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Can we reconcile atmospheric estimates of the Northern terrestrial carbon sink with land-based accounting?

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We estimate the northern hemisphere (NH) terrestrial carbon sink by comparing four recent atmospheric inversions with land-based C accounting data for six large northern regions. The mean NH terrestrial CO_2 sink from the inversion models is 1.7 Pg C year^{-1} over the period 2000–2004. The uncertainty of this estimate is based on the typical individual (1-sigma) precision of one inversion (0.9 Pg C year^{-1}) and is consistent with the min–max range of the four inversion mean estimates (0.8 Pg C year^{-1}). Inversions agree within their uncertainty for the distribution of the NH sink of CO_2 in longitude, with Russia being the largest sink. The land-based accounting estimate of NH carbon sink is 1.7 Pg C year^{-1} for the sum of the six regions studied. The 1-sigma uncertainty of the land-based estimate (0.3 Pg C year^{-1}) is smaller than that of atmospheric inversions, but no independent land-based flux estimate is available to derive a 'between accounting model' uncertainty. Encouragingly, the top-down atmospheric and the bottom-up land-based methods converge to consistent mean estimates within their respective errors, increasing the confidence in the overall budget. These results also confirm the continued critical role of NH terrestrial ecosystems in slowing down the atmospheric accumulation of anthropogenic CO_2.

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Introduction

Quantifying the fate of fossil fuel carbon emissions depends critically on accurate diagnosis of spatial and temporal distribution of natural carbon (C) fluxes over land and ocean. Studies using global atmospheric transport models to infer surface fluxes from surface carbon dioxide (CO_2) concentration observations have estimated the northern mid-latitudes and high latitudes to be a net sink of approximately 2.0–3.5 Pg C year^{-1} [1]. Analyses of surface ocean partial pressure of CO_2 [2–4], atmospheric carbon isotopes [5,6], and atmospheric oxygen measurements [7•] further support that most of this sink must reside in terrestrial ecosystems. However, atmospheric inversion estimates are uncertain because of sparse atmospheric stations and transport model errors [8••].

In parallel with atmospheric inversions, data gathering over land enables estimation of the distribution of surface fluxes [9–12]. These data include firstly, land flux measurements [13] at eddy-flux towers that can be scaled up using models and satellite and climate fields to derive spatially explicit CO_2 flux distributions [14,15] and secondly, inventories of carbon pools in biomass and soils [16–18] that can be repeated over time to deduce long-term mean flux estimates from pool changes.

Despite numerous local studies, complemented by the synthesis of the C balance of some large regions such as China [12], North America [19], Europe [11], and Russia [20,21], the bottom-up terrestrial C accounting approach suffers from data gaps, which requires assumptions for upscaling local data. Land-based data also have gaps in time, and do not cover the same time period in each region. Like the atmosphere-based estimates, the land-based approach is subject to big uncertainties at continental scales.

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Moreover, it is difficult to reconcile inversions of surface-atmosphere CO_2 fluxes with land-based data, because upscaling of ecosystem fluxes must include the less often measured fluxes from lateral transport. Specifically, the ecosystem-atmosphere CO_2 flux is equal to the sum of a carbon stock change and of a carbon flux removed from this ecosystem and displaced by lateral transport. Lateral transport includes carbon embedded in traded products, in rivers (aquatic fluxes), and the atmospheric transport of reduced carbon compound emissions such as CO and biogenic volatile organic compounds that remains undetected by CO_2 inversions [22]. At continental scales, processing and use of products [23] and outgassing from lakes and rivers cause CO_2 sources to the atmosphere, that are accounted by inversions.

The goal of this study is to establish the NH (Northern Hemisphere) terrestrial CO_2 sink and its uncertainty, based upon atmospheric CO_2 inversion fluxes, which we compare with independent bottom-up C accounting estimates from several large regions. We compile and synthesize four atmospheric inversion CO_2 fluxes and regional bottom-up estimates from recent studies [11,12,19,21].

Atmospheric CO_2 mass balance

A positive pole-to-pole atmospheric CO_2 gradient is expected because fossil fuel burning occurs almost entirely in the NH (8.7 ± 0.5 Pg C year^{-1} in 2008) and it takes some time to mix emissions homogeneously throughout the atmosphere. Thus, the persistence of fossil fuel emissions induces a permanent accumulation of CO_2 in the NH compared to the southern hemisphere. The existence of a sink of atmospheric CO_2 in the NH has been inferred from the misfit between the observed inter-hemispheric CO_2 concentration gradient and the one obtained from fossil fuel emissions alone [24••,25]. More precisely, Tans *et al.* [24••] calculated that the CO_2 pole-to-pole gradient expected from fossil fuel emissions alone from 1980 to 1987 was in the range 3.8–5.6 ppm, whereas the observed gradient was only 2 ppm (see their Figure 3). Today, fossil fuel emissions remain concentrated in the NH, but the recent economic growth of China and India is adding emissions toward the Northern Tropics, closer to the Equator.

Both Tans *et al.* [24••] and Keeling *et al.* [26] deduced that, in order to match the measured CO_2 gradient, a sink was needed north of the equator. They used three-dimensional transport models with various sink scenarios in the ocean and on land. Keeling and colleagues reached the conclusion that the NH sink was dominant in the oceans. Tans *et al.* constrained a smaller sink in the ocean than Keeling *et al.* did from sparse ocean observations of the sea-to-air difference in CO_2 partial pressure (ΔpCO_2) and suggested that, by difference, 'a large terrestrial sink at northern temperate latitudes is necessary'.

This finding came out as a surprise to the research community, because the terrestrial sink inferred by Tans *et al.* was huge 'the total terrestrial sink at high northern and temperate latitude varies between 2.0 and 2.7 Pg C yr^{-1}'. There was virtually no direct bottom-up evidence at that time for such a strong uptake of carbon by northern ecosystems. Measurements of atmospheric carbon isotopes that fractionate strongly when CO_2 is absorbed on land and negligibly when CO_2 is dissolved by the ocean, have independently confirmed the existence of an NH terrestrial sink [6,27]. So did measurements of atmospheric oxygen [7•].

In the early 1990s, uncertainties were larger for bottom-up estimates than for atmospheric estimates. Virtually no or very sparse measurements of land fluxes (and of ocean fluxes) were available to confirm the results deduced from the atmospheric CO_2 mass balance. Relying on more atmospheric stations deployed over the NH during the late 1990s, and on a set of nine transport models prescribed with the same fluxes, the TRANSCOM-1 atmospheric transport models' intercomparison study [28,29] showed that there was a significant spread between models in the CO_2 pole-to-pole gradient (range of 2 ppm) with regard to the mixing of fossil fuel emissions. This spread reflects different mixing of atmospheric transport models, in particular vertical mixing. Thus, a biased transport model will provide a biased diagnostics of the NH sink. In particular, a transport model with fast mixing results in a smaller NH sink than a model with more sluggish mixing.

In addition, the co-variation between atmospheric transport and the seasonality of terrestrial CO_2 fluxes can produce a CO_2 latitudinal gradient, even with purely seasonal, annually balanced, land biospheric fluxes. In their model, Tans *et al.* had a very small gradient generated by purely seasonal land flux (0.05 ppm). But Rayner and Law [28] concluded from the nine TRANSCOM-1 model results that 'The annual mean meridional response of the models to seasonal biotic forcing can be classified into two groups. Models which represent turbulent mixing in the planetary boundary layer simulate a pole-to-pole gradient in surface CO_2 that is roughly half as strong as that obtained in the fossil fuel experiment. The other models simulate a very weak meridional structure in these runs'. For instance, Denning *et al.* [30] using a model where transport is consistently coupled with biotic fluxes, found a strong covariance between the seasonal cycle of turbulent boundary layer mixing and CO_2 fluxes over northern lands, inducing a positive CO_2 gradient in the NH of 5 ppm at background atmospheric stations with a purely seasonal biotic forcing. Thus, for such a model, a particularly strong terrestrial sink is needed to match atmospheric CO_2 data.

Later, the TRANSCOM modelers provided runs for the same inversion procedure to optimize the global CO_2 flux

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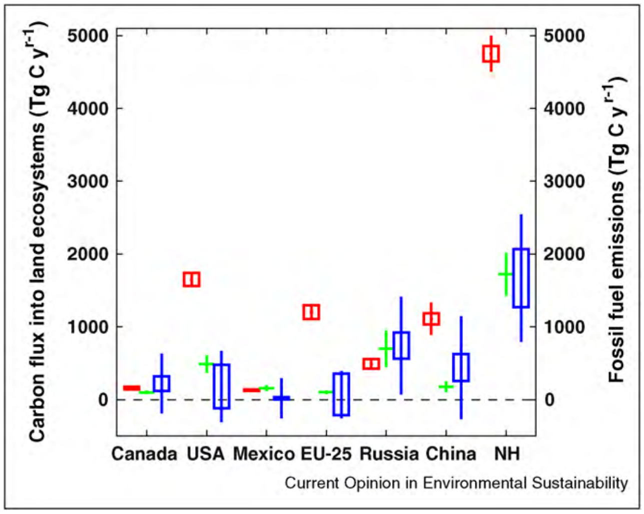
distribution over coarse regions. The results confirmed the existence of a large NH sink and of a significant fraction of that sink in terrestrial ecosystems [1,31,32]. The mean NH terrestrial sink estimate is 2.5 Pg C year^{-1} and the range is from 0.5 to 4.5 Pg C year^{-1}. The uncertainty is due to both sparse atmospheric stations (inversion precision) and to unresolved systematic differences between transport models (transport accuracy). Many other inversions have been published using different settings [33–38]. Their results are qualitatively similar to those of Gurney *et al.* Compiling results from these inversions gives a range of most likely values of the terrestrial NH sink values of 0.5–2.8 Pg C year^{-1} as reported in the IPCC Third Assessment Report [39] and further assessed in the Fourth Assessment report [40].

A recent study by Stephens *et al.* [8••] used independent measurements of vertical profiles of CO_2 in the atmosphere to cross validate the TRANSCOM atmospheric transport models for their optimized fluxes. They found that even if prescribed with total fluxes optimized against surface atmospheric stations data, most of the transport models mixed CO_2 vertically not strongly enough in winter, and maybe too strongly in summer. Excluding the majority of biased models that do not match the observed vertical CO_2 gradient lower the NH sink magnitude down to 1.5 with range of 0.5–2.5 Pg C year^{-1}. Because unrealistic models were removed, this range of NH terrestrial sink is narrower than that of Ref. [1].

Figure 1



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(red) Fossil fuel emissions from energy use statistics. The bar denotes the min–max range of different emission estimates prescribed by the four inversions. (blue) Atmosphere to land ecosystems CO_2 from inversions over the period 2000–2004. Bars denote the min–max range of different mean flux estimates from the four inversions, and whiskers the 1-sigma internal precision of each inversion as defined in the main text. (green) Land C sink, mostly based upon changes in inventories of C stocks, from published bottom-up accounting studies. The whiskers provide the 1-sigma uncertainty of each estimate (1 sigma). Lateral fluxes cause bias between inversion-based CO_2 uptake and accounting-based C accumulation as explained in the final section of this manuscript.

Top-down atmospheric CO_2 inversions

Twenty years after the seminal studies of Tans *et al.* and Keeling *et al.*, we use the results from four recent inversion systems to analyze the NH land sink and its regional distribution. We choose these four inversions because they were available through the Carboscope website (http://www.carboscope.eu/accessed November 2009) and because they are state-of-the-art inversions. These four inversions use most of surface station data available in recent versions of transport models forced by reanalyzed winds. They solve for fluxes on the model grid [41,42] (F Chevallier *et al.*, CO_2 surface fluxes at grid point scale estimated from a 21-year reanalysis of atmospheric measurements. J Geophys Res, unpublished data) or on a large number of regions [43], compared to older inversions using only a limited number of coarse regions [1]. The four systems are the CarbonTracker Europe [44], the JENA-CO_2 inversion Version 3.1 [41] (http://www.bgc-jena.mpg.de/~christian.roedenbeck/download_CO2/) and two LSCE inversions [42] (F Chevallier *et al.*, CO_2 surface fluxes at grid point scale estimated from a 21-year reanalysis of atmospheric measurements. J Geophys Res, unpublished data). The fluxes are calculated over different periods by each inversion. We extracted results from the period 2000–2004 common to the four systems over the six countries for which summary land-based C balance estimates have been published (Figure 1). We have only an estimate of the internal precision of inversion fluxes at the scale of the six countries for the system of Chevallier *et al.* (CO_2 surface fluxes at grid point scale estimated from a 21-year reanalysis of atmospheric measurements. J Geophys Res, unpublished data). So, this uncertainty estimate was applied by default to each inversion. In Ref. Chevallier *et al.* (CO_2 surface fluxes at grid point scale estimated from a 21-year reanalysis of atmospheric measurements. J Geophys Res, unpublished data), there is an error covariance among optimized fluxes in each grid point implying that errors of the mean flux in a given region are not simply obtained by the propagation of independent grid point errors. This also implies that the NH sink error is smaller than the quadratic sum of errors in the six subregions.

The average of the four inversions of NH land sink is 1.7 Pg C year^{-1} for the six regions considered, which represent 65% of the NH land and 71% of the NH vegetated land. The range of the four inversion best estimates is 0.8 Pg C year^{-1}. We note that this range is compatible with the precision of a single inversion, which is of 0.9 Pg C year^{-1} (1-sigma). Inversion precision reflects some of the arbitrary settings, uncertain data and models, and sparse measurements. The interannual

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variability is on average 0.4 Pg C year^{-1} over the period 2000–2004.

Our NH land sink estimate over 2000–2004 thus falls in good agreement with that of Stephens *et al.* [8••], although the period they covered is different (1996–2002). The small between-inversion range for Russia and China shown by Figure 1 is surprising, given the scarcity of atmospheric CO_2 measurement stations over these two regions. We speculate that all the inversions consistently place their flux increment into these two most poorly observed regions, and end up with similar values there. By contrast, over regions with higher density of atmospheric stations like USA and Europe, the between-inversion range is larger than the mean sink.

Finally, it is important to note that the inversions show discrepancy in their prescribed fossil fuel emissions (Figure 1). There is an NH fossil fuel emission range of 0.24 Pg C year^{-1}, and an emission range in any of the six regions studied below 0.2 Pg C year^{-1}. This discrepancy between prescribed emissions is surprisingly large for the USA and Canada, where fossil fuel emissions are known from inventories within 5% [45]. In the EU-25, inconsistent system boundaries between the different countries for reporting emissions could increase the inventories uncertainty by up to 7% [18]. Here we found that the discrepancy between emissions used in the four inversions for each region is as large as the worst case inventory uncertainty of 20% reported for China [45]. Discrepancies between prescribed fossil fuel emissions explain roughly 25% of the range of inversion results for the NH terrestrial sink.

Are inversions consistent with land-based accounting?

The inversion CO_2 fluxes are compared with land-based C flux estimates from the SOCCR report for USA, Mexico, and Canada [19], the CARBOEUROPE-IP program for EU-25 [11,46], the International Institute for Applied System Analysis (IIASA) Russian C accounting project's most recent estimates for Russia [21] and a recent synthesis for China [12]. There is no consistent terrestrial C budget estimation for India and northern hemispheric South Asian countries. Thus, our NH sink estimate corresponds roughly to the NH mid to high latitudes north of 20°N. It is also worth noting that the six regions included do not contain Ukraine, Belarus, Mongolia, Koreas and Japan, which altogether represent 4% of the land area north of 20°N. We stress the fact that the inversion period is shorter than the period covered by C accounting studies. Therefore, part of the differences between top-down and bottom-up is caused by inconsistent time periods.

It is striking to see in Figure 1 that, for each large region, the mean of the four inversions is in agreement with the land-based estimate. One region where the mean of the inversions consistently gives a smaller sink than the land-based approach is the USA. This is possibly reflecting the effect of droughts in 2002 and 2003 in the USA that may have lowered the mean CO_2 uptake in that region during the inversion period 2000–2004. Land-based estimates are not restricted or centered over the same period. In contrast, the inversions over China provide a much larger CO_2 sink than the C accounting approach. This may be due to lateral fluxes or sparse atmospheric station coverage. We speculated above that inversions might add flux increments to balance the meridional CO_2 gradient into the most uncertain and yet productive grid points, thus typically in regions like China. The large inversion uncertainty for China and the EU25 contrasts with the small uncertainty of land-based studies.

The terrestrial CO_2 sink from inversions is expected to be systematically higher than the ecosystem C sequestration inferred from bottom-up accounting methods. This is because CO_2 sinks from inversions do not pick up ecosystem C losses from biogenic volatile organic compounds and wildfire CO emissions. In addition, incomplete fossil fuel combustion emits CO, so that the 'residual' terrestrial CO_2 sink estimated by inversions is lower than if all fossil fuel emissions were assumed to be made of CO_2 as in the four models of this study. Thirdly, ecosystem carbon losses by river conduits and harvest will be seen by inversions but not by land-based inventories of stock changes.

In summary, the NH terrestrial sink estimation is consistent between the top-down and the bottom-up approaches at the scale of the regions considered, given uncertainties associated with each method. The larger range of uncertainty attributed to inversions shed doubts on the ability of this approach to accurately constrain the NH land sink. Indeed, it will take a long time until enough atmospheric sampling stations cover the NH continents to reduce the internal error of inversions. The between-model inversion uncertainty range is within the internal uncertainty of each inversion. Inversion as a method thus provides consistent uncertainty estimates for the four models used in this study. The uncertainty that we report here for inversions is more comprehensive than the one compiled from land-based studies. In particular, the uncertainty of the land-based estimate does not include between-model differences, and is based on expert judgment for some components. In addition, land C inventories are really limited to changes in above ground carbon stocks and really do not assess changes in below ground carbon stocks in a measurable sense (models are used instead to infer soil C changes).

The NH land sink best estimate from this study is of 1.7 Pg C year^{-1}, with a 1-sigma error of 0.9 Pg C year^{-1} in inversions and of 0.3 Pg C year^{-1} in land-based accounting. In answer to the question raised in the title of this

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paper, we can therefore say that the reviewed atmospheric and land-based estimates of the six NH regions considered are consistent with each other. Yet, inversion biases are not estimated, and only one land-based study was available for each region.

Twenty years after the Tans *et al.* [24••] and Keeling *et al.* [26] studies, the surface atmospheric station network has become denser over the NH oceans in the late 1990s and over North America and Europe in the early 2000s, yet leaving Siberia, China, India and South Asia with insufficient coverage by the network of atmospheric stations. Stephens *et al.* [8••] also raised the issue that even an ensemble of 13 models can be *consistently* biased for vertical transport. Here, using a smaller set of four recent inversions, we find that the spread of mean inversion fluxes is smaller than it was in the TRANSCOM [1] study. This gives some hope that between-model differences may be reducing over time. It is time to conduct an update of the TRANSCOM intercomparison program, for comparing both inversion methods and transport models, in order to better assess if the inversion precision is improving over time. An updated comparison will allow an assessment whether model differences rather than data scarcity determine inversion uncertainties.

Perhaps more importantly, both the inversion approach and the land-based accounting need independent evidence to be verified. Both denser networks of atmospheric stations and more accurate transport models are needed to improve inversions. Soil carbon inventories, and more systematic data on aquatic fluxes and wood products will help to increase the accuracy of bottom accounting, as well as designing dedicated bottom-up accounting intercomparison and cross-validation studies.

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