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Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance

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Climate change negotiations aim to reduce net greenhouse-gas emissions by encouraging direct reductions of emissions and crediting countries for their terrestrial greenhouse-gas sinks. Ecosystem carbon dioxide uptake has offset nearly 10% of Europe's fossil fuel emissions, but not all of this may be creditable under the rules of the Kyoto Protocol. Although this treaty recognizes the importance of methane and nitrous oxide emissions, scientific research has largely focused on carbon dioxide. Here we review recent estimates of European carbon dioxide, methane and nitrous oxide fluxes between 2000 and 2005, using both top-down estimates based on atmospheric observations and bottom-up estimates derived from ground-based measurements. Both methods yield similar fluxes of greenhouse gases, suggesting that methane emissions from feedstock and nitrous oxide emissions from arable agriculture are fully compensated for by the carbon dioxide sink provided by forests and grasslands. As a result, the balance for all greenhouse gases across Europe's terrestrial biosphere is near neutral, despite carbon sequestration in forests and grasslands. The trend towards more intensive agriculture and logging is likely to make Europe's land surface a significant source of greenhouse gases. The development of land management policies which aim to reduce greenhouse-gas emissions should be a priority.

Climate stabilization[1] can most effectively be achieved by reducing net emissions of greenhouse gases (GHGs); this can be done by reducing fossil fuel consumption or by enhancing sequestration of atmospheric CO_2. Sequestration can be accomplished through industrial processes or by maximizing the land-surface uptake of GHGs. However, maximizing land-surface uptake requires accurate quantification and improved understanding of the net land-surface GHG balance.

When estimating the GHG balance of Europe, one has to deal with the small-scale variability of the landscape and of emission sources, but simultaneously cover the entire geographic extent of the continent. No single technique spans the range in temporal and spatial scales required to produce a reliable regional-scale carbon balance. 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 (see Fig. 1).

The start of the commitment period of the Kyoto Protocol[2] in 2008 and the imminent international negotiations on future reductions of GHG emissions makes it necessary to quantify and understand the net land-surface GHG balance. This requires, in addition to the continental analysis, carbon balances to be of sufficient detail to allow sectorial analyses at the regional scale — the scale at which policy decisions will most probably be implemented.

We present a new compilation of the GHG balance of the 25 member states of the European Union (EU-25) between 2000 and 2005 and of the European continent by following a dual constraint approach in which the land-based balance derived mainly from ecosystem measurements is confronted with the atmospheric-based balance derived from measurements of GHG concentrations in the atmosphere and inversion models (Fig. 1, Box 1). We present sectorial, continental and regional analyses based on datasets representing the time period between 2000 and 2005.

Greenhouse-gas balance of ecosystems

The terrestrial carbon dioxide sink is the balance between CO_2 assimilation by plants through photosynthesis and emission through auto- and heterotrophic respiration. However, carbon is also lost from ecosystems by non-respiratory processes, such as leaching of organic compounds to rivers, and by disturbances (fire and harvest). The resulting net biome productivity (NBP) represents the long-lasting carbon gain or loss in biomass and soil pools[3].

Analysing the carbon balance of forests, grasslands and crops separately (Fig. 2, Box 1), grasslands seem to have 20% higher gross primary productivity (GPP) than forests and croplands. However, the differences in GPP are within the errors of the eddy covariance method used. The average GPP is surprisingly similar between land-use systems across Europe (1,190±108 g C m^{-2} yr^{-1}, average±standard deviation), even though one might have expected crops and grasslands to have considerably higher GPP than forests owing to greater photosynthetic rates of crop species[4] and fertilizer addition[5]. Crops are also grown on better soils, under better climatic conditions than forests[6], yet crops have a shorter growing season. Physiological differences between plant types are clearly apparent at the leaf level, but disappear at the canopy level[7], because factors such as distribution of radiation, allocation of carbohydrates within the plant and stand density outweigh the differences in photosynthetic rates[8]. This observation is important for predictions of continental GPP because it constrains expectations that global photosynthesis could be substantially increased through breeding or bioengineering.

Across Europe, autotrophic respiration consumes 44 to 53% of GPP (Fig. 2). Again, differences between land-use types are small. Nevertheless, the resultant net primary productivity, the difference between GPP and autotrophic respiration, is substantially higher in grasslands (750 g C m^{-2} yr^{-1}) than in crops or forests (average 534 g C m^{-2} yr^{-1}). Harvest takes 6% (forests) to 23% (crops and grasslands) of the GPP, leaving a variable amount of litter input into soils. Manure application adds carbon to agricultural soils where both litter and manure feed heterotrophic respiration, and contribute to non-respiratory losses through leaching of dissolved organic carbon and fire. Our models suggest that the resultant soil carbon balance is a significant sink in grasslands and forests, but a source to the atmosphere in croplands. This sequestration of soil carbon by grasslands is most probably the result of high fine-root turnover

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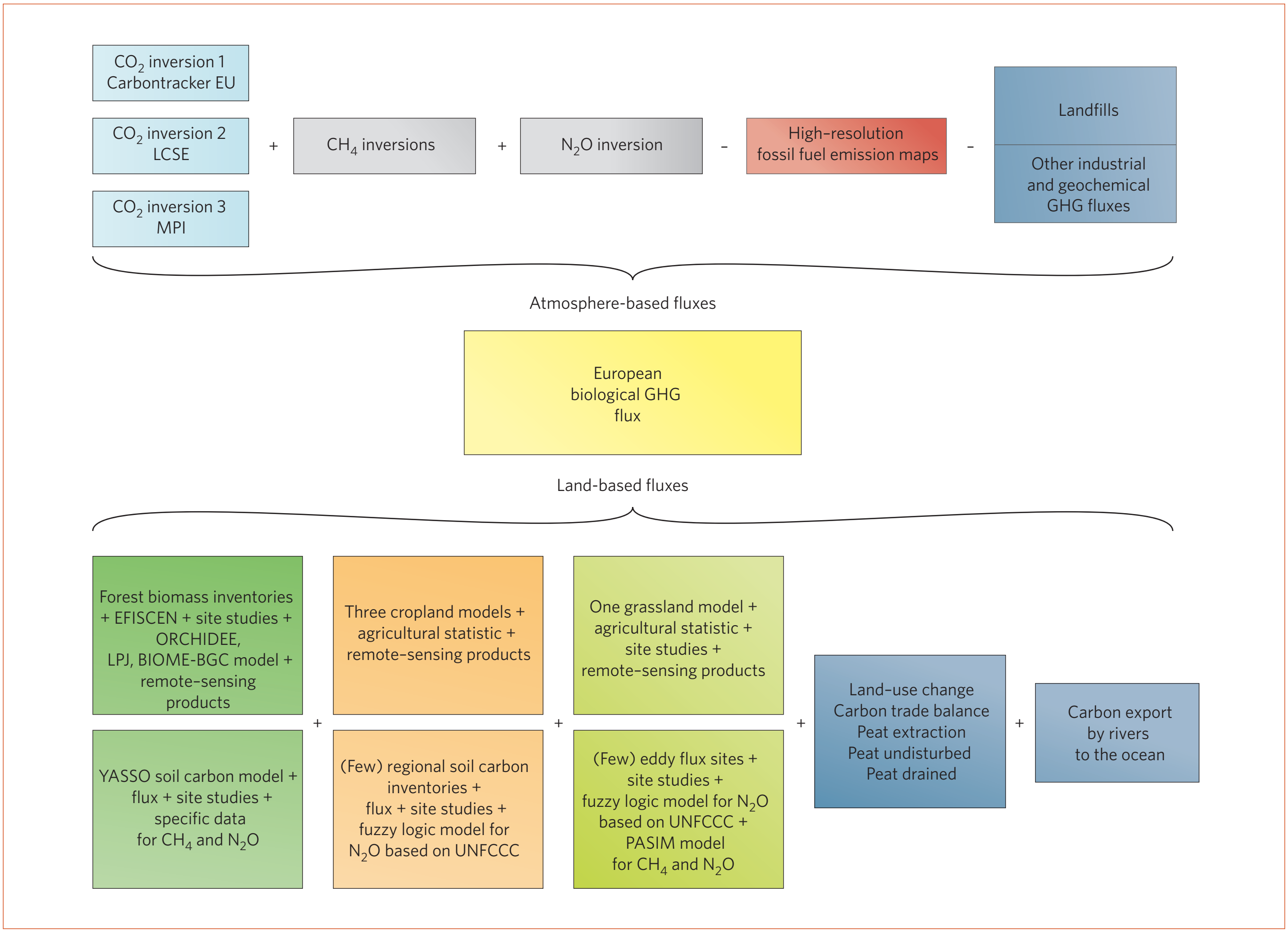

Figure 1 | Data streams entering into the European biological GHG balance. Estimates followed a dual constraint approach combining a top-down atmosphere-based and a bottom-up land-based estimate of fluxes. LSCE, Laboratoire des Sciences du Climat et l'Environment; MPI, Max Planck Institute; UNFCCC, United Nations Framework Convention on Climate Change; EFISCEN, ORCHIDEE, LPJ, BIOME-BGC, YASSO and PASIM are various models.

and reduced carbon losses due to stabilization of organic matter by endomycorrhizal compounds[9].

Even though grasslands seem to equal forests at sequestering carbon into soils, they cannot beat the overall carbon uptake by forests (Fig. 2, Table 1). Forests across Europe have a high total NBP because they accumulate carbon in woody biomass (70% of total NBP). As only a fraction of total wood growth is being harvested at present, total woody biomass is increasing[10]. This increasing stock of wood is partly due to the specific age class distribution of forests that were established following heavy logging during and after both World Wars[10]. These stands are now reaching the age and stem dimensions at which the accumulated biomass can be harvested. Thus, future routine harvesting may reduce the current forest carbon sink. The EU policy of fostering the use of biomass as an energy source[11,12] may even lead to increased forest harvesting, perhaps to a level beyond the rate of wood growth, posing a serious threat to the forest carbon sink. Increased harvesting will most probably result in a reduction of standing biomass, transferring part of the current carbon pool back into the atmosphere, but also substituting fossil fuels or materials that demand more energy in their production.

A unique aspect of our analysis is that we also take into account non-CO_2 GHGs, particularly methane (CH_4) and nitrous oxide (N_2O), which are also exchanged between ecosystems and the atmosphere. These gases absorb infrared radiation much more effectively than CO_2, giving a higher compound-specific global warming potential. Their individual contributions on a 100 year time horizon are here expressed as CO_2-equivalent units[13]. When accounting for CH_4 and N_2O emissions, the carbon balance becomes the net greenhouse-gas balance (NGB). The NGB can be positive, indicating losses of CO_2 and other GHGs to the atmosphere, or negative, indicating uptake from the atmosphere. Cropland NGB is positive owing to the high emissions of N_2O from fertilizers. In contrast, forest NGB is negative owing to the small fluxes of CH_4 and N_2O (ref. 14; Fig. 2) and the storage of carbon in wood over the past decades[10].

Greenhouse-gas balance of Europe and the EU

We used the dual constraint approach to estimate the GHG balance of continental Europe and the EU-25, and checked the top-down estimates from atmosphere-based fluxes against bottom-up land-based fluxes (see Fig. 1). For the top-down approach, we used concentration gradients observed at a network of stations across Europe and previous information on these fluxes (Table 1a, Box 1 and Supplementary Information). These results were the inputs for three inversion models for CO_2 (refs 15–17) and two models for both CH_4 (ref. 18) and N_2O (refs 19–22) that simulated the land–atmosphere GHG flux.

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Biological GHG fluxes were calculated in two ways. First, by subtracting industrial and geological fluxes from the atmospheric fluxes. Second, the land-based biological GHG flux (Table 1b) was derived from the measured stock changes or fluxes in forests[23], grasslands[24], croplands[25] and peatlands[26,27] scaled up with different approaches (see Supplementary Information), taking into account the contribution of additional fluxes induced by land-use change, wood and food trade, river export, methane oxidation and peat extraction (see refs in Table 1). It should be recognized that, as used here, the atmosphere- and land-based approaches are not totally independent — for example, the eddy covariance CO_2 flux measurements were used for up-scaling in the bottom-up approach, as well as in training the land-surface models that initialize the inversions. However, we do not expect this to substantially reduce the difference between the atmosphere and land-based approaches.

The total atmosphere- and land-based biological fluxes are remarkably similar for CO_2, N_2O and total GHG for Europe and EU-25 (Table 1). For CH_4, agreement is not as strong, but the difference is within the uncertainty limits. The good agreement between the atmosphere- and the land-based approaches does not mean that one should dismiss either of the estimates. The unresolved issues in both methods (see Box 1) imply that only the two-pronged approach can give sufficient confidence in the estimated CO_2 and GHG balances.

The similarity of the atmosphere and land-based results justifies calculating the average CO_2 and GHG balance shown in Table 1c. At the scale of the European continent, CH_4 and N_2O emissions fully cancel the biological CO_2 sink (−274±163 Tg C yr^{-1}; null hypothesis: sink = 0, $p = 0.05$), resulting in a near neutral GHG balance of −29±194 Tg C yr^{-1} (null hypothesis: sink = 0, $p = 0.64$). Although the terrestrial CO_2 sink in European ecosystems has compensated for 19% of the fossil fuel CO_2 emissions between 2000 and 2005 (12% of the EU-25 emissions in the same period), this balance drops to zero when considering the total GHG balance.

Our methodological approach used to estimate carbon balances is different to previous estimations[28,29] mainly because we have included new and more realistic cropland models[25], revised estimates of forest heterotrophic respiration[30], incorporated Russian forest inventories[31,32] 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. Land-use change is an important component of the total carbon balance, comprising new infrastructure, deforestation and abandonment of agricultural land. Despite all these methodological improvements, the present estimate of the European carbon

Box 1 | Two constraints, one greenhouse-gas balance

Over the past decades, the scientific community has developed a wide variety of approaches to estimate the GHG balance of a site, region or continent. However, all these approaches rely on assumptions; as yet, there is no direct method for deriving quality-controlled estimates of the GHG balance. The accuracy of any single-approach estimate is dependent on the validity of the underlying assumption, which is largely unknown. However, the diversity of data, models and their inherent assumptions make it possible to circumvent this problem by following a multiple-constraint approach. With this approach, the GHG balance is estimated by at least two methods that are largely independent in terms of data, models or assumptions.

In this study we adopted a dual-constraint approach, estimating the continental GHG balance and its precision and accuracy by combining top-down (or atmosphere-based) and bottom-up (or land-based) estimates (see Fig. 1). The top-down approach relies on discrete flask sampling and continuous measurements of GHG concentrations in the boundary layer, using tall towers and remote stations. These atmospheric measurements constrain atmospheric inversion models in the quantification of the land-surface flux. Because atmospheric mixing averages out small-scale flux variations, and because the atmospheric network is sparse (Supplementary Fig. S2), inversion fluxes have a large spatial footprint (in the order of 1,000 km^2) and large uncertainties (in the order of 50%) (C. Carouge *et al.*, unpublished). The top-down approach followed in this study is based on inverse models, which assume that the GHG sources, including fossil fuel emissions, and the spatial distribution of the land-based sinks are well known. The top-down estimates of the continental GHG balance are then used to estimate the biological GHG balance by subtracting industrial and geological fluxes from the atmosphere-derived fluxes.

Building up the GHG balance from the bottom relies on inventories and a network of flux towers (Supplementary Fig. S3) that monitor the fluxes of CO_2, water vapour and heat between forest, grassland and cropland, and the atmosphere. The underlying eddy-covariance micrometeorological technique has a spatial footprint of few hectares, and a moderate uncertainty (in the order of 20%). Eddy-covariance measurements will not give a complete GHG balance; this is obtained by incorporating downscaled economic statistics, remote-sensing products and soil and vegetation carbon-pool measurements. Soil and vegetation measurements are obtained from either site studies or regional, national and continental inventories. Ideally, GHG balances should be complemented, wherever possible, by measurements of changes in carbon stocks in biomass and soils as ultimate proof of long-term storage in the biosphere. The soil inventories made in this study (Supplementary Fig. S3) may serve as a basis to verify soil sinks in future.

Finally, site-level GHG balances are upscaled to the continental level by empirical methods such as artificial neural networks or by semi-deterministic methods such as ecosystem modelling. In semi-deterministic methods, the site observations are used to parameterize and validate the model. The bottom-up approach followed in this study assumes that the sampling network represents the entire continent.

The overall accuracy of the continental GHG balance can be assessed from the difference between the top-down and bottom-up estimates. Convergence of these largely independent approaches increases confidence in our GHG balance. However, quantifying the uncertainty of a dually constrained GHG balance is more difficult. Although component fluxes obtained by a single approach typically come with a well-defined accuracy, estimates of the uncertainty in different approaches, of the same component or across components, are often inconsistent. Even if all component fluxes were to come with consistent uncertainty estimates, integration would be hampered by conceptual issues such as how to weight representativeness against the accuracy of point measurements: for example, forest inventories with a wide spatial sample, against more accurate but most probably poorly representative site observations? More work is needed in addressing this issue by means of a data-assimilation framework. In the absence of such a framework we have taken a pragmatic approach and estimated the uncertainty by applying methods based on the Monte Carlo technique (see Supplementary Information).

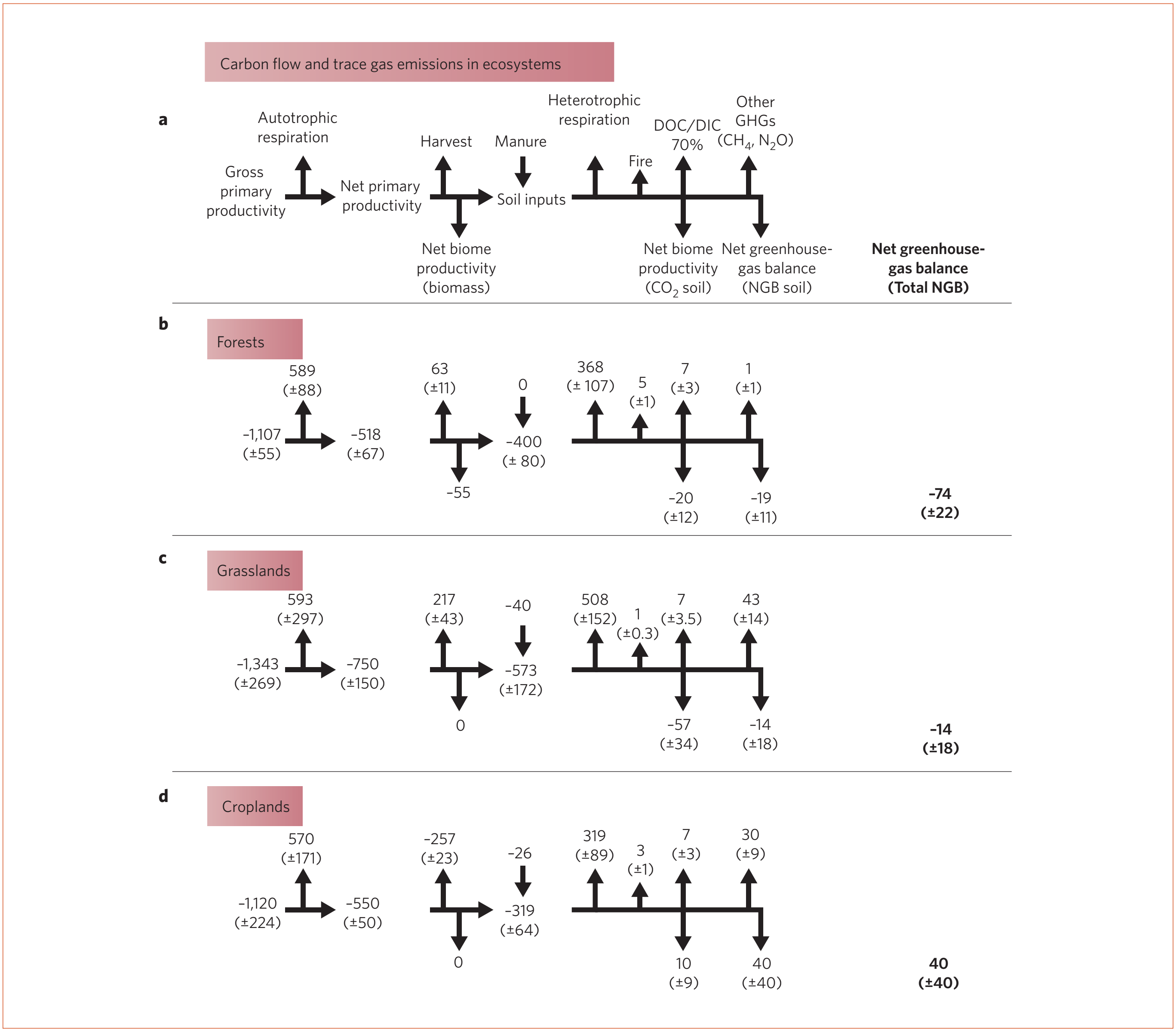

Figure 2 | The flow of carbon dioxide and other greenhouse gases through ecosystems. a, The carbon gains and losses in ecosystems, starting from photosynthesis (gross primary productivity) and ending at a net greenhouse-gas balance, NGB. DOC, dissolved organic carbon; DIC, dissolved inorganic carbon. **b–d**, These panels quantify these parameters and the absolute uncertainty (numbers in brackets indicating plus/minus one standard deviation) for forests (**b**), grasslands (**c**) and crops (**d**) in units of g C m^{-2} yr^{-1}. Greenhouse-gas losses are depicted as upward arrows, greenhouse-gas sequestration (sinks) are depicted as downward arrows.

balance is not statistically different to the previous estimate[28], although sectorial carbon balances do differ. For example, in this study croplands emit much less CO_2 than previously estimated (33 versus 300 Tg C m^{-2} yr^{-1}) and the estimated carbon sink in forest ecosystems is smaller than before (−204 versus −363 Tg C m^{-2} yr^{-1}). These differences are probably caused by improved methodologies rather than by the use of different time periods. The land-based carbon balance does not contain the fossil fuel and energy consumption associated with land management (forestry and agriculture). Carbon emissions from transport and fertilizer production for land management in the EU-25 is estimated to range between 15 and 28 Tg C yr^{-1}, and for Europe the range is 32 to 39 Tg C yr^{-1}. These are low estimates because they do not include the production costs of pesticides, the heating cost of greenhouses, cooling of storage rooms and other indirect energy needs. Nevertheless, it confirms our conclusions that the current GHG costs of land management are higher than its benefits.

Regional distribution of greenhouse-gas sources and sinks

The regional distributions of fluxes as shown in Fig. 3 are limited to inversion-based estimates of the GHG balance because at present the land-based data are too sparse to support regionalized assessments. The map of total CO_2 flux (including fossil fuel and biological fluxes) shows a band of high CO_2 sources running across central Europe, from the UK to northern Italy, continuing into southeast Europe (Fig. 3a,b). These high emissions correspond to the densely populated industrialized regions. A high-resolution geospatial fossil fuel CO_2 database gives more details on the highest emissions in the UK, Germany, the Benelux states and northern Italy, and the lowest emissions in Russia and

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Table 1 | Overview of the CO_2, CH_4, N_2O and GHG balances for the entire European continent and the EU-25 between 2000 and 2005 obtained by atmosphere- and land-based approaches.

a) Atmosphere-based fluxes		Continental Europe		EU-25		References
		Flux (Tg C yr^{-1})	Uncertainty (Tg C yr^{-1})	Flux (Tg C yr^{-1})	Uncertainty (Tg C yr^{-1})	
	Inversion fluxes					
1.	Top-down CO_2 flux (rows 12 + 5 + 28 + 6 + 7)	1,294	350	960	176	15–17
2.	Top-down CH_4 flux[*,†]	395	166	170	67	18
3.	Top-down N_2O flux[*,†]	113	76	90	58	19–21
4.	Subtotal	1,802	394	1,220	195	
	Industrial and geological GHG fluxes[‡]					
5.	Fossil fuel CO_2 emissions	1,586	79	1,052	53	38
6.	Volcanic and geothermal CO_2 flux[§]	10	3	10	3	37,40
7.	Products and landfills	−24	12	−3	2	41,42
8.	CH_4 industry[*,‖]	161	81	61	31	43
9.	CH_4 geological[*,‖]	13	7	6	3	39,40
10.	N_2O industry[*,‖]	36	18	32	16	41
11.	Subtotal	1,782	115	1,158	63	
	Atmosphere-based biological fluxes					
12.	CO_2 flux[¶]	**−313**	164[#]/300[**]	**−120**	73[#]/150[**]	15–17
13.	CH_4 flux (2 − 8 − 9)	221	131[#]/130[**]	103	54[#]/50[**]	
14.	N_2O flux (3 − 10)	77	49[#]/60[**]	58	40[#]/45[**]	
15.	GHG flux (12 + 13 + 14)	−15	215[#]/330[**]	40	100[#]/164[**]	

b) Land-based fluxes		Continental Europe			EU-25			References
		Area (million km^2)	Flux (Tg C yr^{-1})	Uncertainty (Tg C yr^{-1})	Area (million km^2)	Flux (Tg C yr^{-1})	Uncertainty (Tg C yr^{-1})	
	Ecosystem CO_2 fluxes							
16.	Forest biomass	3.39	−157	27[#]	1.45	−80	14[#]	23
17.	Forest soil		−47	8[#]		−29	5[#]	23
18.	Other wooded land	0.50	−16	8	0.16	−5	3	23,28
19.	Grassland	1.51	−85	12[#]	0.57	−32	4[#]	24
20.	Cropland[††]	3.26	33	6[#]	1.08	11	2[#]	23
21.	Peat undisturbed	0.39	−7	4	0.09	−3	2	24,25
22.	Peat drained	0.16	24	12	0.15	13	7	26,28
23.	Subtotal	9.21	−255	35	3.50	−125	17	
	Additional CO_2 fluxes							
24.	Land-use change[‡‡]		−60	30		−20	10	41
25.	Carbon trade balance		20	3		24	4	39
26.	Carbon export by rivers to ocean		−26	9		−10	3	42
27.	Peat extracted		50	9		7	1	26,28
28.	Fossil fuel agriculture[§§]		36	18		22	11	
29.	Subtotal		20	37		23	16	
	Biological GHG fluxes							
30.	CH_4 agriculture[*,‖]		67	34		51	26	43
31.	CH_4 wetlands[*]		35	18		13	7	27
32.	CH_4 oxidation[*]		−7	3		−4	2	45
33.	N_2O agriculture[*,‖]		97	49		70	35	43
34.	Subtotal		192	61		130	44	
	Land-based biological GHG fluxes							
35.	CO_2 flux (23 + 29)		**−235**	50		**−102**	23	
36.	CH_4 flux (30 + 31 + 32)		**95**	38		**60**	26	
37.	N_2O flux (33)		**97**	49		**70**	35	
38.	GHG flux (35 + 36 + 37)		−43	79		28	49	

Table 1 | Continued

c) Average of atmosphere- and land-based biological fluxes		Continental Europe		EU-25	
		Flux (Tg C yr^{-1})	Uncertainty (Tg C yr^{-1})	Flux (Tg C yr^{-1})	Uncertainty (Tg C yr^{-1})
39.	Average biological CO_2 flux (12 & 35)	**−274**	163	−111	84
40.	Average biological GHG flux (15 & 38)	−29	194	34	99

In part **a**, the inversion fluxes show the total GHG inputs from Europe into the atmosphere (rows 1–4). The fraction of these fluxes that do not have a biological origin is given under industrial and geological GHG fluxes (rows 5–11). The atmosphere-based biological GHG fluxes, calculated by subtracting the industrial and geological GHG fluxes from the inversion fluxes, are shown in rows 12–15. In part **b**, the ecosystem CO_2 fluxes (rows 16–23) are separated from the CO_2 fluxes not directly attributable to CO_2 fluxes from specific ecosystems (additional CO_2 fluxes, rows 24–29). Biological non-CO_2 GHG fluxes are given in rows 30–34. The land-based biological GHG fluxes (rows 35–38) are obtained by summation of all CO_2 fluxes within and outside the ecosystems with the non-CO_2 fluxes. The overall average biological GHG fluxes and associated uncertainties are given in part **c**. The uncertainties are estimated by means of Monte Carlo simulations based on in the assumptions shown in Supplementary Table S1. Irrespective of the underlying distribution, the uncertainty is shown as one standard deviation. Positive values indicate uptake by (emissions to) the atmosphere; negative values indicate loss from the atmosphere (sequestration by the biosphere). Flux totals that are significantly different from zero are printed in bold. Land area taken from the Food and Agriculture Organization (http://faostat.fao.org/site/567/default.aspx#ancor).

* CH_4 and N_2O fluxes are expressed as carbon in CO_2-equivalents with a greenhouse warming potential of 100 year horizon.
† Not accounting for urbanization-related emissions.
‡ We refer to industrial fluxes as total flux, including land use and land-use change, minus agriculture.
§ Geological emissions: excluding off-shore sources and Azerbaijan.
‖ Russian Federation corrected for Siberia according to area.
¶ The reported land-based sink was corrected for volcanic emissions and carbon stored in land fills. The uncertainty does not include the uncertainty in fossil fuel emissions, in lack of information about how this uncertainty is spatially distributed. If accounting for this uncertainty, the land-based sink uncertainty will be higher than reported in the table.
# Uncertainties show the range of most likely inversion results. The standard deviation of a uniform distribution needs to be multiplied by 3.45 to obtain the minimum–maximum range.
** Gaussian uncertainty of individual simulations. The range of model outcomes (see previous footnote#) and the Gaussian uncertainty of an inversion are not independent.
†† Including erosion redeposition and burial to deeper horizons.
‡‡ The ecosystem CO_2 and GHG balances were calculated as the sum of the forest, other woodlands, grasslands, peatland and land-use change. The land-based CO_2 and GHG balances were calculated as a sum of the ecosystem, river export, peat extraction, landfill fluxes and geothermal fluxes.
§§ Agricultural fossil fuel use according to the United Nations Framework Convention on Climate Change and fertilizer-use statistics.

in the Scandinavian countries (Fig. 4a). France, where a high proportion of energy is produced from nuclear power, has lower CO_2 emissions than its neighbours. Dividing fossil fuel emissions by population (Fig. 4b), the per capita emissions are fairly evenly spread across western Europe (Fig. 4c). Emission per capita is highest in the Benelux states, but also tends to be high in the northern countries (due to heating) and Mediterranean countries (due to cooling)[33]. Per-capita emissions in Russia are only about half of those in western Europe.

When subtracting fossil fuel emissions from the land–atmosphere CO_2 flux, the land surface becomes a sink for most regions of Europe. The sink is strongest in northeastern Europe (Fig. 3c,d). Mediterranean regions are weak sources, but uncertainties remain high with large differences between the three inversions for western Europe. The outputs from each of the different inversion models used in this study are shown in the Supplementary Information.

The geographic distribution of the biological CH_4 flux shows highest emissions from regions with intensive agriculture and animal husbandry, such as England, Belgium, northern Germany and The Netherlands (Fig. 3e,f). We can also see high CH_4 emissions over eastern Europe, due to the extensive peatlands[26,27]. The biological N_2O emissions from agroecosystems are centred across the UK, northern Belgium, The Netherlands, north Germany, Denmark and France (Fig. 3g,h). These regions with high N_2O emissions seem to be associated with intensive grassland and cropland management.

A map of the land-surface NGB, expressed as CO_2 equivalent (g C m^{-2} yr^{-1}), shows that non-CO_2 gases offset the CO_2 sink shown in Fig. 3i,j. Most of western Europe is a net biological GHG source. Northeastern Europe remains as a CO_2-equivalent sink.

Managing the European land-based carbon sink

At a continental scale, forests remain the most active sinks owing to their wood growth and to the large area they cover in northern and eastern Europe (Fig. 3c). This sink occurs because annual growth exceeds harvesting. However, this may not continue if harvesting of wood for biofuels increases[12]. It has been estimated that atmospheric nitrogen deposition, resulting from fertilizing agricultural systems and fossil fuel burning, enhances the forest carbon sink by 10 to 20% (refs 23,34–36). The hidden cost in fertilization is the concomitant emission of N_2O. Thus higher production in agriculture comes at the expense of increased N_2O emission.

The comparison between the carbon and the GHG balance of continental Europe shows that current land management reduces the terrestrial GHG sink, which could otherwise offset non-biological GHG emissions. The increasing trend towards more intensive agriculture and a vulnerable forest stock of timber leads to the conclusion that the balance is likely to tip, with the land surface of the EU soon becoming an appreciable source of GHGs.

Introducing land management policies aimed at reducing the emission of greenhouse gases should thus be a priority. This should be possible because most of the N_2O emissions are linked to excessive fertilizer applications in croplands. The CH_4 emissions originating from animal husbandry could be reduced by capturing natural methane for bioenergy. Despite its small surface area, farming of former peatland remains a hotspot for biological GHG emissions and could benefit from new management[26].

The GHG balance emphasizes that reducing fossil fuel emissions, by far the most important flux, must be the main target in climate change mitigation. The land surface cannot balance current emissions. The net sequestration of GHGs by the land surface may even diminish as CH_4 and N_2O emissions increase with further intensification of agriculture and forestry. Nevertheless, land management could yet make a positive contribution to mitigating global warming. Managing land as a GHG sink remains an urgent issue in Europe.

Outlook

The GHG balance presented in Table 1 is one of the most detailed studies at the continental scale. Nevertheless, the uncertainties remain high, and for the time being it is not possible to validate the European soil carbon sink as simulated by our models because we lack a repeated grid-based pan-European soil inventory.

A soil inventory is more urgently needed than ever before; it would constrain the bottom-up estimates by an additional tier. A better coverage of intensively managed ecosystems and additional atmospheric monitoring stations in the Balkan region and in Eastern Europe are also needed to reduce the uncertainties in the bottom-up and top-down approaches.

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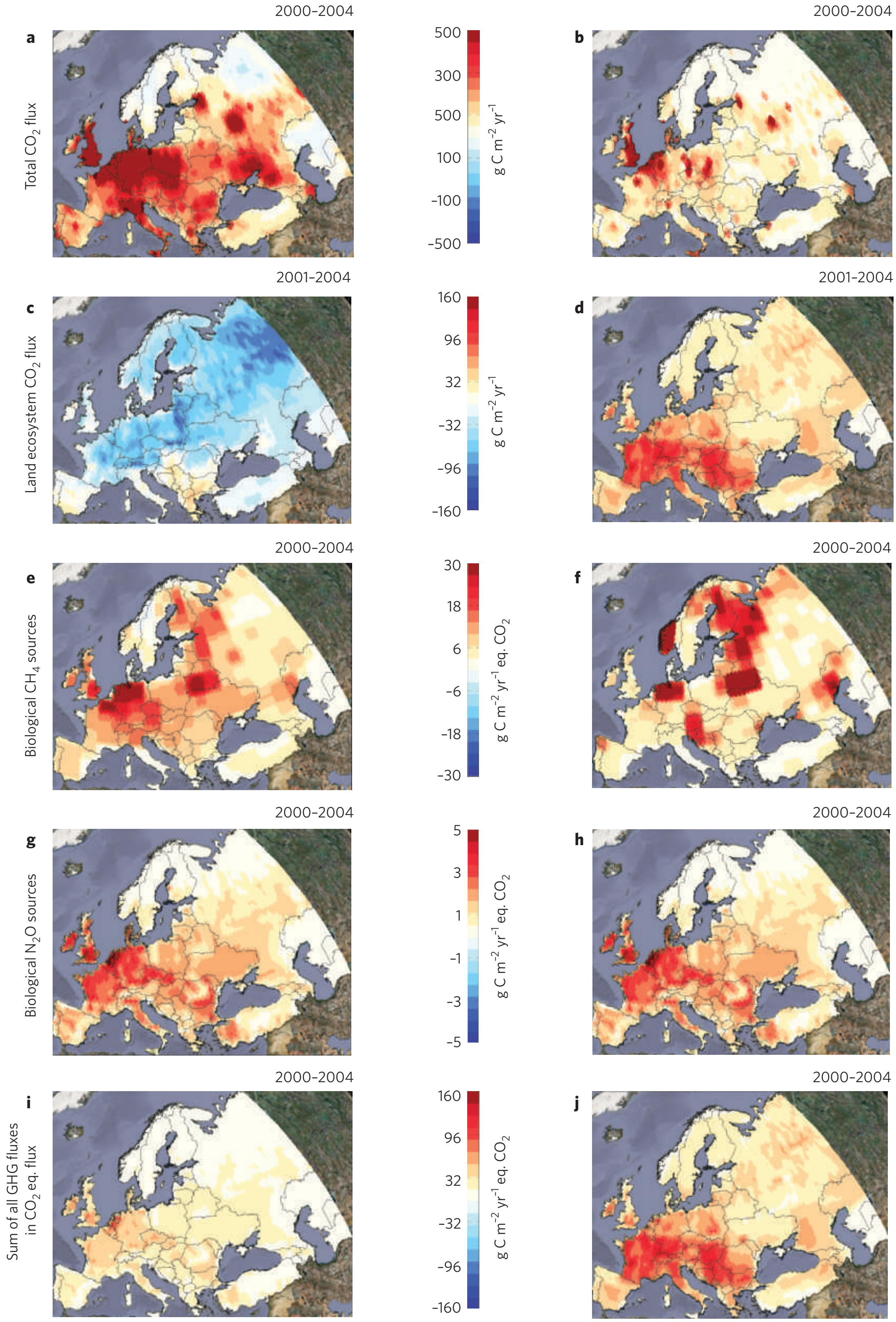

Figure 3 | Geographic distribution of sources and sinks of GHGs across Europe as determined from inversion models. Left panels show absolute fluxes, expressed as g C m^{-2} yr^{-1} CO_2-equivalent: **a**, total CO_2 flux; **c**, land-surface–atmosphere CO_2 flux representing the net biome productivity of ecosystems (see Fig. 2a); **e**, biological CH_4 fluxes; **g**, biological N_2O fluxes; and **i**, the total land-surface–atmosphere CO_2-equivalent greenhouse-gas flux representing the net GHG balance of ecosystems. The uncertainties are given in the adjacent right panels (**b**,**d**,**f**,**h**,**j**). The maps were produced by ordinary kriging methods based on a 1° resolution and surface observations. The resolution is 15′.

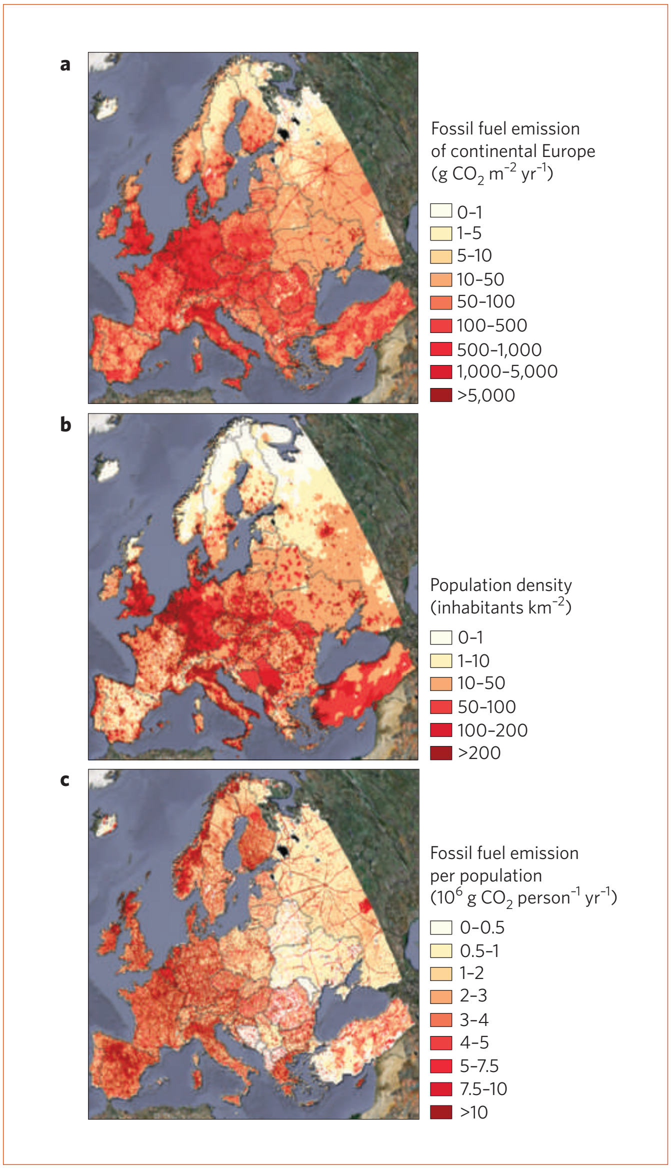

Figure 4 | Fossil fuel emissions of Europe. a, A high resolution map of fossil fuel CO_2 emission in 2005. **b**, The distribution of human population density. **c**, The resulting per-capita emissions across Europe.

Research on land–atmosphere interactions should be extended to include the effects of land use and land management on the GHG balance as well as on the energy and water balances[37]. The previous perspective that centred mainly on CO_2 should be broadened in favour of integrated studies dealing with the biogeochemical and physical aspects of land use and land management as a tool to mitigate climate change.

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Additional information
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