How Much CO_2 Is Taken Up by the European Terrestrial Biosphere?

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DIFFERENT METHODS, DIFFERENT RESULTS. The net ecosystem exchange (NEE) quantifies the net CO_2 flux from the ecosystem to the atmosphere (Chapin et al. 2006); that is, a negative NEE corresponds to a positive (net) sink of CO_2 or a positive (net) uptake of CO_2 by the biosphere. Unfortunately, it is not possible to directly measure how much CO_2 is taken up on continental scales. For this reason, various different indirect approaches have been developed which are sketched in Fig. 1 and outlined in the following.

The conventional and established estimates of the amount of carbon taken up by the European terrestrial biosphere from the Atlantic to the Urals rely on two conceptually different types of ground-based measurements. On the one hand, in situ measurements of atmospheric CO_2 concentrations are globally obtained at about 100 sites on a regular basis (around 10 in Europe, all located within the EU 28 member states). They are used as input for atmospheric inverse models inferring the sources and sinks at Earth's surface (top-down estimates). On the other hand, conventional bottom-up estimates of surface carbon fluxes are obtained from field measurements—for example, employing the eddy covariance method and assessing ecosystem carbon stock change at biome-representative sites and subsequently scaled up to the entire region of interest. Bottom-up estimates (Fig. 2; 0.27 ± 0.16 GtC a^{-1} for 2000–05; Schulze et al. 2009) are consistent with the in situ inversion estimates [Fig. 2; 0.40 ± 0.42 GtC a^{-1} for 2001–04; Peylin et al. 2013; Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5)].

In 2002, near-infrared (NIR) satellite measurements of atmospheric CO_2 concentrations became available [Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY); Burrows et al. 1995; Bovensmann et al. 1999] and together with follow-up satellite missions [*Greenhouse Gases Observing Satellite (GOSAT)*, launched 2009 (Kuze et al. 2009), and *Orbiting Carbon Observatory-2 (OCO-2)*, launched 2014 (Crisp et al. 2004)] a scientific community grew, aiming to use satellite data to further reduce the uncertainties of global and regional sources and sinks of CO_2. Recent results indicate that Europe may take up considerably more carbon per year [e.g., 1.03 ± 0.47 GtC a^{-1} for 2009/10 (Houweling et al. 2015) or 0.95 ± 0.33 GtC a^{-1} for 2003–10 (Reuter et al. 2014); Fig. 2] than previously thought. These estimates are similar to earlier results derived from tropospheric emission spectrometer (TES) thermal infrared (TIR) satellite measurements [1.20 ± 0.17 GtC a^{-1} for 2006 (Nassar et al. 2011); Fig. 2]. However, the different validation studies of the optimized fluxes are inconclusive: Nassar et al. (2011) (combining satellite and in situ data) and Reuter et al. (2014) both find an improvement of the agreement with independent measurements, which is not the case for Houweling et al. (2015).

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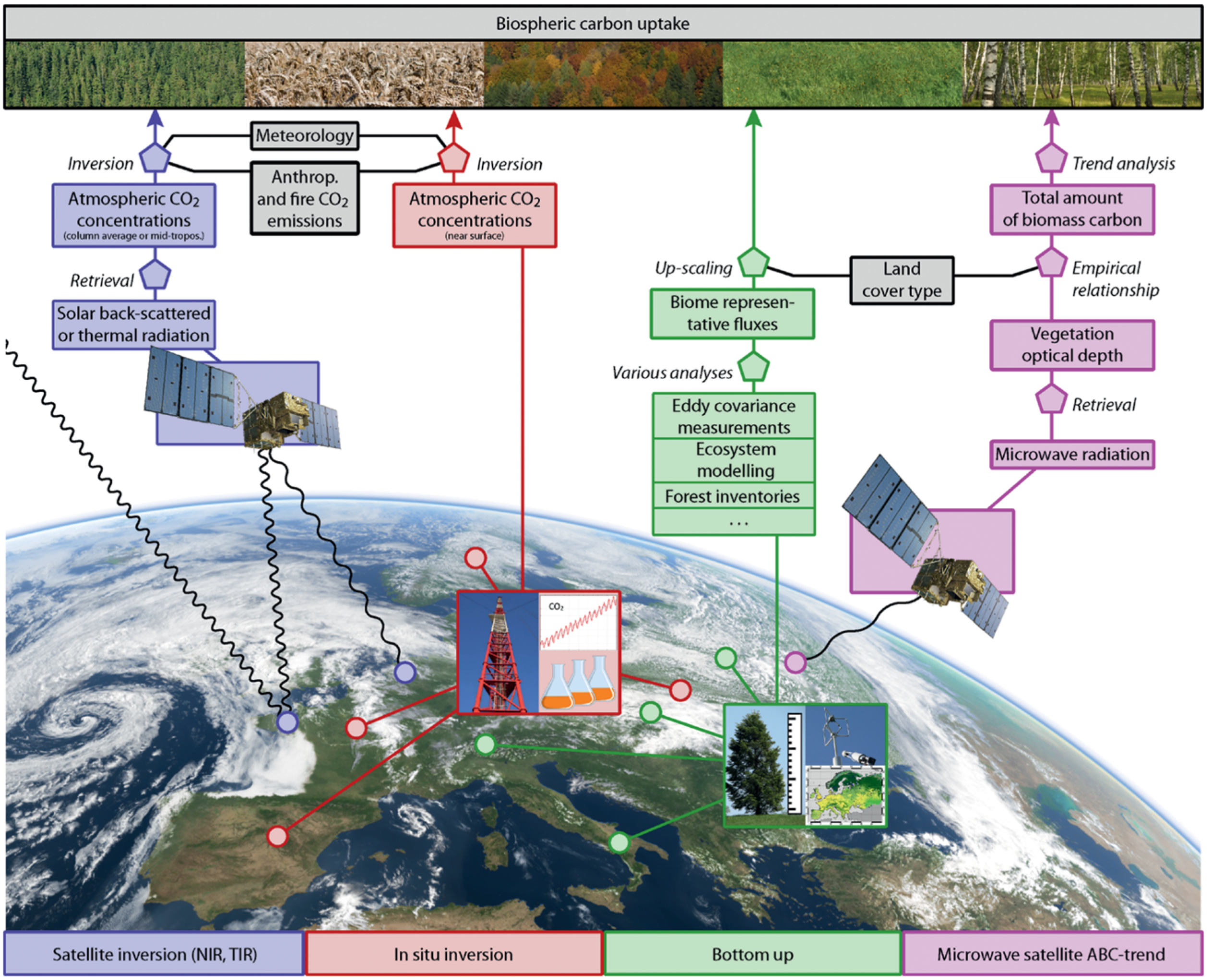

Fig. 1. Schematic overview of different approaches to derive continental-scale biospheric carbon fluxes (see main text for more details). The background figure shows the European continent as seen from the geostationary *Meteosat-9* satellite and has been created with the method of Reuter and Pfeifer (2011).

While the satellite CO_2 measurement techniques are conceptually different from in situ measurements, the inversion techniques are similar in principle. An entirely different approach is followed by scientists analyzing passive microwave satellite measurements yielding above-ground biomass carbon (ABC), which is combined with external information for each land cover type to derive the total amount of biomass carbon. A gain of biomass corresponds to a sink of atmospheric CO_2. Recent satellite-based ABC measurements support the hypothesis of a large European carbon sink with the strongest uptake in the north/east of Europe [0.88 ± 0.31 GtC a^{-1} for 2003–10 (data from Liu et al. 2015); Figs. 2 and 3]. Note that lateral fluxes and storage of harvested biomass (e.g., wood production for furniture) can result in differences between ABC-based and other estimates of the biospheric carbon uptake.

According to Le Quéré et al. (2015), an average of 9.9 ± 0.7 Gt carbon (in form of CO_2) is emitted each year (2005–14) to the atmosphere from human activities including fossil fuel combustion, cement manufacture, and land use change. Approximately half of the CO_2 stays in the atmosphere and results in the continuous increase of atmospheric concentrations (visible in long-term measurements like the famous Keeling curve obtained at Mauna Loa, Hawaii). The other half is taken up by land (3.0 ± 0.8 GtC a^{-1}) and ocean (2.6 ± 0.5 GtC a^{-1}).

Obviously, it is important for the understanding of the global carbon budget whether Europe removes 0.3 or 1.0 GtC from the atmosphere each

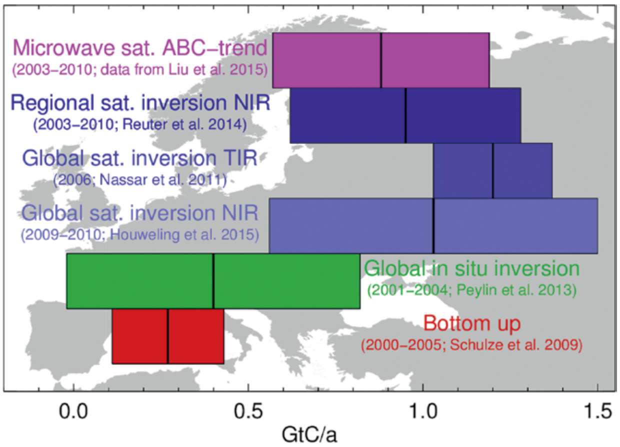

FIG. 2. Current estimates for the European carbon sink from the Atlantic to the Urals. (top)–(bottom) Data from Liu et al. (2015), Reuter et al. (2014), Nassar et al. (2011), Houweling et al. (2015), Peylin et al. (2013), and Schulze et al. (2009). The time period of each estimate is given in parentheses, as significant interannual variability is expected. All uncertainties represent 1 sigma. The satellite inversions also include information from in situ measurements. The estimate from the microwave satellite ABC trend is based on retrievals of vegetation optical depth and represents the total carbon stock of forests and the total biomass carbon for nonforests (Liu et al. 2015); the error bar represents the trend uncertainty of the linear fit.

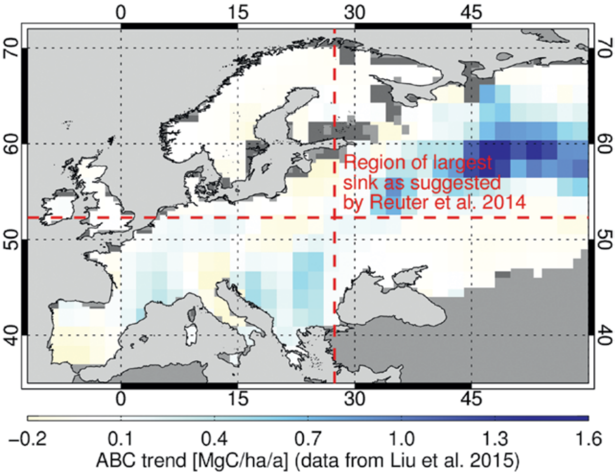

FIG. 3. ABC trend (2003–10) from passive microwave satellite measurements [data from Liu et al. (2015)]. The red dotted lines indicate the regions investigated by Reuter et al. (2014), who found indications that eastern Europe may contribute more than western Europe and northern Europe more than southern Europe to the overall European carbon sink, even though the differences were not statistically significant.

year. Consequently, the large discrepancy between conventional bottom-up and in situ inversion estimates on the one hand and new evidence from different kinds of satellite measurements on the other hand is currently subject to intense discussions (e.g., Chevallier et al. 2014; Reuter et al. 2014; Houweling et al. 2015; Feng et al. 2016).

POTENTIAL EXPLANATIONS. In situ measurements of atmospheric CO_2 are highly accurate (precision and accuracy ~0.1–0.2 ppm), have been well established for decades, and allow measurements at any time of day and season. Furthermore, the biospheric signals in the atmospheric CO_2 concentration are largest near the surface. The inversion results of individual research groups are broadly consistent (despite using different methods and assumptions) and consistent with conventional bottom-up estimates (Fig. 2; Peylin et al. 2013; Schulze et al. 2009).

On the other hand, satellites in principle allow global coverage with measurements over remote sites and oceans, where no in situ measurements are made. Satellite measurements in the NIR probe the whole atmospheric column, not only the near-surface air as usually done by in situ measurements. Both the horizontal and vertical scales of satellite data are closer to the scales of model grid boxes, which leads to a reduction in representativeness errors, compared with localized in situ point measurements (McKain et al. 2012). The results of different CO_2 retrieval and inversion techniques, different instruments, and independent measurement principles (ABC trend, NIR, or TIR CO_2 inversion) are reasonably consistent at showing a stronger European sink.

Feng et al. (2016) suspected biases of the satellite data as explanation for the discrepancy but concluded that without further dedicated measurements it can neither be proven nor rejected that European ecosystems are taking up a larger-than-expected amount of CO_2.

As mentioned earlier, satellites allow global coverage, in principle. However, the spatial and temporal sampling may be anything but homogeneous. As an example, NIR satellite CO_2 measurement is possible only under favorable illumination conditions. This results in few or no measurements in northern Europe during the dormant season so that the corresponding surface fluxes are dominated by the a priori fluxes (Reuter et al. 2014). Additionally, NIR satellite CO_2 measurements are obtained only under clear-sky conditions, which has the potential to introduce biases (Corbin et al. 2009).

According to Gurney et al. (2002), the sparseness of in situ measurement sites is a main reason for the relatively large flux uncertainties associated with inversions of these measurements, and Bruhwiler et al. (2011) found that the derived European carbon flux critically depends on the spatial coverage of the used measurement sites. For example, Chevallier et al. (2010) and Reuter et al. (2014) speculated that the sparseness of measurement sites may hinder some in situ inversion models from discriminating between the European and Eurasian TransCom (Gurney et al. 2002) regions and that additional surface in situ measurement sites in the eastern part of Europe may help to confirm a larger European carbon sink. The findings of Kim et al. (2016) support this hypothesis because when adding Siberian in situ measurements to their inversion system, the carbon uptake in Europe was enhanced while it decreased in the Eurasian boreal TransCom region. However, although the European sink was enhanced in all analyzed years, the enhancement was most times moderate (≤ 0.15 GtC a^{-1}), and was strong (≥ 0.35 GtC a^{-1}) in only 2 (of 8) years.

Uncertainties of conventional bottom-up estimates may also contribute to the discrepancy. They suffer from the large heterogeneity of land carbon cycle processes and land use. For example, eddy covariance sites cannot fully sample the full range of conditions, which can introduce uncertainties in upscaling methods such as that of Jung et al. (2011). In contrast to NIR satellites, these flux sites can operate during unfavorable illumination conditions. However, when turbulence is low (i.e., often at night), eddy covariance sites cannot provide reliable data. Additionally, eddy covariance sites often show an energy imbalance between the sum of eddy fluxes of sensible and latent heat and the available energy, which can have implications for the inferred CO_2 fluxes (e.g., Wilson et al. 2002). Schulze et al. (2009) used forest inventory data which (after 1998) only covered the EU 25 member states. Thus, significant forest gain in eastern Europe (Potapov et al. 2015) may not be sufficiently accounted for. Note also that their bottom-up estimates for grass- and croplands were based in large part on ecosystem models. Recently, Stephenson et al. (2014) revealed that carbon accumulation increases continuously with tree size. This means that one could speculate on deficiencies in the process parameterizations of tree growth models created prior to their publication. Generally, an accurate land cover classification (including uncertainty) and the representativeness of used measurement sites are critical for reliable flux estimates.

Additionally, it should be noted that the compared estimates partly cover different time periods (Fig. 2) so that the interannual variability (linked to, e.g., temperature and moisture anomalies; Ciais et al. 2005; Bastos et al. 2016) may explain parts of the discrepancy. However, the inversion experiments of, for example, Basu et al. (2013), Chevallier et al. (2014), and Houweling et al. (2015) have in common that the European carbon sink also increases considerably when analyzing satellite CO_2 data instead of or additionally to in situ measurements without changing the time period.

HOW TO PROCEED? In summary, despite the importance for the understanding of the global carbon cycle and, therefore, for reliable climate projections, and despite the political and economic relevance (e.g., emission trading and international climate negotiations), there is currently no consensus on how much CO_2 is taken up by the European terrestrial biosphere and the discrepancy between the different estimates is poorly understood.

Additional in situ measurement sites are needed to better constrain the surface fluxes of the northeastern part of Europe with inverse models, where the strongest uptake is expected. Field campaigns in this region, including flux and biomass measurements, can contribute to bottom-up estimates and serve as an additional anchor point for ABC satellite measurements. Regularly updated inventories and land cover classification are also essential for reliable bottom-up estimates. Likewise, reliable estimates of the flux uncertainties from bottom-up methods that should include, for example, all kinds of upscaling uncertainties and propagated measurement errors are essential. Specifically, some studies estimate eddy covariance flux uncertainties by expert judgment (e.g., Luyssaert et al. 2007) or neglect this source of uncertainty (e.g., Jung et al. 2011). In this context, the utilization of Bayesian statistics could help to improve future uncertainty estimates.

In addition to the continuation of existing satellite missions, new satellite missions are needed to provide denser and more accurate and precise measurements of the atmospheric CO_2 concentration (Bovensmann et al. 2010; Buchwitz et al. 2013; CEOS 2014; Ciais et al. 2014, 2015; Butz et al. 2015).

To get the best out of these data, retrieval algorithms need to be further improved and thoroughly scrutinized. This comprises i) the minimization of regional and temporal retrieval biases, ii) realistic uncertainty estimates including potential spatial and temporal error correlations, iii) an expansion of the validation of the retrieved atmospheric concentrations and corresponding uncertainty estimates (e.g., Reuter et al. 2011, 2013; Guerlet et al. 2013; Kulawik et al. 2016), iv) enhanced sensor calibration activities, v) the quantification of the influence and identification of potential bias patterns and sampling issues (e.g., Reuter et al. 2014; Feng et al. 2016), and vi) the validation of the derived fluxes (e.g., Broquet et al. 2011; Reuter et al. 2014; Houweling et al. 2015).

Aligned with this, inverse modeling tools need to be optimized for the characteristics of the satellite data—for example, by minimizing model errors due to prescribed emissions, chemistry, or transport, by better accounting for error correlations of the retrievals, and/or by simultaneously fitting the parameters of a bias model (e.g., Basu et al. 2013; Reuter et al. 2014). Additionally, further analysis of the statistical hypotheses made in the satellite retrieval algorithms and those made in the inversion systems are needed (Chevallier 2015). Validation measurements—for example, with Total Carbon Column Observing Network (TCCON; Wunch et al. 2011) ground-based remote sensing, aircraft, or AirCore (Karion et al. 2010) balloon instruments—are essential for the validation of satellite and inverse modeling data.

This long list of cross-disciplinary efforts outlines a promising direction to arrive at a commonly accepted estimate of the European carbon sink in the future.

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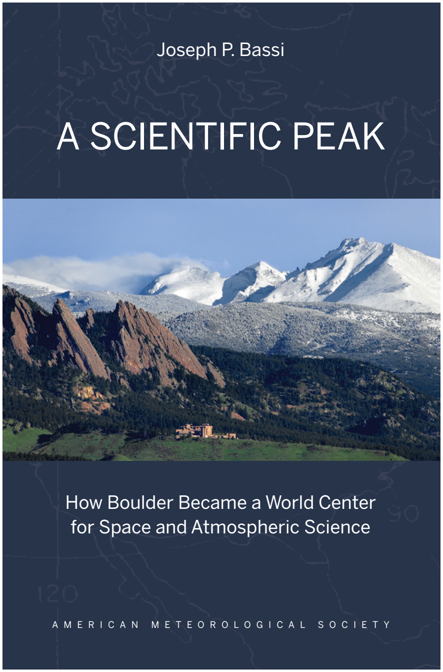


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