Europe and limited to the terrestrial ecosystems sink. The study identified the effect of rising [CO_2] in combination with Nr-deposition and forest re-growth as the important explanatory factors for this net carbon storage. However, the modelling-experiments did not account for changes in the age structure of woody vegetation, a potentially important contributor.

Some modelling-experiments zoomed in on a single ecosystem and its specific characteristics. The effect of changes in age structure of forest has been subjected to separate modelling-experiments (Bellassen et al., 2011; Zaehle et al., 2006). For Europe, ORCHIDEE-FM, another branch of ORCHIDEE, integrating climate change, increasing atmospheric [CO_2], net forest cover change and changing age structure of forest shows spatial variation in the main drivers. Locally, climate change and changing age structure often determine temporal changes in the forest C-sink, whereas at the continental scale, increasing atmospheric [CO_2] drives the increase of the forest sink (Bellassen et al., 2011). A modelling-experiment with a similar capacity but making use of a LPJ (Zaehle et al., 2006) instead of ORCHIDEE-FM (Bellassen et al., 2011) found that climate change and increased atmospheric [CO_2] resulted in a net increase in the vegetation carbon stock of −57 Tg C y^{-1} in the 1990s over the EU-25. Afforestation doubled the sink strength by −118 Tg C y^{-1}. Despite its local importance for determining the carbon balance on the European scale, changes in harvest intensity decreased C-sequestration by 5 Tg C y^{-1} in forest vegetation and thus had a small impact on the European scale. Both Zaehle et al. (2006) and Bellasen et al. (2011) attributed a modest contribution of changing age structure to the current C-sink and both models were capable of reproducing large-scale forest inventory statistics.

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Contrary to the inventory-based estimates (Table 1), model simulations estimated a small but uncertain CO_2 C-sink in croplands (Ciais et al., 2010b). This sink was attributed mainly to past and current management, and to a minor extent the shrinking areas of arable land consecutive to abandonment during the 20th century (Ciais et al., 2010b). When assessing the effects of rising atmospheric [CO_2], changing climate, and agro-technology changes on the carbon balance of European croplands, agro-technology changes and varieties selection were found to be largely responsible for the sink rather than rising [CO_2] and climate change (Gervois et al., 2008). Sink uncertainty for croplands was dominated by unknown historical agro-technology changes (Ciais et al., 2010b; Kutsch et al., 2010; Ceschia et al., 2010) and model structure (Ciais et al., 2010b) with the model potentially missing processes that contribute to the observed C-source i.e. ploughing. Errors in climate forcing played a minor role (Ciais et al., 2010b).

The above mentioned modelling-experiments limited their simulations to CO_2 uptake and emissions. However, the same European ecosystems and biological product pools that were a CO_2-sink were a source for CH_4, CO and N_2O (Table 2). When converted to a common unit i.e. Tg C in CO_2-eq y^{-1} the C-sink is most likely offset by the global warming potential of CH_4 and N_2O. As a consequence, the European ecosystems and biological product pools are a GHG source of 105 ±100 Tg C in CO_2-eq y^{-1} to the atmosphere and thus contribute to global warming (Table 4). This finding confirms previous data-driven (Schulze et al., 2009, 2010) and model-based (Zaehle et al., 2011) studies.

To our best knowledge there are no comprehensive attribution studies of the GHG balance, which for Europe appears to be a source of GHG to the atmosphere (Table 4). However, global GHG-species-specific studies possibly shed some light on the global drivers of N_2O and CH_4 emissions. Before 1960, agricultural expansion, including livestock production, may have caused globally significant mining of soil nitrogen, fuelling a steady increase in atmospheric nitrous oxide (Davidson, 2009). After 1960, the rate of the increase rose, due to accelerating use of synthetic nitrogen fertilizers. Both agricultural expansion and use of synthetic nitrogen fertilizers are highly relevant

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for Europe.

The emissions of atmospheric methane were investigated by using two atmospheric inversions to quantify the distribution of sources and sinks for the 2006–2008 period, and a process-based model of methane emissions by natural wetland ecosystems (Bousquet et al., 2010). At the global scale, a significant contribution of CH_4 emissions was thought to come from wetlands in Eurasia where annual changes in precipitation where thought to be the underlying driver (Bousquet et al., 2010). However, other studies put forward other drivers i.e. more efficient rice production (Fuu Ming et al., 2011), unlikely to be important for Europe, or changes in petroleum production and use (Aydin et al., 2011). It remains to be quantified how relevant these global drivers are in explaining the European CH_4 emissions.

Integrated studies of the interactions of carbon (i.e. CO_2, CH_4, BVOC, CO) and nitrogen (N_2O) dynamics, land use (intensity) changes and environmental changes (i.e. increasing atmospheric [CO_2], climate change, increasing [O_3], changes in direct versus diffuse light) are needed to further improve the quantitative understanding of the driving forces of the European land carbon balance. Although such simulations may become available within a couple of years for forest, grasslands or croplands, a single simulation simultaneously accounting for the different ecosystems (including aquatic ecosystems) may not be available within the next 5 yr or so. The major constraints in realizing such simulations are: (a) model development in of support of such simulations and (b) lack of multi-factorial field experiments that can be used to validate such model outcome.

3.5 Fossil fuel cost of the C sinks

The carbon sink is often presented as a free service from "nature" to "mankind" and in this section we test whether this statement is justified for the Europe. It has been shown that land management is among the main drivers of the European ecosystem-based sink (See Sect. 3.4). It should, however, be recognized that land management requires the input of energy. Hence there is a CO_2 cost to realize the ecosystem-based C-sink. In Table 1 this CO_2 cost is accounted for in the following fluxes: 5a "Burning

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and product use CO_2", 4a "Peat, wood and charcoal burning CO_2" and 4b "other biofuel burning CO_2". In this section we used life cycle analysis (LCA) to estimate how much of the CO_2 emitted through fluxes 4a and 4b and 5a can be allocated to land management.

Based on our LCA assumptions (see Sect. 2.6) we estimated that the CO_2 cost for ecosystem management is 65 Tg C y^{-1} for cropland, 14 Tg C y^{-1} for grassland and 10 Tg C y^{-1} for forest (Table 5). Total emission for land management is thus 89 Tg C y^{-1} which represents less than 10 % of the total European emissions from fossil fuel burning. However, when the land sink rather than the fossil fuel emissions are used as a reference, emissions due to land management practices (i.e. ploughing, harvesting, fertilizing, etc.) can no longer be ignored.

Current agricultural ecosystems are a source of 21 Tg C y^{-1} (Table 1) and to create this source another 65 Tg C y^{-1} is emitted through energy use for land management (including fertilizer and herbicide production and application). Management of grasslands is a small sink: the ecosystems store about 24 Tg C y^{-1} their management emits about 14 Tg C y^{-1}. Forest management is doing considerably better: only 0.02 and 0.04 Tg of C are emitted to sequester 1 Tg C in the ecosystem. We hypothise that in addition to fossil fuels consumed to manage the forest C-sink, the sink strength in European forests is an indirect result of high fossil fuel consumption, as has been shown for Austria (Erb et al., 2008; Gingrich et al., 2007). Part of the current forest sink is thought to be a result of society's decreasing dependency on forest biomass resulting in harvest levels well below wood increment. This situation is maintained by the fact that the energy and raw material previously provided by forests has now been substituted by fossil fuel based energy and products.

It should be noted that undisturbed peatlands are observed to be C-sinks (Table 1) but at no management cost as these systems are typically unmanaged (Table 5). The annual C balance of undisturbed peatlands is however highly sensitive for weather conditions. For example summer droughts, which are becoming more frequent, may turn both ombrotrophic and minerotrophic mires into net sources of C (Saarnio et al., 2007).

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Rivers, lakes and reservoirs act as C-sinks (Table 1) but the structure of their management cost is somehow different from terrestrial ecosystems as it constitutes mainly of the cost for constructing canals and dams of which we had insufficient information to estimate their cost.

It should be noted that our cost analysis was strictly limited to ecosystem management. Hence, subsequent processing of the food and raw material was not included. Such inclusion is likely to change the outcome of the LCA substantially. The CO_2 cost for food processing in the EU-27 is at least 12 $Tg\,C\,y^{-1}$ between 2001 and 2005 (item 1.AA.2.E in UNFCCC, 2007) and thus relatively low compared to its production costs. The CO_2 cost of wood processing and especially pulp and paper production, is with 8 $Tg\,C\,y^{-1}$ between 2001 and 2005 (item 1.AA.2.D in UNFCCC, 2007) high compared to the production cost of the wood itself. Also the CO_2 costs for managing the biological product pool are expected to be substantial but not included in this LCA. Given the assumptions and the accounting boundary of this LCA, the results should be considered as indicative rather than final. Nevertheless it clearly demonstrates the point that the European C-sink in ecosystems and biological product pools is not a free service but comes at a considerable CO_2 cost.

4 Conclusions

This study confirmed that the European land surface (including inland waters and urban areas) is a net source for CO_2, CO, CH_4 and N_2O. However, for all ecosystems except croplands, C uptake exceeds C release and us such part of the CO_2 released through fossil fuel burning is removed from the atmosphere and sequestered in both terrestrial and inland aquatic ecosystems. Note that the aquatic systems are estimated to contribute second most to fossil fuel uptake, and thus rank above the European croplands and grassland. Given their surface area, this makes the inland waters a hotspot for C sequestration.

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If global CO_2 uptake would be uniformly distributed over the globe, the region under study is expected to sequester −45 to −105 Tg C y^{-1}. Based on three independent approaches we estimated the European C sequestration to amount −210 ± 70 Tg C y^{-1}. Owing to its large uncertainty, the additional uptake of 96 to 156 Tg C was not statistically significant but was nevertheless seen as an indicator that the European land surface (including inland waters) takes up more C than the global average. Along the same lines of reasoning, the region under study represents less than 4 % of global photosynthesis but realizes 8 to 18 % of the global C-sink.

If the C cost for ecosystem management is taken into account, the net uptake of ecosystems was estimated to decrease by 45 % but still indicates substantial C-sequestration. Also, when the balance is extended from CO_2 towards the main GHGs, C-uptake by terrestrial and aquatic ecosystems is compensated for by emissions of GHGs. As such the European ecosystems are unlikely to contribute to mitigating the effects of climate change.

Until present it appears impossible to estimate independent temporally resolved GHG balances over Europe for 1991–2000 and 2001–2009 due to lack of data. For several of the fluxes, all available data needed to be combined in a single and therefore temporally undefined estimate. We assigned our estimate to the period 2001–2005 but made use of data from other time periods. Hence, we did not succeed in obtaining high temporal consistency as stated in the objectives of this study and therefore temporal patterns in the GHG balance are not supported by this data compilation.

Achieving high spatial consistency, another objective of this study, was reasonably well achieved as most data products come with a well defined spatial extent, however, it remains unclear whether all products could be considered representative for the whole spatial domain as often only subregion(s) of the under study were sampled. These inconsistencies are not reflected in the GHG balances for 2001–2005; for five out of six budget components a good agreement was found between the flux-based and inventory based approach. Poor agreement was only observed for the biological product pool.

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Good agreement between fluxes, inventories and inversions (Table 2) increases our confidence that the current estimate of the GHG balance is unlikely to be strongly biased. However, due to largely unknown uncertainty of most data products the uncertainty of both net land-atmosphere CO_2 balance and land C-uptake remains high. Given that both the net land-atmosphere CO_2 balance and the land C-uptake are determined by a few large fluxes i.e. emissions from fossil burning, change in C content of forests, etc. the uncertainty of these key components needs to be formally estimated before efforts could be made to reduce the uncertainty. Reduced uncertainties in combination to the already high accuracy would further increase our confidence in the European GHG balances.

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Table 1. Spatial and temporal extent of the component fluxes and stock changes of the European C and GHG balance. For the spatial extent the ISO3166 country is used. Component fluxes are expressed in Tg C y^{-1} for CO_2, CO and CH_4, Tg CO_2-eq C y^{-1} for CH_4 (global warming potential of 23 over 100 yr; shown between brackets) and Tg CO_2-eq C y^{-1} for N_2O (global warming potential of 298 over 100 yr; shown between brackets) for the periods 1996–2000 and 2001–2005. Estimates of the different sources of uncertainty and heterogeneity for the fluxes are expressed in Tg C y^{-1} for CO_2, CO and CH_4 and Tg CO_2-eq C y^{-1} N_2O. The uncertainty and heterogeneity for the fluxes and stock changes are expressed in Tg C. The following uncertainties and heterogeneities (defined in Sect. 2.5) are reported: **(a)** Quasi uniform range of likely model outputs derived from sensitivity analyses (standard deviation of a uniform distribution), **(b)** Normally distributed uncertainty due to the set-up of the inversion model and is typically obtained through the Bayesian approach (standard deviation of a normal distribution), **(c)** Expert estimate of the total uncertainty (%), **(d)** Spatial heterogeneity (standard deviation of a normal distribution), **(e)** Temporal heterogeneity (standard deviation of a normal distribution).

Component	Spatial extent	Temporal extent	1996/ 2000	2001/ 2005	Uncertainty and heterogeneity (a)	(b)	(c)	(d)	(e)	Sources
Freshwater ecosystems										
1a River, lake and estuary GPP	Temperate and boreal ecosystems	Undefined	n.a.	−49	n.a.	n.a.	50	n.a.	n.a.	Bastviken
1b River, lake and estuary outgassing CO_2	Temperate and boreal ecosystems	Undefined	n.a.	73	n.a.	n.a.	50	n.a.	n.a.	Bastviken
	Watersheds draining into the Atlantic Ocean, Artic, Baltic, North, Mediterranean and Black sea	Undefined	n.a.	60	n.a.	n.a.	50	n.a.	n.a.	Ciais
1b' River, lake and estuary outgassing CH_4	Temperate and boreal ecosystems	Undefined	n.a.	1 (11)	n.a.	n.a.	50	n.a.	n.a.	Bastviken A
	Temperate and boreal ecosystems	Undefined	n.a.	4 (16)	n.a.	n.a.	50	n.a.	n.a.	Bastviken B
	All exc. UNK	Undefined	n.a.	0.6 (5)	n.a.	n.a.	50	> 0.1	n.a.	Saarnio
	Watersheds draining into the Atlantic Ocean, Artic, Baltic, North, Mediterranean and Black sea	Undefined		2 (12)	n.a	n.a	50	n.a.	n.a	Abril
1b''' River, lake and estuary outgassing N_2O	Temperate and boreal ecosystems	Undefined	n.a.	(10)	n.a.	n.a.	50	n.a.	n.a.	Bastviken
1c Lateral transport to ocean	Watersheds draining into the Atlantic Ocean, Artic, Baltic, North, Mediterranean and Black sea	Undefined	n.a.	22	n.a.	n.a.	50	n.a.	n.a.	Ciais
	Watersheds draining into the Atlantic Ocean, Artic, Baltic, North, Mediterranean and Black sea	Undefined	n.a.	49	n.a.	n.a.	50	n.a.	n.a.	Raymond

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Table 1. Continued.

Component	Spatial extent	Temporal extent	1996/2000	2001/2005	Uncertainty and heterogeneity (a)	(b)	(c)	(d)	(e)	Sources
Land ecosystems										
2ab NEE	Global on 1° × 1° grid	1983–2008	−905	−876	n.a.	n.a.	50	35	68	Jung
	Global on 0.5° × 0.5° grid	1990–2008	−1048	−1030	n.a.	n.a.	50	45	72	Papale
2c Lateral transport to freshwater (exc. DIC)	Watersheds draining into the Atlantic Ocean, Artic, Baltic, North, Mediterranean and Black sea	Undefined	n.a.	−72	n.a.	n.a.	50	n.a.	n.a.	Ciais
2d Ecosystem fires CO_2	Global on 0.5° × 0.5° grid	1997–2009	n.a.	4	n.a.	n.a.	50	0.3	1.5	Van der Werf
2d' Ecosystem fires CH_4	Global on 0.5° × 0.5° grid	1997–2009	n.a.	<0.1	n.a.	n.a.	50	> 0.1	> 0.1	Van der Werf
2d" Ecosystems fires CO	Global on 0.5° × 0.5° grid	1997–2009	n.a.	0.3	n.a	n.a	50	> 0.1	0.1	Van der Werf
2d"' Ecosystems fires N_2O	Global on 0.5° × 0.5° grid	1997–2009	n.a.	(0.3)	n.a	n.a	50	>0.1	0.1	Van der Werf
2e Storms & insect disturbance	All exc. CYP, EST, ISL, LVA, LTU, MLT	Mean for 1950–2000	6	n.a.	n.a.	n.a.	50	n.a.	n.a.	Schelhaas
2fgh Net (decay, vegetation fires and regrowth) from land-use change	All exc. ALB, BIH, CYP, MKD, MLT, UNK& SCG	Mean for 2000–2009	n.a.	1	n.a.	n.a.	50	0.8	n.a.	Grassi
2i BVOC emissions	Global on 1° × 1° grid	1983–1995	18	n.a.	n.a.	n.a.	50	0.6	n.a.	Lathière
2j (a) Cropland emissions N_2O	All exc. ALB, BIH, HRV, CYP, ISL, MKD, MLT, SCG, NOR, UNK & CHE	Mean for 1991–2000	n.a.	(62)	n.a.	n.a.	50	3	n.a.	Wattenbach
	All exc. ALB, BIH, HRV, CYP, ISL, MKD, MLT, SCG, NOR, UNK & CHE	Mean for 1991–2000	(64)	n.a.	n.a.	n.a.	50	2	n.a.	Dechow
2j (b) Grassland emissions N_2O	All exc. ALB, BIH, HRV, CYP, ISL, MKD, MLT, SCG, NOR, UNK & CHE	Mean for 1991–2000	n.a.	(24)	n.a.	n.a.	50	1	n.a.	Wattenbach
	All exc. ALB, BIH, HRV, CYP, ISL, MKD, MLT, SCG, NOR, UNK & CHE	Mean for 1991–2000	(21)	n.a.	n.a.	n.a.	50	1	n.a.	Dechow
2k Marshes emissions CH_4	Watersheds draining into the Atlantic Ocean, Artic, Baltic, North, Mediterranean and Black sea	Undefined	n.a.	0.2 (1)	n.a.	n.a.	50	n.a.	n.a.	Abril
2l Peatland emissions CH_4	SWE, FIN, DEU, GBR	2000–2002	n.a.	2 (15)	n.a.	n.a.	50	n.a.	n.a.	Bryne
	Watersheds draining into the Atlantic Ocean, Artic, Baltic, North, Mediterranean and Black sea	Undefined	n.a.	1 (9)	n.a.	n.a.	50	n.a.	n.a.	Abril
2kl Marshes and peatland emissions CH_4	Watersheds draining into the Atlantic Ocean, Artic, Baltic, North, Mediterranean and Black sea	Undefined	n.a.	1 (10)	n.a.	n.a.	50	n.a.	n.a.	Abril
	All exc. UNK	Undefined	n.a.	1 (8)	n.a.	n.a.	50	0.3	n.a.	Saarnio
2m Agricultural (including cattle) emissions CH_4	All exc. ALB, BIH, CYP, MKD, MLT, UNK & SCG	1990–2008	7 (63)	7 (60)	n.a.	n.a.	50	0.3	0.3	UNFCCC
Biological products										
3a (a) Peat harvest for fuel production	CZE, EST, FIN, DEU, HUN, IRL, LTU, NOR, POL, SWE & GBR	1999	10	n.a.	n.a.	n.a.	50	1	n.a.	IPS
3a (b) Wood harvest for fuel production	All exc. UNK	2001–2010	n.a.	16	n.a.	n.a.	50	1	1	FAO
3b (a) Peat harvest for other uses	CZE, EST, FIN, DEU, HUN, IRL, LTU, NOR, POL, SWE and GBR	1999	4	n.a.	n.a.	n.a.	50	0.4	n.a.	IPS
3b (b) Wood harvest for other uses	All exc. UNK & CYP	2005	n.a.	86	n.a.	n.a.	50	4	n.a.	GFRA
3b (c) Crop harvest for other uses	All exc. UNK	2000	n.a.	378	n.a.	n.a.	50	17	n.a.	Haberl & Krausmann

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Table 1. Continued.

Component	Spatial extent	Temporal extent	1996/ 2000	2001/ 2005	Uncertainty and heterogeneity (a)	(b)	(c)	(d)	(e)	Sources
3b (d) Grazing for other uses	All exc. UNK	2000	n.a.	161	n.a.	n.a.	50	8	n.a.	Haberl & Krausmann
3c Export	All exc. UNK	2000	n.a.	−142	n.a.	n.a.	50	6	n.a.	Haberl & Krausmann
3d Import	All exc. UNK	2000	n.a.	161	n.a.	n.a.	50	6	n.a.	Haberl & Krausmann
3cd Net trade	All exc. UNK	2000	n.a.	19	n.a.	n.a.	50	4	n.a.	Haberl & Krausmann
3e (a) Decay of products in landfills CO_2	All exc. ALB, BIH, CYP, MKD, MLT, UNK & SCG	1990–2008	1	1	n.a.	n.a.	50	0.1	0.1	UNFCCC
3e (b) Burning of agricultural residues C	All countries	2000	n.a.	28	n.a.	n.a.	50	3	n.a.	Haberl & Krausmann
3e (c) Decay of products outside landfills CO_2& CH_4	All exc. UNK	2000	n.a.	529	n.a.	n.a.	50	n.a.	n.a.	Residual Haberl & Krausmann
3e' Decay of products in landfills CH_4	All exc. ALB, BIH, CYP, MKD, MLT, UNK & SCG	1990–2008	6 (51)	5 (43)	n.a.	n.a.	50	0.2	0.3	UNFCCC
3e''' Decay of products in landfills N_2O	All exc. ALB, BIH, CYP, MKD, MLT, UNK & SCG	1990–2008	(<0.1)	(<0.1)	n.a.	n.a.	50	< 0.1	< 0.1	UNFCCC
Burning of bio-fuels										
4a (a) Peat burning CO_2	CZE, EST, FIN, DEU, HUN, IRL, LTU, NOR, POL, SWE & GBR	1999	10	n.a.	n.a.	n.a.	15	1	n.a.	IPS
4a (b) Wood & charcoal burning CO_2	All exc. UNK	2001–2010	n.a.	16	n.a.	n.a.	50	1	1	FAO
4a' (a) Peat burning CH_4	CZE, EST, FIN, DEU, HUN, IRL, LTU, NOR, POL, SWE & GBR	1999	0.3 (3)	n.a.	n.a.	n.a.	50	> 0.1	n.a.	IPS
4a' (b) Wood & charcoal burning CH_4	All exc. UNK	2001-2010	n.a.	0.5 (4)	n.a.	n.a.	50	> 0.1	> 0.1	FAO
4a'' (a) Peat burning CO	CZE, EST, FIN, DEU, HUN, IRL, LTU, NOR, POL, SWE & GBR	1999	1	n.a.	n.a.	n.a.	50	0.1	n.a.	IPS
4a'' (b) Wood & charcoal burning CO	All exc. UNK	2001–2010	n.a.	2	n.a.	n.a.	50	0.1	0.1	FAO
4b Other bio-fuel burning CO_2	Global on 0.1° × 0.1° grid	Undefined	n.a.	53	n.a.	n.a.	50	n.a.	4	Wang
4b' Other bio-fuel burning CH_4	Global on 0.1° × 0.1° grid	Undefined	n.a.	2 (16)	n.a.	n.a.	50	n.a.	n.a.	Wang
4b'' Other bio-fuel burning CO	Global on 0.1° × 0.1° grid	Undefined	n.a.	5	n.a.	n.a.	50	n.a.	n.a.	Wang
Fossil fuels										
5a Burning and product use CO_2	All exc. ALB, BIH, CYP, MKD, MLT, UNK & SCG	1990–2008	1173	1193	n.a.	n.a.	10	53	18	UNFCCC
	Region on 1° × 1° grid	1990–2007	1109	1109	n.a.	n.a.	7	51	35	CDIAC
5a' Burning and product use CH_4	All exc. ALB, BIH, CYP, MKD, MLT, UNK & SCG	1990–2008	4 (34)	3 (29)	n.a.	n.a.	50	0.2	0.2	UNFCCC
5a'' Burning and product use CO	All exc. ALB, BIH, CYP, MKD, MLT, UNK & SCG	1990–2008	20	15	n.a.	n.a.	50	1	2	UNFCCC
5a''' Burning and product use N_2O	All exc. ALB, BIH, CYP, MKD, MLT, UNK & SCG	1990-2008	(37)	(29)	n.a.	n.a.	50	2	2	UNFCCC
Geological processes										
6a Silicate and carbonate weathering	Global 1 km × 1 km grid	Undefined	−13	−13	n.a	n.a	50	0.6	n.a	Hartmann & Moosdorf
6b Geothermal-volcanic CO_2	CZE, DEU, GRC, HUN, ISL, ITA & ESP	Undefined	> 10	> 10	n.a.	n.a.	25	2	n.a.	Etiope
6b' Natural hydrocarbon seepage and geothermal exhalations CH_4	ALB, AUT, BGR, CZE, DNK, FRA, DEU, GRC, HUN, ISL, ITA, NLD, POL, ROU, ESP, CHE & GBR	Undefined	> 0.5 (>4)	> 0.5 (>4)	n.a.	n.a.	25	0.04	n.a.	Etiope
6c Cement and lime production	All exc. ALB, BIH, CYP, MKD, MLT, UNK & SCG	1990–2008	35	35	n.a.	n.a.	50	1	1	UNFCCC
6d Lithogenic carbon from carbonate weathering	Global 1 km × 1 km grid	Undefined	7	0.1	n.a	n.a	50	0.4	n.a	Hartmann & Moosdorf
7a Oxidation of non-CO_2 gasses	Global 1.9° × 3.75°grid	Mean for 1995–2005	63	63	n.a.	n.a.	50	n.a.	1	Szopa
7b Net non-CO_2 export to adjacent regions										?
7c Dust emission and sedimentation	Global 4° × 5°grid	Mean for 20 yr	−0.5	−0.5	n.a.	n.a.	50	n.a.	n.a.	Yue
7d net BVOC and POC transport to adjacent regions										?

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Table 1. Continued.

Component	Spatial extent	Temporal extent	1996/2000	2001/2005	Uncertainty and heterogeneity (a)	(b)	(c)	(d)	(e)	Sources
Atmospheric processes										
7e net CO_2 transport to adjacent regions										?
7f Rain contained DOC on freshwater ecosystems	All countries	Undefined	−0.4	n.a.	n.a.	n.a.	50	n.a.	n.a.	Willey
7g Rain contained DOC on land ecosystems	All countries	Undefined	−13	n.a.	n.a.	n.a.	50	n.a.	n.a.	Willey
Biomass stocks changes										
8a Above and below ground	All exc. UNK	Mean for 1990–1999 2000–2007	112	135	n.a.	n.a.	50	n.a.	n.a.	Pan
8b Dead wood	All exc. UNK	Mean for 1990–1999 2000–2007	2	2	n.a.	n.a.	50	n.a.	n.a.	Pan
Changes in soil and biomass stocks										
9a Artificial areas	No data available	Undefined	n.a.	0	n.a.	n.a.	n.a.	n.a.	n.a.	Assumption
9b Arable land and permanent crops	AUT, BEL, DNK, FIN, FRA, DEU, GBR	Undefined	21	21	n.a.	n.a.	50	42	n.a.	Ciais
9c Arable land on drained peatland	FIN, SWE, NLD, NOR, GBR	Undefined	n.a.	24	n.a.	n.a.	50	n.a	n.a	Lohila
9d Pastures and mosaics	BEL, GBR, FRA	Undefined	n.a.	−24	n.a	n.a	50	16	n.a.	Ciais
9e Forest (inc. biomass)	EU-27 All exc. UNK	Mean for 2000–2005 Mean for 1990–1999 2000–2007	n.a. −266	−121 −219	n.a. n.a.	n.a. n.a.	50 50	130 n.a.	n.a. n.a.	Tupek Pan
9f Forest (inc biomass) on drained peatland	FIN	Mean for 1990–2008	n.a.	−4	n.a.	n.a.	50	n.a.	n.a.	Lohila
9g Semi-natural vegetation	All exc. UNK	2000	n.a.	−2	n.a.	n.a.	50	n.a.	n.a.	FRA
9h Open spaces and bare soils	No data available	Undefined	n.a.	0	n.a.	n.a.	n.a.	n.a.	n.a.	Assumption
9i Peatlands	SWE, FIN, DEU, GBR	2000–2002	n.a.	−3	n.a.	n.a.	50	n.a.	n.a.	Bryne
9j Water bodies	Temperate and boreal ecosystems Watersheds draining into the Atlantic Ocean, Artic, Baltic, North, Mediterranean and Black sea	Undefined Undefined	n.a. n.a.	−41 −19	n.a. n.a.	n.a. n.a.	50 50	n.a. n.a.	n.a. n.a.	Bastviken Ciais
Harvested product stock change										
10a Wood	All exc. CYP, EST, ISL, LVA, LTU, MLT	2000	−2	n.a.	n.a.	n.a.	50	n.a.	n.a.	Eggers
10b Food	All countries	1990–2009	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Assumption
Landfill stock change										
11a Wood stock change in landfills	All exc. CYP, EST, ISL, LVA, LTU, MLT	2000	−17	n.a.	n.a.	n.a.	50	n.a.	n.a.	Eggers
11b Food stock change in landfills	EU-27	2008	n.a.	−6	n.a.	n.a.	n.a.	n.a.	n.a.	Decay function
12 Fossil fuel stock change										?
13 Geological stock change										?
Atmospheric stock change										
14a Atmospheric CO_2 stock change	Global 1° × 1° grid Global 5° × 4° grid Global 1° × 1° grid Global 3.75° × 2.5° grid Global 1° × 1° grid	2000–2007 1996-2008 1996–2004 1988–2008 1995–2008	n.a. 654 860 n.a. 772	1239 664 n.a. 1076 840	100 30 35 n.a. n.a.	150 150 150 400 n.a.	n.a. n.a. n.a. n.a. n.a.	60 29 43 43 44	71 153 157 142 137	Peters Jena Inversion Peylin Chevallier Transcom
14a' Atmospheric CH_4 stock change	Global 1° × 1° grid	1984–2008	20 (179)	20 (184)	45	50	n.a.	1	0.5	Bousquet
14a" Atmospheric CO stock change	Global 3.75° × 2.5° grid	2002–2009	n.a.	39	10	n.a.	n.a.	2	22	Fortems-Cheiney
14a'a" Atmospheric non-CO_2 C stock change	Global 1.9° × 3.75° grid	Mean for 1995–2005	90	90	n.a.	n.a.	n.a.	n.a.	3	Szopa
14a"' Atmospheric N_2O stock change	Regional 1° × 1° grid	2006–2007	n.a.	(113)	40	45	n.a.	5	1	Thompson
	Regional 1° × 1° grid	2006	n.a.	(152)	n.a.	n.a.	n.a.	6	n.a.	Corazza

Table 2. Carbon (Tg C y^{-1}) and GHG (Tg C in CO_2-eq y^{-1}) balance for CO_2, CO, CH_4 and N_2O between 2001 and 2005 estimated from inversions, inventories and flux-based approaches (only for CO_2). * Estimate based on upscaled EC-measurements.

	CO_2	CO	CH_4	N_2O	Total
Inversion					
C-balance	896 ± 375	39 ± 10	20 ± 15	–	995 ± 375
GHG-balance	896 ± 375	–	184 ± 135	130 ± 70	1210 ± 405
Inventory-based					
C-balance	993 ± 190 *943 ± 540	23 ± 5	21 ± 5	–	1037 ± 190 *987 ± 540
GHG-balance	993 ± 190*943 ± 540	–	181 ± 45	125 ± 35	1299 ± 200 *1249 ± 545

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Table 3. Balance closure for CO_2, CO and CH_4 between 2001–2005. The inventory-based stock change of C was used as a reference to express the relative importance of the missing C (%).

	Stock-change (Tg C y^{-1})	Flux-based (Tg C y^{-1})	Missing C (Tg C y^{-1})	Missing C (%)
Inland aquatic ecosystems	−25 ± 12	−39 ± 17	−8 ± 60	5
Land ecosystems	−146 ± 85	−184 ± 180	−36 ± 590	20
Biological products	−25 ± 10	−115 ± 195	88 ± 420	40
Atmospheric non-CO_2 CO	39 ± 10	2 ± 15	−35 ± 20	15
Atmospheric non-CO_2 CH_4	19 ± 9	7 ± 10	−11 ± 11	5
Atmospheric non-CO2 All	58 ± 13	9 ± 31	−50 ± 36	25

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Table 4. Three quasi-independent estimates of the land-based carbon (Tg C y^{-1}) and GHG (Tg C in CO_2-eq y^{-1}) balances of Europe between 2001 and 2005. The C balance accounts for CO_2, CH_4, CO and other C fluxes. The GHG balance accounts for CO_2, CH_4, CO, other C and N_2O.

	C-sink	GHG-sink
Inversion-based	−356 ± 330	−42 ± 360
Inventory-based	−201 ± 80	105 ± 100
Fluxes-based	−251 ± 220	55 ± 230

Table 5. CO_2 cost of land management in Europe based on life cycle analysis. The inventory-based sink was used to estimate the CO_2 cost per unit sink strength.

Land-use type	CO_2 cost ($Tg\ C\ y^{-1}$)	CO_2 cost per surface area ($g\ C\ m^{-2}$)	CO_2 cost per sink strength (–)
Artificial areas		?	?
Arable land and permanent crops (exc. drained peatlands)	65	59	3.1
Pastures and mosaics	14	11	−0.6
Forested land	10	6	−0.02 to −0.04
Semi-natural vegetation	?	?	?
Open spaces and bare soils	0	–	0
Wetlands	0	0	$-\infty$
Water bodies	?	?	?

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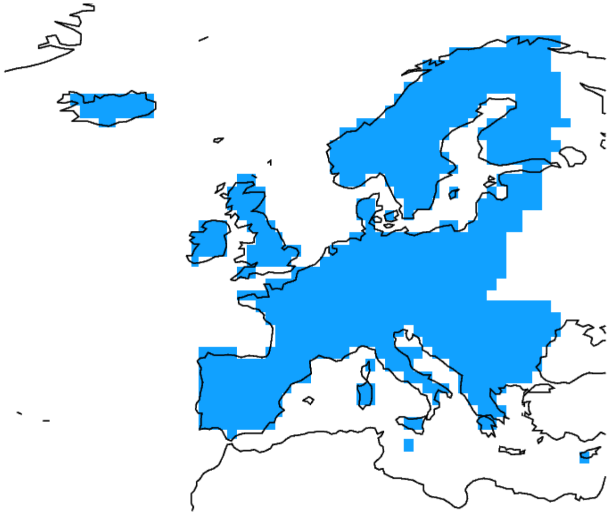

Fig. 1. Spatial extent of the region under study including: Albania (ALB), Austria (AUT), Belgium (BEL), Bosnia and Herzegovina (BIH), Bulgaria (BGR), Croatia (HRV), Cyprus (CYP), Czech Republic (CZE), Denmark (DNK), Estonia (EST), Finland (FIN), France (FRA), Germany (DEU), Greece (GRC), Hungary (HUN), Iceland (ISL), Ireland (IRL), Italy (ITA), Kosovo (UNK), Latvia (LVA), Lithuania (LTU), Luxembourg (LUX), Macedonia (MKD), Malta (MLT), the Netherlands (NLD), Norway (NOR), Poland (POL), Portugal (PRT), Romania (ROU), Serbia and Montenegro (SCG), Slovakia (SVK), Slovenia (SVN), Spain (ESP), Sweden (SWE), Switzerland (CHE) and United Kingdom (GBR)

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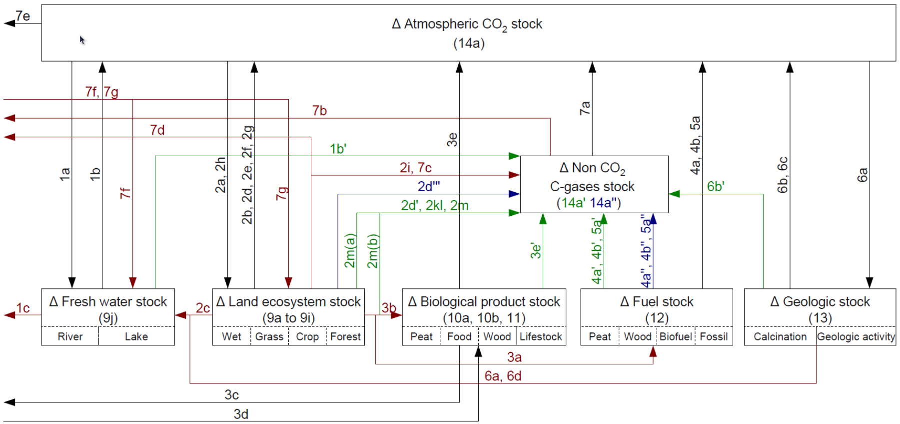

Fig. 2. Accounting framework of the C balance. The framework is based on a mass balance approach and given that for Europe most of the components have been independently estimated, different schemes may be used to estimate the variable of interest i.e. the net land-atmosphere exchange. In this study we applied three quasi- independent accounting schemes based on: (1) atmospheric inversions, (2) flux measurements and (3) carbon inventories. Black arrows indicate CO_2 fluxes, green indicates CH_4 fluxes, blue indicates CO and red indicates other C-fluxes. Labelling is explained in Table 1.

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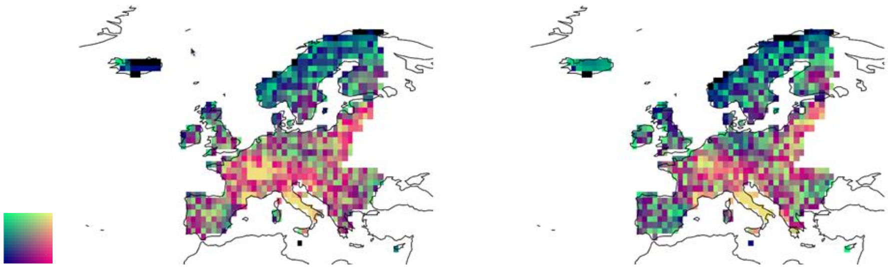

Fig. 3. Relative importance of the inversion-derived interannual variability of the CO_2 flux for the two periods under study **(a)** 1996–2000 and **(b)** 2001–2005. The colour scale ranging from blue to green (y-axis) indicates an increasing magnitude of the interannual variability where the scale ranging from blue to purple (x-axis) indicates an increasing importance of the CO_2 flux. Hence, blue pixels indicate regions with small CO_2 flux characterized by a small interannual variability of this flux, purple pixels show regions where the flux is important but characterized by low interannual variability and green pixels have high interannual variability but small CO_2 fluxes.

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