

Forest stand age information improves an inverse carbon flux estimate

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Forest stand age information improves an inverse North American carbon flux estimate

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Abstract

Atmospheric inversions have become an important tool in quantifying carbon dioxide (CO₂) sinks and sources at a variety of spatiotemporal scales, but associated large uncertainties restrain the inversion research community from reaching agreements on many important subjects. We enhanced an atmospheric inversion of the CO₂ flux for North America by introducing spatially-explicit information on forest stand age for US and Canada as an additional constraint, since forest carbon dynamics are closely related to time since disturbance. To use stand age information in the inversion, we converted stand age into an age factor, and included the covariances between sub-continental regions in the inversion based on the similarity of the age factors. Our inversion results show that, considering age factors, regions with recently-disturbed or old forests are often nudged towards carbon sources, while regions with middle-aged productive forests are shifted towards sinks. This conforms to stand age effects observed in flux networks. At the sub-continental level, our inverted carbon fluxes agree well with continuous estimates of net ecosystem carbon exchange (NEE) upscaled from eddy covariance flux data (EC) based on MODIS data. Inverted fluxes with the age constraint exhibit stronger correlation to these upscaled NEE estimates than those inverted without the age constraint. While the carbon flux at the continental and sub-continental scales is predominantly determined by atmospheric CO₂ observations, the age constraint is shown to have potential to improve the inversion of the carbon flux distribution among sub-continental regions, especially for regions lacking atmospheric CO₂ observations.

1 Introduction

The atmospheric concentration of carbon dioxide (CO₂) is rising, leading to a positive radiative forcing of climate and a systematic increase in surface air temperature. Observations of global atmospheric CO₂ concentration have been one of the most important

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datasets for quantifying and understanding the global carbon cycle. Before the 1990s, scientists used CO₂ measurements from a limited number of sites to analyze the temporal variability of the global carbon cycle. As more sites were added to the global observation network, inverse techniques were developed to understand both temporal and spatial distributions of carbon exchange across the globe. However, current observation sites are still sparse relative to the size of the global surface, limiting the number of regions that can be robustly inverted. Most inverse studies solved for ~ 20 source regions (e.g. Enting et al., 1995; Rayner et al., 1999; Fan et al., 1998; Gurney et al., 2003; Bousquet et al., 2000; Gurney et al., 2004; Baker et al., 2006; Law et al., 2003b; Patra et al., 2005; Bruhwiler et al., 2011), but these large-region inversions could lead to large spatial aggregation errors due to surface heterogeneity (Kaminski et al., 2001) despite some exceptions of inversion systems with many more regions (Houweling et al., 1999; Kaminski et al., 1999; Rödenbeck et al., 2003; Michalak et al., 2005; Peylin et al., 2005; Peters et al., 2007). Although solving for more regions potentially allows more information to be extracted from the CO₂ concentration observations, it can also introduce large biases if individual regions remain unconstrained. To reduce these biases, a prescribed spatial relationship in flux error covariance is often used as an extra constraint in solving the large number of unknown fluxes (e.g. Rödenbeck et al., 2003; Michalak et al., 2005; Peylin et al., 2005; Peters et al., 2005, 2007; Zupanski et al., 2007; Schuh et al., 2009).

Deng et al. (2007) used several continental sites to pursue a detailed CO₂ inversion for North America, and experimented with the use of two meteorological parameters, temperature and precipitation, to further constrain the spatial patterns of CO₂ fluxes across the continent. The effect of this “meteorological covariance” is apparent in that the inverted fluxes of a local region containing observation site(s) and a region without an observation site under similar climate are constrained in a more balanced manner than the case without using the covariance. This effect is particularly apparent when the simulated concentration deviates significantly from the local CO₂ concentration observations. The inferred fluxes, however, could be biased due to the fact that large diurnal

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variations of the planetary boundary layer (PBL) at continental sites cause large diurnal variations of CO₂ concentrations, while a transport model without considering the diurnal variations is used to simulate the atmospheric CO₂ concentrations. To reduce these biases, we implemented an inversion considering the diurnal variations of the surface CO₂ exchange of the terrestrial ecosystems and the atmospheric boundary layer dynamics (Deng and Chen, 2011). However, the traditional diagonal a priori uncertainty matrix was used in these schemes, and the spatial correlation between regions was not considered.

Carbon sinks and sources on land have been attributed to two types of mechanisms (Houghton, 2007): physiological (or metabolic) and demographic (or disturbance). Physiological mechanisms driven by variations in climate, elevated atmospheric CO₂, and increased nutrient inputs from air pollution have been intensively studied to estimate the possible responses of terrestrial ecosystems to global climate change and to attribute responses to specific factors. In terrestrial ecosystems, vegetation assimilates carbon and stores it in biomass through photosynthesis, and the biomass is in turn transferred into soil as dead organic matter. Carbon is released back to the atmosphere through respiration by plants (autotrophic respiration) and the decomposition of soil organic carbon by microbes (heterotrophic respiration). Plant photosynthesis and respiration tend to respond differently to temperature. Respiration exponentially increases with temperature (Kirschbaum, 1995; Davidson and Janssens, 2006), while photosynthetic uptake has an optimum temperature and is highly sensitive to increasing CO₂ (Atkin, 2003; Campbell et al., 2007). Water stress can decrease photosynthetic uptake in various plant functional types (Chaves et al., 2002), while soil water can inhibit microbial decay of soil organic matter at excessively high and low water contents (Orchard and Cook, 1983; Skopp et al., 1990; Howard and Howard, 1993; Yuste et al., 2003). Terrestrial ecosystem models can explicitly simulate the effects of climate and atmospheric composition on these physiological mechanisms. Similarly, oceanic carbon models have been incorporated into coupled climate-carbon models to account for the feedbacks between the carbon cycle and the evolving physical climate (Cox et al.,

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et al. (2006) pointed out that the change in ecosystem structures, especially the age-class structure of forests, is at least as important as the change driven by physiological mechanisms. Recently, observations of carbon fluxes derived from the Fluxnet-Canada network using the eddy covariance technique have also reinforced the strong relationships between forest age and carbon fluxes (e.g. Coursolle et al., 2006; Zha et al., 2009). The demographic variations associated with forest disturbance and regrowth may therefore be considered as a low-frequency force superimposed on the physiological effects mostly determined by both short-term and long-term variations in climate.

The first continental forest-stand age product for North America derived from forest inventory data, large fire polygons, and remotely-sensed data (Pan et al., 2011) provides a new source of information to re-evaluate the carbon sources and sinks across the continent as affected by age-class distributions and ecosystem productivity. Forest stand age information has never been incorporated into atmospheric CO₂ inversions due to lack of global or continental-scale data, and thus using this continental stand age map provides an opportunity to add an additional constraint to atmospheric CO₂ inversions. Our research questions are: (1) is the stand age information useful to improve atmospheric CO₂ inversion? (2) How can we reasonably integrate stand age information into an atmospheric inversion scheme? We approach these questions using the spatially explicit information of forest stand age (Pan et al., 2011) to construct the a priori carbon flux covariance matrix to account for the spatial correlation of prior flux errors between regions. Inversions are conducted with and without considering stand age in order to examine the effects of stand age on inverted fluxes. The usefulness of including forest age information in our inversion is explored through analyzing the spatial correlation of the inverted fluxes with an independent flux field over temperate North America derived from site-level eddy covariance flux data and coast-to-coast satellite data from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Xiao et al., 2008, 2011).

2 Transport model and inversion technique

2.1 Forward modeling framework

2.1.1 Global surface fluxes

5 There are four major reservoirs of carbon that affect the global carbon cycle on the time scale of seconds to millennia: the atmosphere, oceans, reserves of fossil fuels, and terrestrial ecosystems including vegetation and soil. On the time scale of years to centuries, the carbon exchanges between three of the reservoirs (oceans, fossil fuels, and terrestrial ecosystems), and the atmosphere determine the CO₂ content in the air. We use four surface flux datasets to simulate the atmospheric

10 CO₂ concentration in a forward modeling framework: (i) the fossil fuel emission field (<http://carbontracker.noaa.gov>), which is constructed based on the global, regional and national fossil-fuel CO₂ emission inventory from 1871 to 2006 (CDIAC) (Marland et al., 2009) and the EDGAR 4 database for the global annual CO₂ emission on a 1° × 1° grid (Olivier et al., 2005); (ii) the hourly terrestrial ecosystem exchange produced by the Boreal Ecosystem Productivity Simulator (BEPS) (Chen et al., 1999), which is driven by NCEP/NCAR reanalyzed data (Kalnay et al., 1996) and remotely sensed leaf area index (LAI) (Deng et al., 2006), and for which a special treatment is taken to neutralize the annual flux at each grid; (iii) the flux of CO₂ across the air-water interface based on the results of daily CO₂ fluxes using the OPA-PISCES-T model forced by daily wind stress and heat and water fluxes from the NCEP reanalyzed data for 2000 to 2007

20 (Buitenhuis et al., 2006); and (iv) the monthly mean fire emission available from the Global Fire Emissions Database version 2 (GFEDv2) (Randerson et al., 2007; van der Werf et al., 2006).

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2.1.2 Atmospheric transport modeling

The terrestrial carbon flux exhibits strong seasonal and diurnal variations. The atmospheric CO₂ concentration over land often shows greater seasonal and diurnal variations as a result of the temporal covariations between the atmospheric transport and the surface flux, producing a rectifier effect (Denning et al., 1995, 1996a,b). In order to include the diurnal CO₂ variations in the simulations, an atmospheric transport model that can simulate the diurnal cycle of the atmosphere must be used. TM5 (Global Chemistry-Transport Model) (Krol et al., 2003, 2005) is a model that is able to accommodate diurnal variations in PBL. TM5 used in this study is a transport-only version of the TM5 chemistry transport model and is a fully linear operator on CO₂ fluxes. Tracer transport (advection, vertical diffusion, cloud convection) in TM5 is driven by offline meteorological fields taken from the European Centre for Medium Range Weather Forecast (ECMWF) model. All physical parameterizations in TM5 are kept as close as possible to the ECMWF formulation to achieve compatibility between them. TM5 offers the possibility to use online two-way nested grids, giving it regional-scale capabilities in a global framework. In this project, we define a global 6° × 4° grid with a nested grid within that focuses on North America at 3° × 2° based on Peters (2004, 2005). The model transport of TM5 has been extensively evaluated using ²²²Rn and SF₆ (Krol et al., 2005; Peters et al., 2004), and TM5 performs consistently well in atmospheric transport model intercomparisons (Law et al., 2008; Patra et al., 2008).

We use the four surface fluxes introduced above from the terrestrial ecosystem, ocean, fossil-fuel burning, and biomass burning as input to the forward transport model to simulate atmospheric CO₂ concentration. However, there are substantial differences between the simulated concentration and the observed atmospheric CO₂ concentration. These differences indicate that large biases exist in the input surface fluxes, and they often serve as the driving force to inversely calculate optimal surface fluxes.

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2.2 Inverse modeling framework

Inverse modeling techniques compare simulated CO₂ concentrations in the atmosphere with observations at discrete sites over the globe. The spatial and temporal distributions of the difference between the simulated and observed values are used to infer the spatial and temporal patterns of the carbon flux. In Bayesian synthesis inversion (Tarantola, 1987), the following objective function (Rayner et al., 1999) is employed:

$$J = \frac{1}{2}(\mathbf{M}\mathbf{s} - \mathbf{c})^T \mathbf{R}^{-1}(\mathbf{M}\mathbf{s} - \mathbf{c}) + \frac{1}{2}(\mathbf{s} - \mathbf{s}_p)^T \mathbf{Q}^{-1}(\mathbf{s} - \mathbf{s}_p). \quad (1)$$

where \mathbf{M} is a matrix representing a transport (observation) operator; \mathbf{c} is a vector of the observations; \mathbf{s} is an unknown vector of the carbon fluxes of all regions to be inverted at monthly time steps combined with the assumed initial well-mixed atmospheric CO₂ concentrations; \mathbf{s}_p is the a priori estimate of \mathbf{s} ; and uncertainties of \mathbf{c} and \mathbf{s}_p are expressed in covariance matrixes \mathbf{R} and \mathbf{Q} .

A total of 3000 forward simulations were conducted in this study to form the transport (observation) operator (\mathbf{M}) of five years (2000–2004) for the 50 regions. For each month and region, a flux of 1 Pg C is prescribed in the TM5 model for forward transport computation to determine the contribution of each region to the CO₂ concentration at each observation site since January of 2000. There are strong diurnal variations in boundary layer dynamics, surface fluxes, and observed CO₂ concentrations over land, and the correlation among them could have a considerable effect on the inversion result (Denning et al., 1996a). To handle these diurnal variations appropriately in a monthly inversion, we sampled the simulations to construct a transport (observation) operator for continental sites. For tower sites, afternoon hours were sampled to avoid the error-prone simulations under stable and stratified nocturnal atmospheric conditions near the ground. For non-tower continental sites, the sample collection times for discrete observation records associated with the CO₂ dataset described in the next section were used as a weight in modifying the monthly transport (observation) operator (\mathbf{M}).

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The same weight was also used to sample simulated CO₂ concentrations from prior fluxes of fossil fuel combustion, biosphere, ocean, and biomass burning, respectively as used in Eq. (2).

3 Data and methods

As mentioned earlier, currently, the number of atmospheric CO₂ observation sites is still small relative to the size of the global surface. Moreover, these observation sites are unevenly distributed over the globe. Therefore, the inversion of CO₂ flux is underdetermined (Deng et al., 2007). Additional constraints, such as a priori flux uncertainties, are needed to further constrain the inverse problem. In this section, we will first describe all the inputs used in this study, and then devise a new a priori uncertainty matrix based on the forest age map for North America (Pan et al., 2011).

3.1 CO₂ concentration data and model-data mismatch error

The GLOBALVIEW-CO2 data (GLOBALVIEW-CO2, 2008) were used to produce the monthly CO₂ concentration data. The GLOBALVIEW-CO2 consists of both extrapolated and interpolated data. We selected the synchronized and smoothed values of actual observations to compile our CO₂ concentration dataset from 209 sites across the globe (Fig. 1) over the period from July 2001 to December 2004. Based on this CO₂ concentration dataset and the forward modeling discussed in Sect. 2.1, the vector \mathbf{c} in Eq. (1) can be further expressed as

$$\mathbf{c} = \mathbf{c}_{\text{obs}} - \mathbf{c}_{\text{ff}} - \mathbf{c}_{\text{bio}} - \mathbf{c}_{\text{ocn}} - \mathbf{c}_{\text{fire}} \quad (2)$$

where \mathbf{c}_{obs} is the monthly CO₂ concentration derived from GLOBALVIEW-CO2; \mathbf{c}_{ff} , \mathbf{c}_{bio} , \mathbf{c}_{ocn} , and \mathbf{c}_{fire} are simulated CO₂ concentrations from fluxes of fossil fuel combustion, biosphere, ocean, and biomass burning, respectively.

The model-data mismatch includes errors associated with observations (instrument errors) and errors from modeling the observations. Various approaches (Rayner et al.,

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1999; Rödenbeck et al., 2003; Baker et al., 2006; Gurney et al., 2004; Michalak et al., 2005; Bruhwiler et al., 2011) have been used to determine the model-data mismatch. We used a method based on categorization of sites similar to Baker et al. (2006). We divided the observation sites into five categories, each with its own assigned constant (σ_{const}) and variable portion (GVsd) that is computed monthly from the standard deviation of the residual distribution of the average monthly variability (var) files of GLOBALVIEW-CO₂ 2008. Then the mismatch error covariance as a diagonal matrix, **R**, can be defined with the error variance of month *i* by

$$R_{ii} = \sigma_{\text{const}}^2 + \text{GVsd}_i^2 \quad (3)$$

The categories and respective σ_{const} are: Antarctic sites (0.15 ppm), oceanic sites (0.30 ppm), land and tower sites (1.25 ppm), mountain sites (0.90 ppm), and aircraft samples (0.75 ppm).

3.2 Prior fluxes and uncertainties

The prior flux estimates for both oceans and lands in this study were set to zero after we subtracted the modeled contributions to the CO₂ concentration from fossil fuel combustion, biosphere, ocean and biomass burning (see Eq. 2, also Sect. 2.1). The vector *s* to be optimized is thus the deviation from the prior fluxes.

The sources of uncertainty in the air-sea CO₂ flux are multifold, including the error of reanalyzed meteorological data, the error of the estimated parameters in the OPA-PISCES-T model, and the error caused by the model structure. Estimating the uncertainties of the model outputs is therefore extremely difficult. The spread (0.5 Pg C yr⁻¹) of ocean uptakes in four ocean models (Le Quéré et al., 2007; Rodgers et al., 2008; Lovenduski et al., 2008; Wetzal et al., 2005) provides a good reference of uncertainty in bottom-up modeling. Rödenbeck et al. (2003) also used 0.5 Pg C yr⁻¹ as his prior global ocean flux uncertainty. Considering that the a priori used in this study is at the upper bound of those four ocean uptakes, we used an uncertainty of 0.67 Pg C yr⁻¹, distributed among 11 ocean regions according to Baker et al. (2006).

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The sources of uncertainty in the land surface flux are more complicated than those of the air-sea surface exchange. Fossil fuel emissions have small uncertainties ($\pm 6\%$ of the global fossil fuel emissions, Marland, 2008) that are often not considered in atmospheric inversions. Gurney et al. (2005) demonstrated that ignoring the uncertainties of fossil fuel emissions in time and space could effectively bias the seasonal pattern of surface fluxes and significantly change the distribution of inverse fluxes in a high resolution inversion. The estimates of vegetation fire emissions are uncertain to about 20% (1σ) on global, annual scales (van der Werf et al., 2010). Similar to fossil fuel emissions, the uncertainties of vegetation fires could not be handled separately in this inversion study. It should be noted that, however, any inverse estimate of the terrestrial carbon flux excluding fire emissions and fossil fuel emissions could be biased by these uncertainties. Compared with the error in the spatio-temporal distribution of emissions from fossil fuel combustion and vegetation fires discussed above, the heterogeneous distributions of carbon assimilation and respiration of terrestrial ecosystems in both space and time are even more error-prone. With these considerations in mind, we used an uncertainty of 2.0 PgCyr^{-1} (based on a similar regional scheme of TRANSCOM 3) for the global land surface that is spatially distributed based on the annual NPP distribution simulated by BEPS. These are used to specify the diagonal elements of the a priori uncertainty covariance matrix (\mathbf{Q}), and the off-diagonal elements that provide information about the spatial correlation of the a priori errors between regions are all set to 0.

3.3 Forest stand age information and a priori uncertainties

Forest stand age is a fundamental factor that affects net carbon accumulation by forest ecosystems (Chapin et al., 2002; Bradford et al., 2008; Apps et al., 2006). Forest age is associated with the various forest stand development stages, i.e. young stands shortly after disturbance are likely to be sources of carbon while middle-aged stands are likely to be sinks. Forest stand age information has not yet been explicitly used in global forest carbon cycle studies due to lack of spatially-explicit information. As mentioned earlier, a map of stand age for US and Canada has recently been produced (Pan et al., 2011).

We used the stand age map to further constrain CO₂ fluxes over North America. The functional relationship between the forest age and NEP is exceedingly complicated (Chen et al., 2003; Turner et al., 1995; Law et al., 2003a), and therefore we did not directly estimate NEP from the age information. Instead, we used the forest age map as a covariate to describe the relative spatial distribution of carbon sinks and sources among the 30 regions in North America. Chen et al. (2003) developed a general semi-empirical mathematical function to describe the relation of NPP with age over large areas as

$$NPP(\text{age}) = a \left(1 + \frac{b \left(\frac{\text{age}}{c} \right)^d - 1}{\exp \left(\frac{\text{age}}{c} \right)} \right) \quad (4)$$

where the parameters a , b , c , and d are functions of the mean annual air temperature. To extract information from stand age while avoiding the calculation of absolute NPP values, we normalized the chronosequence curve against the maximum NPP (i.e. NPP_{\max}),

$$f_s = \frac{NPP(\text{age})}{NPP_{\max}} \quad (5)$$

where NPP_{\max} is the maximum value of $NPP(\text{age})$ for age = 1 to 250 yr. f_s ranges between 0 and 1, with large values representing mature forests and small values representing young or old forest in terms of NPP value. This normalization accentuates the general pattern of NPP variation with age while the absolute values of NPP under the influence of meteorological conditions (precipitation, temperature and radiation) are modeled by BEPS and included as part of the prior carbon flux. Figure 2 shows the distribution of f_s for North America.

This ratio was then scaled to a quantity (f_r) at the inversion regional level as an area-weighted average of f_s , and within the regional level we defined an age factor as

$$f(\text{age}) = f_r - f_c \quad (6)$$

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where f_c is the mean of f_r for all North American regions. Similar to f_s , the first term (f_r) in Eq. (6) also ranges between 0 and 1 with small, medium and large values representing young, old, and mid-age forests, respectively. The purpose of subtracting f_c from f_r is to balance the influences of this consideration between regions with forest age information and regions without forest age information. We introduced this NPP-based age factor into our atmospheric inversion for the net carbon flux because NEE variations with age are mostly determined by NPP variations with age. Heterotrophic respiration, which depends not only on the new organic matter transferred to the soil (proportional to current NPP) but also on the amount of soil carbon accumulated over thousands of years, varies much less than NPP with forest stand age (Amiro et al., 2010), although there are some higher values at younger sites.

To combine the regional age factor into the a priori flux uncertainty, we constructed the following exponential covariance matrix for a specific month:

$$\mathbf{Q} = \begin{bmatrix} \sigma_1^2 & (r_1\sigma_1)(r_2\sigma_2)\frac{|f_1f_2|}{f_1f_2}e^{-\frac{|f_1-f_2|}{l}} & \dots & (r_1\sigma_1)(r_n\sigma_n)\frac{|f_1f_n|}{f_1f_n}e^{-\frac{|f_1-f_n|}{l}} \\ (r_2\sigma_2)(r_1\sigma_1)\frac{|f_2f_1|}{f_2f_1}e^{-\frac{|f_2-f_1|}{l}} & \sigma_2^2 & \dots & (r_2\sigma_2)(r_n\sigma_n)\frac{|f_2f_n|}{f_2f_n}e^{-\frac{|f_2-f_n|}{l}} \\ \vdots & \vdots & \ddots & \vdots \\ (r_n\sigma_n)(r_1\sigma_1)\frac{|f_nf_1|}{f_nf_1}e^{-\frac{|f_n-f_1|}{l}} & (r_n\sigma_n)(r_2\sigma_2)\frac{|f_nf_2|}{f_nf_2}e^{-\frac{|f_n-f_2|}{l}} & \dots & \sigma_n^2 \end{bmatrix} \quad (7)$$

where σ_i , f_i , and r_i are the standard deviation, the regional age factor, and the percentage of forest cover for region i , respectively; l is the integral scale, or de-correlation length-scale.

The guiding principle in constructing this matrix is that in the nested inversion there are insufficient atmospheric CO_2 stations over North America, and the spatial patterns of the prior surface fluxes could be used to constrain the inversion for small regions. This constraint may be accomplished by using the covariance of the errors between various small regions. Errors in flux estimates for regions with similar age factors are expected to be better correlated than those for regions with dissimilar age factors. This

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relative changes of inverted fluxes in region 9, and its adjacent region 10 are good examples to illustrate this mechanism. As mentioned above, a lot of old forests grow in region 9, while more middle-aged productive forests proliferate in region 10. Accordingly, negative and positive regional age factors are derived for region 9 and region 10, respectively. These age factors transform into the a priori covariance matrix, and consequently, the negative correlation between region 9 and 10 arose from the covariance matrix design (Eq. 7) and this leads region 10 to become a larger sink and region 9 to become a smaller sink. The resulting sink size is reduced in region 9, but the sink strength is still strong because of the constraint of atmospheric CO₂ concentration measurements around the region in the inversion process. Moderate sinks in British Columbia were previously estimated through ecosystem modeling, and climate warming and CO₂ fertilization had positive effects on the forest growth in this region (Chen et al., 2003). Based on the same principle, in the northern USA, the sink sizes are reduced in regions with recent disturbances or aged forests (e.g. Region 19), or with low forest cover (e.g. Region 20) (Pan et al., 2011); the uptake in southeast USA is strengthened in the highly managed forest regions where forests in predominantly productive ages could actively sequester CO₂ from the atmosphere.

Since we have plausible explanations for the changes revealed by applying the forest stand age information to our inversion results, and these changes conform to our understanding of the relationship between forest stand age and carbon balance, we examined these changes in more detail. We considered separately the physiological mechanisms that could improve the modeling of the seasonal and diurnal cycle, and the demographic mechanisms that could be used to further define the spatial distribution of carbon sinks and sources. The relevant questions are (1) whether the modeled changes alter our understanding of the role of North America in the global carbon budget, and (2) how large are the changes in the spatial distribution of the terrestrial carbon exchange over North America?

A paired *t* test shows that considering the stand age factor did not significantly change the total flux of all 30 North American regions in 2003 ($p = 0.9866$). It is

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understandable that the total annual carbon flux for the whole region, inferred with the stand age factor, does not change significantly from that inferred without considering the stand age factor in the US and Canada. Because the forest stand age information is only available for North America in this application, we centralize f_r by removing f_c (the mean of f_r for all regions) in Eq. (6) as the age factor, to cancel the possible influences on other regions outside of North America where forest age information is not available. In a balanced global carbon cycle, this leads to an insignificant change in the annual total flux for North America as shown in the paired t test.

However, we found that the change in the spatial distribution of the inverted fluxes is much stronger than the change in the annual total carbon uptake. The root-mean-square of the differences of inverted fluxes for the 20 North American regions (from region 9 to region 28) between inversions with and without considering the forest stand age factor is calculated to be 10 Tgyr^{-1} . This is 7 times the magnitude of the change in annual mean fluxes, equivalent to 23% of the mean absolute flux of these 20 regions. We also note that despite being one of the most densely observed regions, the problem is still strongly underdetermined when the inversion is conducted in a higher spatial resolution with the same set of observations. The added value of stand age information might increase as the spatial resolution increases. At higher resolutions, it would be more difficult to extract carbon source and sink information from CO_2 alone, and the forest stand age should be seen as complimentary to the CO_2 observations to reduce uncertainties in the inverse estimates. However, we need to ensure that the addition of this new dataset keeps our inversion results consistent with other sources of information, and does not introduce irreconcilable NEE estimates. Therefore, we compared them with another set of independent regional estimates of NEE upscaled from eddy covariance flux measurements that were neither used in the inversions nor in the construction of the stand-age map.

4.2 Comparison with independent flux estimates

Eddy covariance flux towers provide continuous measurements of net ecosystem carbon exchange (NEE) for various terrestrial ecosystems, but these measurements only represent the carbon fluxes at the scale of the tower footprint (about 1 km²) and areas that have very similar characteristics. Therefore, the site-specific eddy covariance measurement results are not well suited for validating estimates of regional carbon fluxes. Recently, Xiao et al. (2008, 2011) used a data-driven approach to extrapolate the NEE measurements to large areas using a variety of data streams from MODIS, and developed a gridded NEE dataset with high spatial (1 km) and temporal (8-day) resolutions for temperate North America over the period 2000–2006. This NEE dataset was derived from EC and MODIS data, and is therefore referred to as EC-MOD. The EC-MOD dataset covers most of the North American regions (Regions 9–30). At cropland sites where strong CO₂ assimilation signals can be captured by the EC measurement, but CO₂ release from the consumption of the yield offsite would spread to a fairly large area (Ciais et al., 2007; Schuh et al., 2010) that are not measured by EC instruments, we decided to neutralize the croplands grids to avoid overestimation of the carbon uptake. We are aware that this is a drastically simple treatment of a complicated matter, as the percentage of the export of agricultural products out of a region would influence our inversion results for the region. However, for the purpose of this study, this simple treatment provides a useful basis for our analysis of carbon sinks in forested areas.

Figure 4 shows the comparison of the inverted fluxes of North America with and without the age constraint and the EC-MOD flux with neutral croplands of regions 9 to 30 in 2003. It is very encouraging to see that the inversion results and the EC-MOD flux show similar spatial patterns. This figure clearly shows that the large sink regions of EC-MOD coincide with our inverted sink centers. These two estimates exhibit similar magnitudes in northern regions (regions 9–17). In the northeastern and southeastern US, however, EC-MOD sinks are much larger than inversion results. These large discrepancies may be caused by the fact that the eddy covariance measurement sites are usually located

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at productive, undisturbed vegetation areas, and measured carbon fluxes are larger than the averages over the landscape. In addition, even though MODIS data are used for the spatial extrapolation that can capture the spatial variability to a certain extent, the carbon dynamics associated with forest age are not explicitly considered in the spatial extrapolation (Xiao et al., 2008, 2011). An old forest stand, for example, would have similar leaf area to a middle-aged stand but have more biomass and higher autotrophic respiration. In other words, the EC-MOD product would have included some age effect as far as the above-ground productivity is concerned, and this makes it worthwhile for comparison with atmospheric inversion with the age constraint.

Further comparisons of our inversions with EC-MOD flux estimates show that the inversion with age constraint is better correlated with EC-MOD fluxes (Fig. 5). The age constraint increases the R^2 value by 26 %. The increase in slope (11 %) towards the unity and decrease in the intercept (4 %) of the regression (Fig. 5b) are signs of improvement achieved through using the age information in the atmospheric inversion. It should be noted that, however, this may only expose one aspect of the complicated problem. Most of the eddy flux sites may also be selected at age around their peak carbon uptake. This likely preference in site selection could positively bias the EC-MOD sink estimation when the forest age information is not used in the spatial extrapolation from the site measurements.

Several regions exhibited large discrepancies between our inversion results and EC-MOD fluxes. For example, our inversion results show that drought-dominated regions 23, 24, and 25 are nearly carbon neutral, while EC-MOD flux estimates indicated sources for regions 24 and 25, and a minor sink (0.03 Pg yr^{-1}) for region 23. These discrepancies may imply that the CO_2 concentration observations used are not sufficient to constrain our inversion results for these regions, and it is possible that mutual compensating effects may exist between regions 23, and 24 and 25, and between region 25 and regions to the east. These hypotheses are consistent with the information revealed from the a posteriori error covariance matrix produced in our inversion calculation. We found that a posteriori error for region 23 negatively correlates with those for

regions 24 and 25, while regions 24 and 25 are positively correlated and region 25 is negatively correlated with regions 26, 27, and 28.

4.3 Further remarks

The inversion approach to estimate carbon fluxes relies on the observations of CO₂ concentration. The observations integrate information on many aspects, including both temporal and spatial distributions of surface CO₂ exchanges. Therefore, the source and sink problem of CO₂ can be solved easily if we have enough highly precise CO₂ observations and a perfect atmospheric transport model. North America is one of the most densely observed regions, and the spatial distribution of the surface carbon exchange is better constrained there than over other continents where observations are sparse. Though the incorporation of stand age in North America only slightly improves the inversion estimates of net carbon flux, the implication of the positive effect is that adding the forest stand age information could bring more pronounced improvements to the inverse estimates of carbon fluxes over other less observed continents. Further improvement could also be expected if we pursue higher resolution inversions over North America (or Europe) as discussed in Sect. 4.1.

This study opens the way for further development of the approach established in this paper. We used a simple function (Eq. 4) to capture the basic relationship between NPP and forest stand age. Although the normalized NPP-age relationship includes the influence of temperature, other site conditions, such as water availability might also have influence on the relationship. Further, it is obvious that a NEP function with stand age would be a better covariate of the full forest carbon cycle than the NPP-age relationship used in this study. The correlations we established may only reflect a major part of links between regions, so a general NEP function needs to be developed in the future, along novel ways to incorporate this relationship into the dual-data inversion approach. The stand age information can also be incorporated into a long-term terrestrial ecosystem model to simulate NEP as the a priori instead of being used to construct the a priori uncertainty matrix as we did in this study. The use of forest age

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information could be extended to the global land surface and to a multi-year inversion as soon as the map covering the global land surface is available. Before that, we can examine this dual-data inversion approach at a finer resolution in a region where more CO₂ observations and forest stand age information are both available. Although the influence of forest stand age information on the inverted carbon flux distribution could be large or small because it is complimentary information to the atmospheric CO₂ observations, the uncertainties of the inverted fluxes would certainly be decreased as more constraints are incorporated. We can, therefore, gain increased confidence from the dual-data inversion approach.

5 Conclusions

The spatially explicit information on forest stand age (Pan et al., 2011) was used to establish the spatial correlation between regions through an a priori covariance matrix, which further constrained the CO₂ flux inversion for the sub-continental regions across North America. Our results show no fundamental changes to the aggregated spatial patterns of CO₂ fluxes across North America when the stand age information is included in the inversion as the large-scale sinks and sources are basically driven by atmospheric constraint. The use of stand age information in the inversion brings adjustments in the distribution of the inverted fluxes among regions of dissimilar forest ages representing different stand development stages. In recently-disturbed or old forest regions, the inverted fluxes often move towards the source direction, while regions with middle-aged productive forests, especially the highly managed southeastern US forests, were nudged toward larger sinks. The a posteriori uncertainties are large in southeastern US regardless of the inclusion of the stand age information.

The relatively high level of agreement of the spatial patterns between our inversions and independent carbon flux estimates (EC-MOD) derived from eddy covariance flux measurements and remotely-sensed data increases our confidence in inferring the surface carbon flux through atmospheric inversion. The inverted spatial distribution

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of the carbon flux with the forest stand age constraint is better correlated with EC-MOD estimates than that without the age constraint (R^2 increased from 0.46 to 0.58). Considering the likely bias induced by preferential EC site selection, we would expect that the EC-MOD product could be improved by using forest age information in the spatial extrapolation from sites to a region. A useful direction to pursue in future work would be to use forest age information in both top-down and bottom-up modeling so that the spatial distribution pattern of the terrestrial sink, especially over less observed continents, can be better resolved, as forest stand age has first order effects on the spatial distribution of forest carbon sources and sinks. These effects are superimposed on the large-scale patterns of the carbon flux determined by climate.

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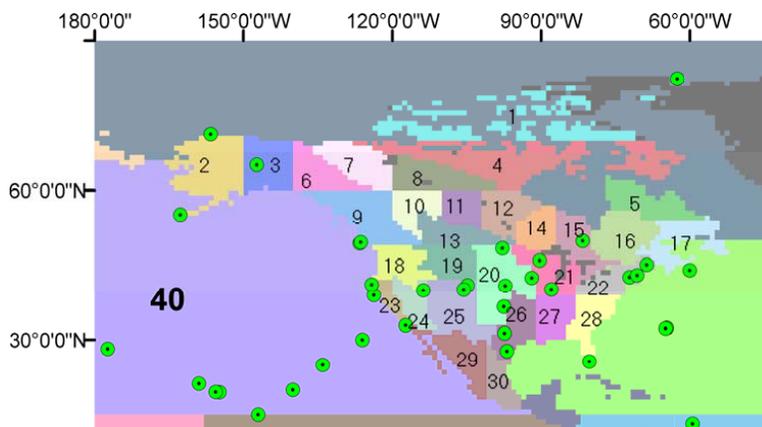
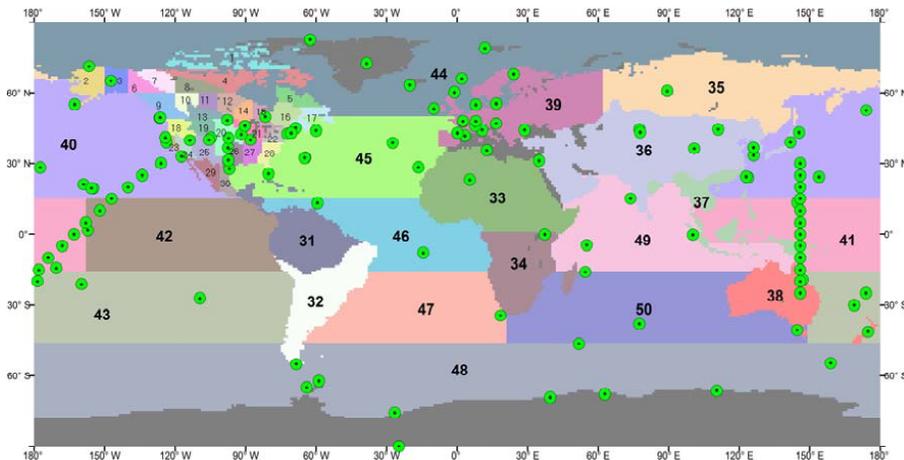


Fig. 1. An inversion scheme: 30 regions in North America and 20 regions for the rest of the globe. Locations of 209 CO₂ observational sites are also indicated.

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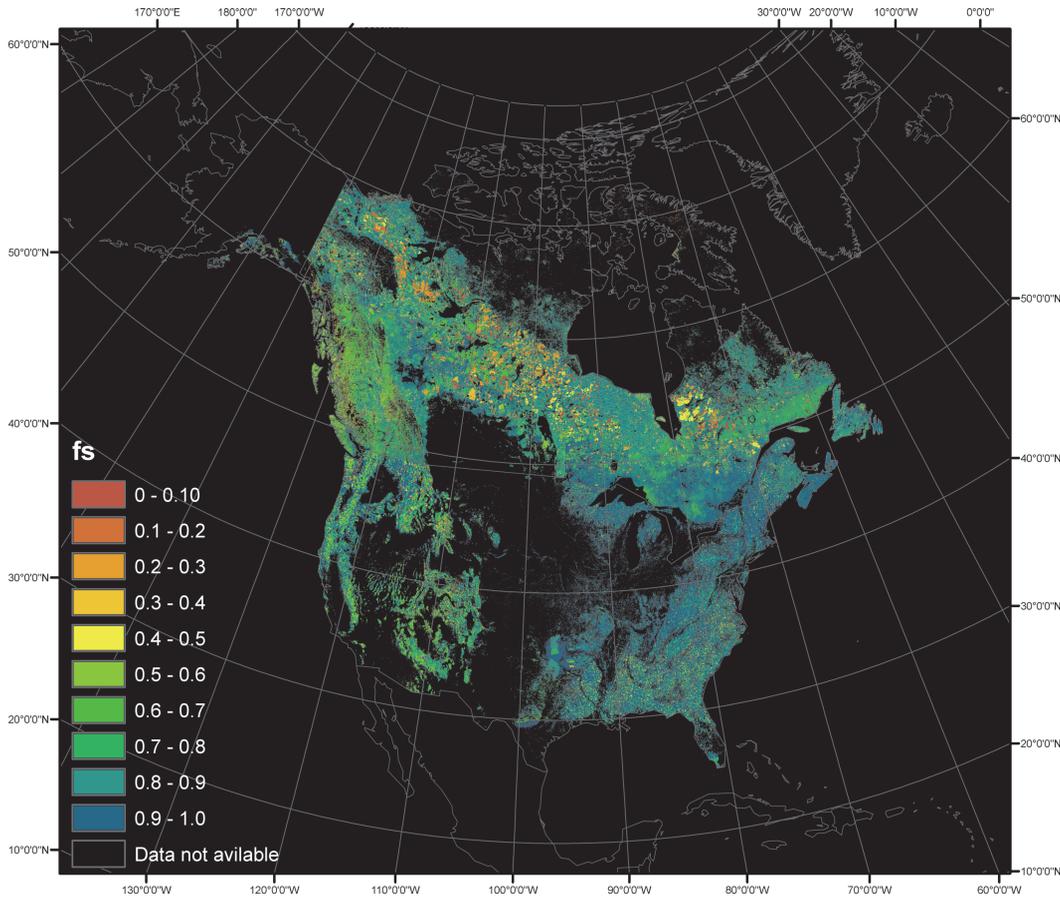


Fig. 2. The distribution of f_s for North America where forest stand age information is available.

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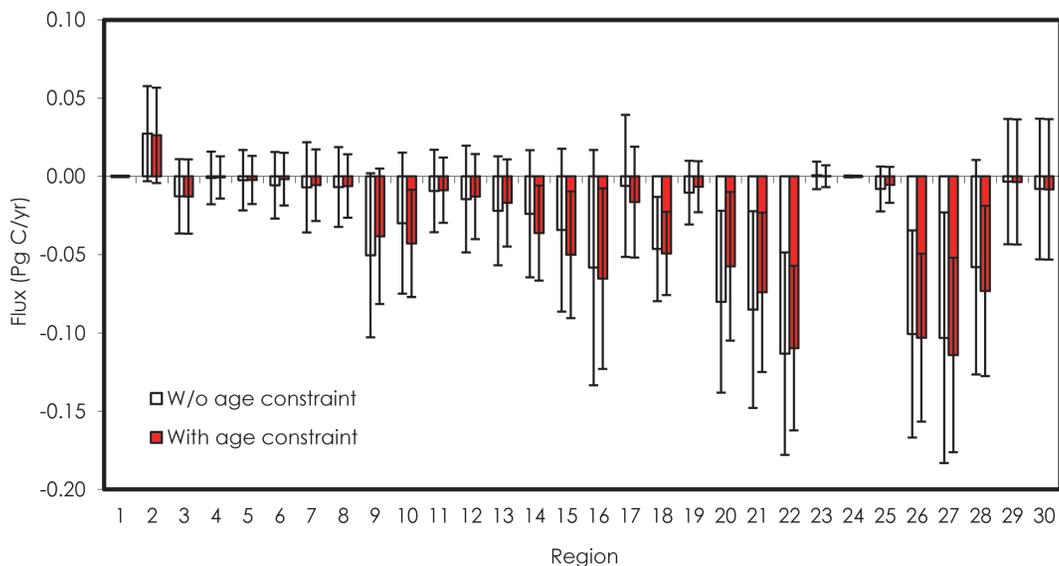


Fig. 3. Inverted CO₂ fluxes and uncertainties for 30 North America regions when the forest-stand age information is not considered as a constraint (1) and when it is considered as a constraint (2).

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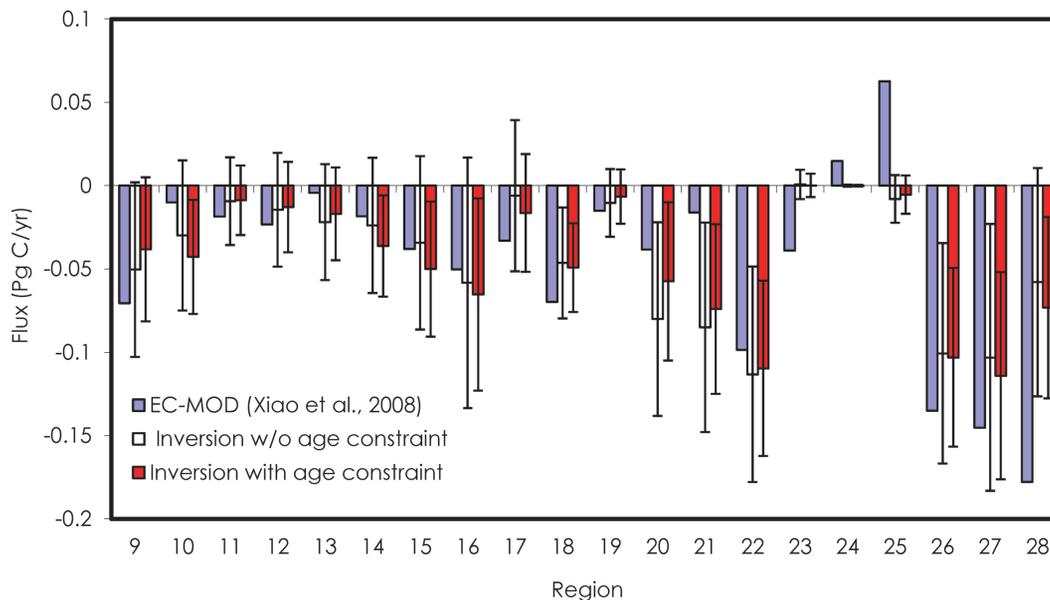


Fig. 4. CO₂ fluxes and uncertainties for 20 North America regions (region 9 to 28) estimated from three different approaches: (1) the EC-MOD method (Xiao et al., 2008), and no uncertainty information is available, (2) inversion method without age constraint, (3) inversion method with age constraint.

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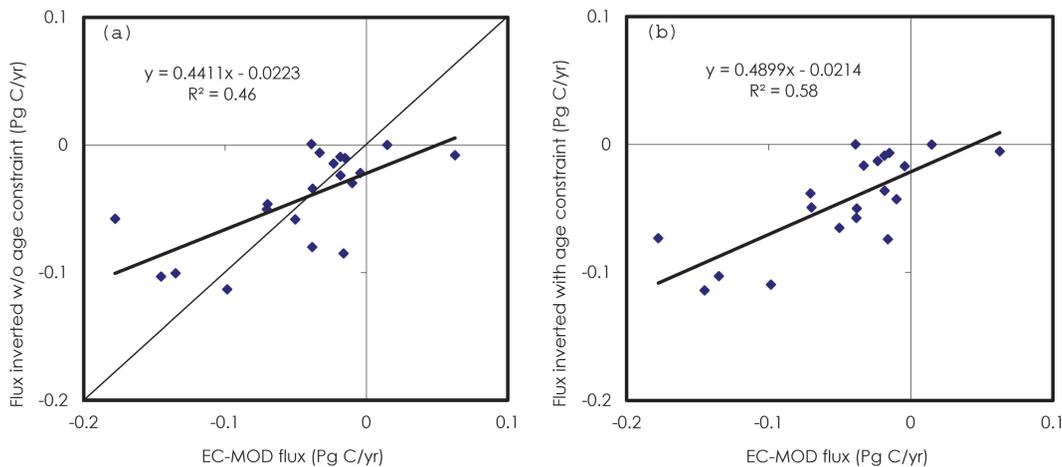


Fig. 5. CO₂ fluxes for 20 North America regions (region 9 to 28) estimated from two inverse approaches vs. EC-MOD method. The inverse approaches are **(a)** inversion without age constraint, and **(b)** inversion with age constraint.

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