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Observing CO2 from space: A Decade of progress from NASA's Orbiting Carbon Observatories (OCO-2 and OCO-3)

Key Points:

- The ratio between lateral carbon fluxes and carbon stock change can be up to 2.0 on a regional scale
- Lateral carbon fluxes must be considered to reconcile top-down estimates and national inventories
- Top-down updates to prior net carbon exchange are correlated with net lateral fluxes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Significant Influence of Lateral Carbon Fluxes on Regional U.S. Carbon Budgets

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Abstract Observations of atmospheric carbon dioxide (CO_2) are expected to play a critical role in monitoring, reporting, and verification designed to track progress toward the reduction goals of greenhouse gas emissions. In this study, we construct a comprehensive regional carbon budget for seven National Climate Assessment regions of the contiguous United States (CONUS) over 2015–2020. We demonstrate that lateral carbon movement across regions, along with their resulting endpoint CO_2 emissions, represent a major contributor to the interpretation of regional net surface-atmosphere fluxes of CO_2. When accounting for lateral carbon fluxes, "top-down" flux estimates from v10 Orbiting Carbon Observatory 2 (OCO-2) Modeling Intercomparison Project (MIP) agree, within uncertainty, with inventory-based carbon stock change estimates in six out of seven National Climate Assessment regions - except for the Southwest. The total net carbon exchange from the top down is 925 ± 339 Tg carbon per year (Tg C/year), consistent with the 974 Tg C/year estimate from the inventory. Notably, lateral carbon flows in the form of harvested wood products and riverine carbon burial are responsible for an estimated 16% of the total carbon stock changes occurring across CONUS. Averaged over the seven regions, accounting for lateral transport and their endpoint carbon emissions improves the consistency between inventory and top-down estimates by 31%. Our study presents a roadmap for reconciling the inventories and top-down atmospheric inversions at sub-national scale and highlights the importance of accurate representation of lateral carbon flows for using top-down estimates with national inventories.

Plain Language Summary As nations commit to reducing greenhouse gas emissions, reliable systems for monitoring and verifying carbon fluxes at national and sub-national levels are essential. This study generates a detailed carbon budget for seven National Climate Assessment regions across CONUS over 2015–2020, revealing the critical role of lateral carbon fluxes—such as harvested wood products and riverine carbon burial—in shaping the changes in carbon stock and net exchange of carbon dioxide between the land and atmosphere across the contiguous United States. Our findings show that their omission can significantly affect the attribution of top-down estimates for regional carbon budgets. Incorporating lateral carbon transfers will be key to improving the accuracy and consistency of regional carbon monitoring systems that are needed to guide and verify carbon emissions management.

1. Introduction

Reducing CO_2 emissions is essential to slow the rise of atmospheric CO_2 and mitigate the impacts of climate change. However, achieving these reductions requires accurate, transparent, and trustworthy information on national and sub-national carbon budgets, along with clear insight into how these budgets evolve over time. Monitoring, reporting, and verification provides the mechanism needed to track the effectiveness of climate mitigation strategies, and to provide reliable data to design, implement, and adjust climate policies. Underlying these systems, National Greenhouse Gas Inventories (NGHGIs) combine sectoral-level activity data, such as the amount of fuel burned or area of forest cleared, with emission factors that describe emissions per unit of activity.

Together, these inputs enable governments to estimate greenhouse gases emissions and removals of atmospheric carbon dioxide (CO_2) from all sectors at the national level.

Yet, NGHGIs face significant challenges. They often depend on national statistics, which may be incomplete, outdated, or inconsistent across sectors. Furthermore, the emission factors used are frequently derived from global or regional averages, which do not always reflect local conditions, such as differences in technology, land management practices, or ecological variability. Furthermore, the inventories are focused on emissions associated with anthropogenic activity and do not provide a full estimation of the carbon budget. As a result, NGHGIs can produce biased and uncertain estimates of emissions. Atmospheric "top-down" methods offer a valuable independent methodology and complement activity-based inventory approaches. By using atmospheric CO_2 measurements to infer surface–atmosphere CO_2 fluxes, top-down inversions can provide a globally and regionally consistent estimate of carbon budgets. Reconciling, or harmonizing, top-down atmospheric approaches with inventories holds great promise for increasing confidence in national and regional carbon budgets, ultimately strengthening the evidence for monitoring outcomes from climate actions.

However, comparisons between top-down flux inversions and inventory-based budgets are complicated by the lateral movement of carbon across landscapes and regions. Top-down flux inversions quantify carbon exchange in the vertical direction. In contrast, lateral movements of biomass and other forms of carbon lead to a displacement from where it is absorbed by land-based pools to where it is released to the atmosphere (Byrne et al., 2023; Ciais et al., 2022; Deng et al., 2022, 2025; Poulter et al., 2025). Because these lateral flows are generally carbon neutral integrated over the globe over a long period of time (removals are balanced by displaced emissions), these transfers are not tracked directly by NGHGIs, apart from harvested woody products. National inventories report carbon stock changes in defined pools, not the full movement of carbon across space. As a result, accounting for lateral carbon flows is essential when comparing inventory-based estimates with top-down flux inversion results (Ogle et al., 2015; West et al., 2011).

A notable effort in reconciling top-down flux inversions and inventory budgets is the Regional Carbon Cycle Assessment and Processes-2 (RECCAP-2) project (Ciais et al., 2022). RECCAP-2 collects and synthesizes carbon budget estimates over 10 continental scale regions, aiming to reconcile atmospheric top-down inversion estimates with biogeochemical model simulations and national inventories. Deng et al. (2022, 2025) represents another effort that tries to reconcile top-down flux estimates and national inventories. The smallest spatial scale under both RECCAP-2 and Deng et al. (2022, 2025) remains at the national level. Few studies have attempted to reconcile CO_2 flux estimates between top-down atmospheric inversion and inventory estimates at finer, sub-national scales.

Investigating sub-national GHG budgets is important for both scientific understanding and for guiding GHG emissions management efforts. Nationwide aggregates such as NGHGIs provide limited insight into the geopolitical, economic, and ecosystem processes that act on a regional scale to govern emissions and emission trends. In the United States, for example, agricultural practices vary considerably across regions (Foley et al., 2011; Tilman et al., 2002). Humid forests of the east differ markedly in management practices and responses to climate and environmental change from the forests of the arid and semi-arid west (Vose et al., 2016). In addition, sub-national governments—such as states, provinces, or cities—are increasingly committing to ambitious climate mitigation measures and need robust, localized carbon budget information to guide their policies (Hultman et al., 2020). Substantial progress has been made in evaluating CO_2 fluxes using top-down and inventory methods for cities (Lauvaux et al., 2020; Turnbull et al., 2019; Wilmot et al., 2024), but efforts to improve our understanding of regional-scale ecosystem fluxes have been limited. The value of such joint, regional top-down and inventory efforts has been illustrated dramatically by our progress in understanding regional methane emissions (Alvarez et al., 2018; Barkley et al., 2021; Cusworth et al., 2024; Nesser et al., 2024).

One notable effort to achieve regional-scale reconciliation between top-down and inventory estimates of ecosystem net carbon exchange (NCE) was the North American Carbon Program Midcontinent Intensive (MCI, Ogle et al., 2006). That study included enhanced regional atmospheric CO_2 observations (Miles et al., 2012) and high-resolution, mesoscale atmospheric inversion systems (Lauvaux et al., 2012; Schuh et al., 2013) combined with gridded agricultural inventory data including lateral flows (West et al., 2011), which proved to be essential for understanding NCE in this region (Schuh et al., 2013). The resulting regional-scale reconciliation efforts (Cooley et al., 2013; Schuh et al., 2013) demonstrated the complementary strength of top-down inversions and bottom-up inventories for monitoring annual NCE at regional scales (Ogle et al., 2015). Both methods were shown to have comparable uncertainty at the scale of the U.S. Midwest (Schuh et al., 2013). To our knowledge, this type of regional top-down, inventory evaluation of NCE has not been attempted, since the launch of Orbiting Carbon Observatory–2 (OCO-2), which has greatly increased the density of atmospheric CO_2 observations.

In this study, we will address this knowledge gap by providing detailed carbon flows for each of the seven regions associated with the US National Climate Assessment (https://www.c2es.org/content/national-climate-assessment/) within contiguous United States (CONUS) and aim to reconcile the regional carbon budget from inventories with top-down atmospheric CO_2 flux inversions. We will compare the NCE from the v10 OCO-2 model intercomparison project (MIP) (Byrne et al., 2023) top-down inversions with the inventory estimates by accounting for detailed lateral carbon flows from both anthropogenic and natural sources. We will examine where top-down flux estimates agree, within uncertainty, with inventory-based carbon stock change estimates in the National Climate Assessment regions averaged over a 6-year period (2015–2020), to reduce the impact of climate-driven variations in carbon fluxes between years. With a focus on CONUS, where inventory estimates are most detailed, our study provides a roadmap for developing a subnational carbon budget and identify knowledge gaps in harmonizing top-down atmospheric inversion and inventories at sub-national level.

2. Methods to Reconcile Regional Carbon Budget Estimates Between Inventories and Top-Down Flux Inversions

We created a carbon budget inventory for seven National Climate Assessment regions over 2015 through 2020. Fossil fuel (FF) emission estimates and carbon stock changes are calculated regionally using methods consistent with reporting by the national greenhouse gas inventory (EPA, 2023). This includes FF emissions, carbon stock changes in forests, grasslands and croplands, and changes in harvested wood product (HWP) stocks. To compare with the top-down flux inversion results over these seven regions, we combine carbon stock changes and FF emissions with lateral fluxes, which generate no net emission or uptake when integrated across the United States. The endpoint of the lateral movement is where the CO_2 is returned to the atmosphere, which we call as endpoint emissions. These sources are typically not addressed in inventories but are included in our analysis so that the inventory estimates can be directly compared with top-down estimates over CONUS. The lateral carbon transport and endpoint fluxes include harvested woody and crop products, river lateral transport, livestock and human respiration, biofuel emissions, residual crop emissions, and CO_2 degassing in riverine and lake systems. The final NCE based on inventory is then calculated as

$$\mathrm{NCE}_{\mathrm{inventory}} = \mathrm{NCE}_{\mathrm{forest}} + \mathrm{NCE}_{\mathrm{crop+grassland}} - \text{river lateral transport} + \text{fossil fuel} \tag{1}$$

where negative sign indicates carbon uptake from the atmosphere. In the following, we describe calculations of $\mathrm{NCE}_{\mathrm{forest}}$, $\mathrm{NCE}_{\mathrm{crop+grassland}}$, river lateral transport, and FF emissions in Sections 2.1 to 2.4, and NCE from top down flux inversion in Section 2.5.

2.1. Inventory-Based Forest Carbon Budget

Roughly 32% of the U.S. land area is forested (Domke et al., 2024). Figure 1a shows the forest stock changes resulting from CO_2 uptake by forests and the annual net lateral carbon fluxes and their pathways to the atmosphere. After accounting for lateral carbon fluxes and endpoint emissions, the NCE over the forest based on the inventory data is then calculated as

$$\mathrm{NCE}_{\mathrm{forest}} = -\Delta \mathrm{C}_{\mathrm{forest}} - \mathrm{Harvest}_{(\mathrm{wood})} + \text{biofuel} + \text{residual flux} \tag{2}$$

where negative sign indicates carbon uptake from the atmosphere. Changes in forest carbon stocks ($\Delta \mathrm{C}_{\mathrm{forest}}$) are tracked as part of the NGHGIs and described in Section 2.1.1. Wood harvests, tracked by the National Forest Inventory (NFI) (Section 2.1.2), result in the lateral removal of carbon from forests. Once harvested, wood can be burned as biofuel (Section 2.1.5) or become a HWP. These products can have a variety of lifecycles (Taylor et al., 2023). We track changes in HWP carbon stocks and trade based on the national greenhouse gas inventories (Sections 2.1.3 and 2.1.4). After accounting for these processes, the residual harvested wood carbon is assumed to be released back to the atmosphere (Section 2.1.6).

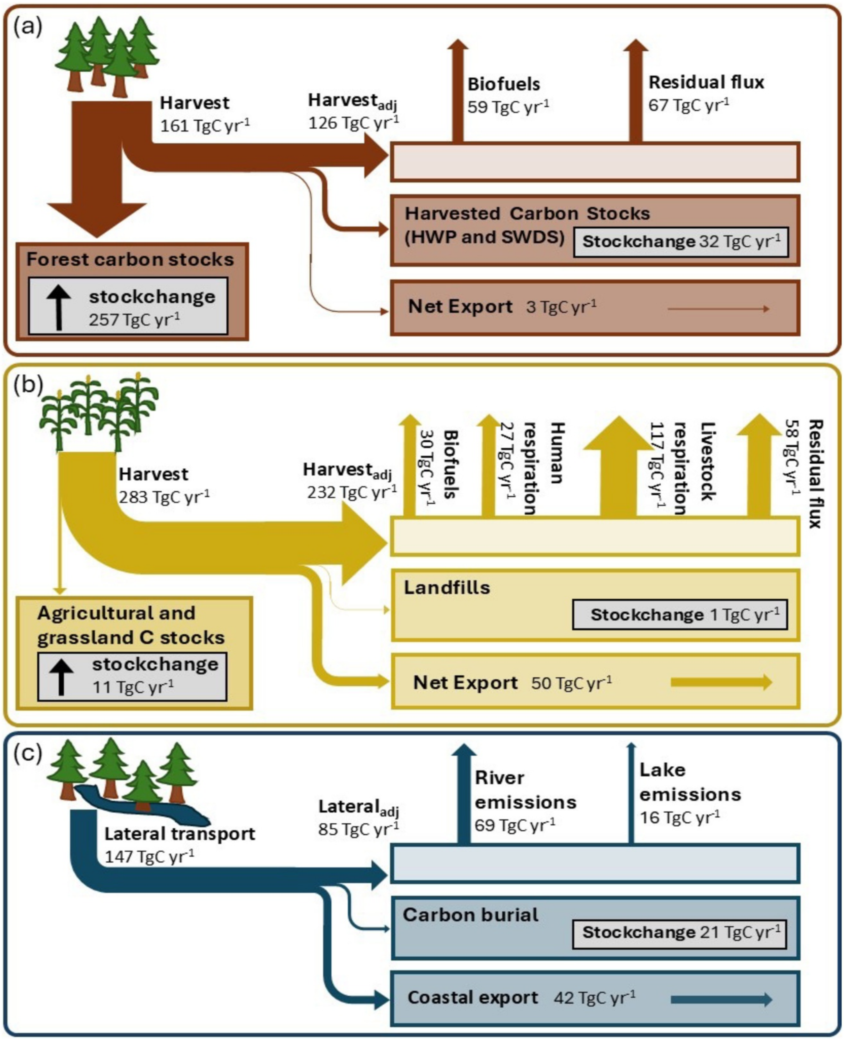

Figure 1. Annual net carbon stock changes and lateral carbon flows for (a) forests, (b) croplands and grasslands, and (c) mediated by the water cycle. (a) Carbon uptake by forests leads to local carbon stock increases and lateral transport through forest harvests. This harvested carbon translates into increased harvested wood product carbon stocks, net international trade, or re-emission to the atmosphere through biofuel emissions, decomposition, and combustion. (b) Carbon uptake in croplands and grasslands leads to local carbon stock changes and lateral transport through crop harvests. This harvested carbon in crop products translates into increased landfill carbon stocks, net international trade, or re-emission to the atmosphere through biofuel emissions, decomposition, livestock/human respiration and combustion. (c) Leaching from ecosystems results in riverine and lake emissions to the atmosphere, burial in terrestrial water bodies, and export to the ocean. The values in this figure are for the CONUS budget. All terms are also broken down into regional values (Table S1 in Supporting Information S1).

2.1.1. Forest Carbon Stock Changes

State changes in forest carbon stocks (ΔC_{forest}) are estimated from annual NFI plots established and measured by the Forest Inventory and Analysis program within the U.S. Department of Agriculture Forest Service (Domke et al., 2024). Direct measurements or variables from the NFI are the basis for estimating carbon densities (i.e., per-unit-area estimates of carbon stocks) for the forest ecosystem carbon pool (i.e., aboveground biomass, belowground biomass, dead wood, litter, and soil). Plot-level estimates are used to estimate land area (by use) and inform stand age transition matrices across time, which can be summed annually for an estimate of forest carbon stock change for forest land. A general description of the land use and stand age transition matrices that are informed by the annual NFI is described in Coulston et al. (2015). The annual NFI data in the CONUS allows for empirical

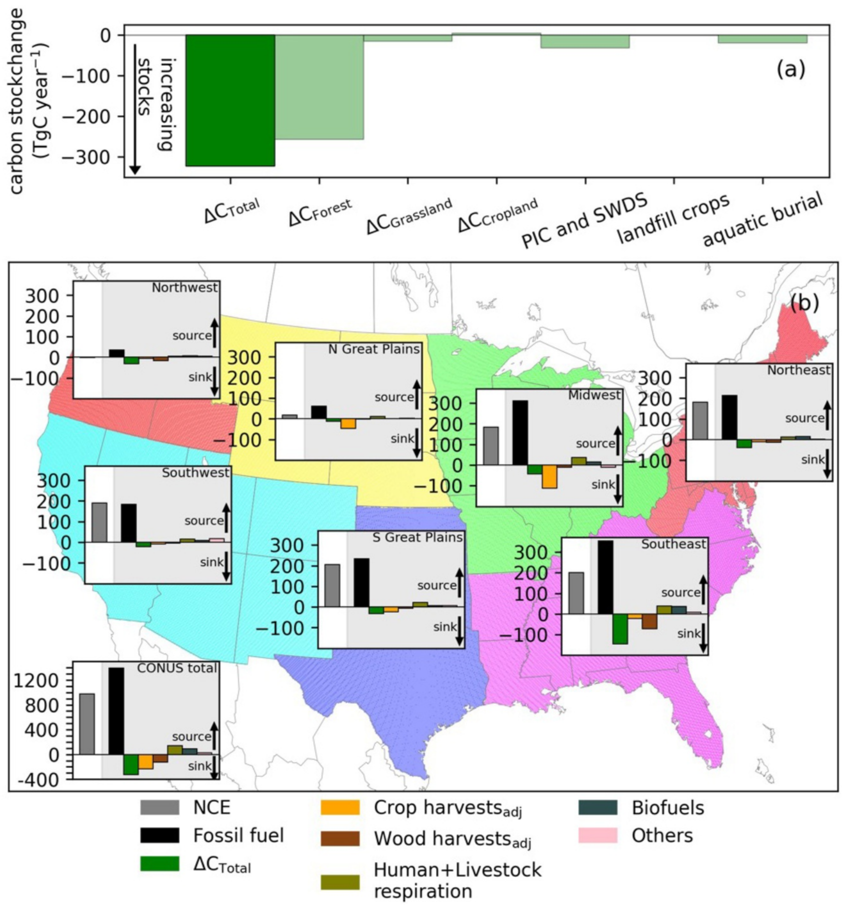

Figure 2. Regional carbon budget for CONUS produced in this study. (a) 2015–2020 mean change in CONUS integrated terrestrial carbon stocks derived using inventories. (b) Regional 2015–2020 net surface-atmosphere CO_2 fluxes (NCE) for the U.S. Climate Assessment regions. The gray shaded region shows the component flux estimates that sum to NCE, including fossil fuel and industrial processes and product use emissions, ΔC_{Total}, crop harvest, wood harvest, respiration, biofuel combustion and others (incineration, trade, lake and river emissions, coastal carbon export, and residual crop and forest emissions). Unit: Tg C/year.

estimation of the net change in forest ecosystem carbon stocks for each of the states (Domke et al., 2024). The compiled forest stock changes are reported in Figure 1a and contribute to total stock change in Figure 2.

2.1.2. Wood Harvests

Wood-based materials harvested from forests serve as a major lateral flux of carbon within CONUS. We used the NFI to obtain state-level harvest removal estimates from the most recent inventories in each state. Removals (i.e., trees that were cut, utilized or not (C), and trees removed from the land basis (D) between previous measurement (t) and the current measurement ($t + 1$)) of aboveground biomass of trees (at least 2.54 cm diameter at breast height or at root collar) were estimated for the midpoint of the measurement interval. The estimates of removals were converted to average annual removals by summing C and D and dividing by the time in years (rounded to the nearest tenth) between measurements (Δt) for individual plots (Bechtold & Patterson, 2015).

$$\text{Annual removals} = (\text{C} + \text{D})/\Delta\text{t} \tag{3}$$

To estimate the total removals for each state, the individual plot estimates are averaged at the stratum level (i.e., percent canopy cover was used for stratification). Removals for each plot are summed and then divided by the observed plot area and the mean proportion of stratum h observed plot areas falling within the population (i.e., forest land within each state), yielding an estimate of the removals per-unit-area. The per unit area estimates are then summed across all plots within each stratum and divided by the total number of plots in the stratum to yield the stratum mean. The strata mean are averaged using the strata weights and then multiplied by the total land area to obtain the estimated total removals for each state. To reconcile inventory estimates with top-down flux inversion results, we calculate the portion of annual wood harvests released to the atmosphere within a short time over CONUS. This fraction is captured by top-down inversions but excluded from inventories. It represents the harvest not allocated to harvested wood products (HWPs) ($HWP_{stock\text{-}change}$) or exports, which we define as the adjusted harvested wood flux. It is calculated as

$$\text{Harvestwood}_{adj} = \text{Harvest wood} - HWP_{stock-change} - \text{net export} \tag{4}$$

We describe $HWP_{stock\text{-}change}$ and wood trade in Sections 2.1.3 and 2.1.4, respectively.

2.1.3. HWP Carbon Stocks Change

Harvested Wood Products (HWPs) are wood-based materials harvested from forests, which are used for products, such as furniture, plywood, paper, and paper-like products. Once in a product, the carbon can be emitted to the atmosphere over time through decomposition or when the wood product is combusted (EPA, 2023; Wei et al., 2023). The emission rate varies considerably among different product pools, such as lumber in a house, which can last decades to centuries. Following (EPA, 2023), we divide HWPs into products in use (PIC) and solid waste disposal sites (SWDS).

The annual change in stock of HWPs in use from consumption is reported in Table A from Section 3.13 of Annex 3 of the National Greenhouse Gases Inventory (EPA, 2023). For this study, we report the 2017–2020 mean value of 13.95 Tg C year^{-1} in stock change of HWPs. The total carbon stock of HWPs in use from consumption is also reported as 1,510.5 Tg C (2015–2020 mean, Table A-188).

As with products in use, the annual change in stock of HWPs in SWDS from consumption is reported in Table A-190 from Section 3.13 of Annex 3 of the National Greenhouse Gases Inventory (EPA, 2023). For this study, we report the 2017–2020 mean value of 17.6 Tg C year^{-1}. The total carbon stock of SWDS in use from consumption is also reported as 1,120.5 TgC (2015–2020 mean, Table A-188). Due to a lack of state-level estimates, we assume that these HWP stock changes occur uniformly across the CONUS and calculate area-weighted partitioning for each state.

2.1.4. Wood Trade

Trade of HWPs is reported in Table A-190 from Section 3.13 of Annex 3 of the National Greenhouse Gases Inventory (EPA, 2023). The annual imports of wood, paper products plus wood fuel, pulp, recovered paper, and roundwood/chips amount to 16.5 Tg C year^{-1} (2017–2020 mean). Exports of the same quantities amount to 19.7 Tg C year^{-1} (2017–2020 mean). The net trade number is about 3 Tg C/year, as reported in Figure 1a. Due to a lack of state-level estimates, we assume that wood trade occurs proportional to wood harvest in each state.

2.1.5. Wood Biofuel

Biofuel emissions are obtained from the EPA State GHG Emissions and Removals data set (EPA, 2022), and are the combined emissions from the industrial, electric power, residential and commercial sectors. These emissions allocate the national-level wood CO_2 emissions to states based on the percentage of wood used in each sector by state, according to the state Energy Data System data (Energy Information Administration, 2022). The wood fuel directly releases carbon to the atmosphere, which is part of $\text{Harvestedwood}_{adj}$ defined in Section 2.1.2. Wood biofuel contributes to the total biofuel reported in Figure 2.

2.1.6. Residual Wood Emissions

Harvestwood_{adj} can have several pathways released to the atmosphere, including biofuel emissions, decomposition, or combustion not captured in biofuel emissions. This can include carbon released at a mill before it becomes a product or from decomposition in disposal sites. As these emissions are challenging to track directly, we take these emissions to be the residual of harvested carbon that is not accounted for in biofuel emissions, HWP stock changes, or trade:

$$\text{Residual wood emissions} = \text{Harvestedwood}_{adj} - \text{wood biofuel} \quad (5)$$

Because of the lack of better information on emissions from HPW and state-level net wood trade information, we assume that these residual emissions occur uniformly across the CONUS and calculate area-weighted partitioning for each state.

2.2. Inventory-Based Croplands and Grasslands Carbon Budget

The total cropland area was 160,111 thousand hectares, and the total grassland area was 339,138 thousand hectares in 2020. These numbers vary from year to year due to land use change and more information is provided in EPA (2023). Figure 1b shows the annual lateral fluxes and stock changes resulting from CO_2 uptake by crops and grasses. After accounting for lateral carbon fluxes and endpoint emissions, the NCE over the cropland and grassland based on the inventory data is calculated as

$$\begin{aligned} \text{NCE}_{crop+grass} = & -\Delta C_{crop+grass} - \text{Harvest}_{(crop+grass)} + \text{respiration}_{human+livestock} + \text{biofuel} \\ & + \text{missed respiration} \end{aligned} \quad (6)$$

Changes in cropland and grassland carbon stocks (ΔC_{crop}) are tracked as part of the national greenhouse gases inventory and described in Section 2.2.1. Lateral fluxes due to crop harvests (Section 2.2.2), international trade (Section 2.2.3), biofuel emissions (Section 2.2.4), livestock (Section 2.2.5) and human respiration (Section 2.2.6), crop accumulations in landfills (Section 2.2.7) are all described individually. The residual imbalance between these lateral flux components is assumed to be missed respiration occurring during harvest, transport, processing, or possibly composting, which is not tracked in the inventory (Section 2.2.8).

2.2.1. Grassland and Cropland Carbon Stock Changes

Carbon stock changes for croplands ($\Delta C_{croplands}$) and grasslands ($\Delta C_{grasslands}$) were estimated for 2015 to 2020 using the method from the national greenhouse gases inventory (EPA, 2023). Estimates were based on the land use histories compiled in the USDA National Resources Inventory (NRI) ((Nusser & Goebel, 1997; USDA NRCS, 2018b). National Resources Inventory is a two-stage land survey with primary sampling units that are stratified based on township and range from the United States Public Land Survey. There are a total of 571,396 survey locations included in this analysis.

The DayCent ecosystem model was applied to estimate biomass, litter and soil organic carbon stock changes that occur on croplands and grasslands with mineral soils (EPA, 2023; Ogle et al., 2023). DayCent simulates plant production, litter and soil organic matter dynamics, plant and soil water dynamics, and soil temperature regimes (Gurung et al., 2020; Parton et al., 1987, 1998). The model is applied to land use histories compiled in the NRI, and management data were based on several sources, including NRI, Conservation Effects Assessment Project data (USDA NRCS, 2018a), Agricultural Resource Management Surveys (USDA ERS, 2020), and Operational Tillage Information System (OpTIS) tillage and cover crop data set (Hagen et al., 2020); OpTIS data were provided by Regrow Agriculture, Inc.), EPA Manure Management Database (EPA, 2023), and USDA Census of Agriculture (USDA-NASS, 2019). These data are combined to simulate crop types, planting and harvesting dates, tillage management, mineral and organic nitrogen management, cover crop usage, and irrigation. Other model drivers include weather data from PRISM (PRISM Climate Group, 2022) and soil characteristics from the Soil Survey Geographic Database (Soil Survey Staff, 2020). Crop production for major commodity crops (i.e., corn, soybeans, wheat, cotton, sorghum, and other close-grown crops similar to wheat, such as oats and barley) is simulated using the NASA-CASA production algorithm (Potter et al., 1993, 2007), which is informed by the Enhanced Vegetation Index (EVI) from the MODIS vegetation products (MOD13Q1 and MYD13Q1). The production of grasslands and minor crops is not informed by EVI data but rather simulated using a production algorithm capturing the impact of crop growth potential, water availability, temperature, and nutrient stress on production (Parton et al., 1987). Carbon stock changes associated with NRI survey locations for federally managed grasslands were not modeled with DayCent, and the stock changes were approximated based on estimates from the nearest NRI survey locations with grassland cover on non-federal lands. In addition, carbon stock changes for organic soils (i.e., Histosols) were modeled with a simpler method using CO_2 emission factors as described in (Ogle et al., 2003), which captures the influence of drainage on carbon losses from soils in croplands and grasslands. The changes in litter and biomass C stock changes were not estimated for National Resource Inventory survey locations with organic soils, but these soils are a smaller fraction of the overall land base, that is, less than 1% (EPA, 2023). The estimates for the National Resource Inventory survey locations were aggregated to a 0.625° × 0.5° for 2015 to 2020.

2.2.2. Crop Harvest

Crop yields, which represent the amount of crop biomass removed from the field during harvest events, have been estimated using county-level crop yield data from the USDA—National Agricultural Statistics Service (USDA-NASS, 2020). The following equation was applied to derive the C content of crop yields:

$$Y_C = Y_{\mathrm{NASS}} \times \mathrm{DM} \times \mathrm{C}_f \tag{7}$$

where Y_C is the crop yield, in units of carbon, Y_{NASS} is the annual county-level crop yield data from USDA—NASS, DM is the dry matter content for each crop, and C_f is the carbon content of the crop biomass. We used crop-specific factors for dry matter and carbon content (Ogle et al., 2015; West et al., 2011) to obtain the amount of carbon removed at harvest. Crop yields were estimated for more than 20 crops, which together represented 99% of total US crop production (USDA-NASS, 2020). Uncertainty in estimates for all input data and factors was propagated through a Monte Carlo analysis with 10,000 replicates. The results are based on the mean and 95% confidence intervals from the final distribution of values.

Some of the harvested crop products are disposed in landfills and contribute to the carbon stocks in these waste management systems or are exported to other countries. We calculated and adjusted harvest crop flux ($\mathrm{Harvestcrop}_{\mathrm{adj}}$) to track the subset of harvested crop that is remitted to the atmosphere over a short time frame after lateral movement. Similar to $\mathrm{Harvestwood}_{\mathrm{adj}}$, $\mathrm{Harvestcrop}_{\mathrm{adj}}$ is the portion of carbon that is not contributing to stock changes in landfills ($\mathrm{landfills}_{\text{stock-change}}$) or exported. It is calculated as

$$\mathrm{Harvestcrop}_{\mathrm{adj}} = \text{Harvest crop} - \mathrm{landfills}_{\text{stock}-\text{change}} - \text{net export.} \tag{8}$$

Crop trade and landfill stock changes are described in 2.2.3 and 2.2.7. The carbon in $\mathrm{Harvestcrop}_{\mathrm{adj}}$ can follow several pathways, including biofuel emissions, human and livestock respiration, and the residual emissions from landfills and other losses. Each of these pathways is described in the following subsections.

2.2.3. Crop Trade

National totals were obtained from RECCAP2 (Poulter et al., 2025), which were estimated from FAOSTAT data (Alvarez et al., 2018; Barkley et al., 2021). Due to a lack of state-level estimates, we distribute the national totals to each state in proportion to crop yield.

2.2.4. Crop Biofuel

Biofuel emissions were obtained from the EPA State GHG Emissions and Removals data set (EPA, 2022), representing the combined emissions from ethanol and biodiesel. National level emissions were allocated to states using the percentage of gasoline by state for ethanol and biodiesel in the transportation sector based on Federal Highway Administration data, and the percentage of gasoline by state for ethanol in the commercial and industrial sectors based on State Energy Data System data (Energy Information Administration, 2022).

2.2.5. Human Respiration

Human CO_2 emissions from respiration were estimated by combining data on the distribution of human population and on dietary intake of food. Spatially explicit population density maps from the Global Human Settlement Layer data product (European Commission: Joint Research Centre, 2023) at 30 arc second resolution were used as a source for human population density. To calculate the total caloric intake of the human population, we relied on caloric intake data at the country level from the FAOSTAT database of food security indicators. The FAO database provides information about the total dietary energy requirements (in units of kcal per capita per day) as well as information about the average supply of protein and fat (in units of grams per capita per day). We converted these metrics into an estimate of the total CO_2 emission from humans (in units of grams of carbon per capita per year) according to the following procedure. First, we calculated the dietary carbohydrate intake per capita. We converted the protein and fat supply into energy units by assuming energy densities of 4 kcal per gram and 9 kcal per gram for protein and fat, respectively. Then, we subtracted the daily energy supply calculated for protein and fat from the total daily energy requirement to arrive at the daily carbohydrate energy supply. Finally, we converted the daily carbohydrate energy supply into mass units assuming an energy density of 4 kcal per gram for carbohydrates. To calculate the carbon emissions from the daily mass consumption rate of protein, fat and carbohydrates, we used a carbon content of 0.76, 0.53, and 0.44 for fat, protein and carbohydrates, respectively (Cheng et al., 2017; Rouwenhorst et al., 1991). Finally, to calculate the total carbon emissions from humans, we multiplied the population density (in units of people per m^2) with the sum of the daily carbon consumption from protein, fat and carbohydrates (in units of grams of carbon per capita per day). This implicitly assumes that all food taken up is respired locally to CO_2 either metabolically or after being excreted from the body.

2.2.6. Livestock Respiration

Livestock carbon emissions were estimated at the county level for the CONUS from 2015 to 2020 based on the population of livestock species and a carbon balance of livestock feed intake and carbon outputs (e.g., milk or eggs) and emitted through flatus, enteric fermentation, and manure/excrements, following equations and parameters described in IPCC (2006) (West et al., 2011; Wolf et al., 2015). The mass balance estimates the carbon respired as CO_2 over a given year, excluding changes in carbon stored in livestock mass (Equation 6).

$$\mathrm{LE}_{C-\mathrm{CO2}} = F_C - (P_C + M_C + \mathrm{EF}_{\mathrm{CH4}}), \tag{9}$$

where, $\mathrm{LE}_{C-\mathrm{CO2}}$ is livestock respiration as CO_2, in units of carbon; F_C is feed intake by livestock species corrected by dry matter and C concentration; P_C is carbon content of products (e.g., milk and egg) output; M_C is the carbon content of manure/excrements; and $\mathrm{EF}_{\mathrm{CH4}}$ is carbon emitted in enteric fermentation as CH_4 and flatus.

While animal size changes over time, it was assumed to be constant in our effort (following West et al. (2011) and Wolf et al. (2015)). Annual populations of meat- and milk-producing cattle, meat- and egg-laying poultry, swine, goats, sheep, horses, and mules were obtained from USDA-NASS (2020). We note that county-level data was only available for 2017 following the agricultural census interval. Thus, the population at the state level from 2015 to 2020 annual USDA—NASS surveys was distributed to the county level based on the fraction of each livestock type per county in the 2017 census.

Also, data are only collected during the census for some livestock types (e.g., goats, horses, mules, and turkeys). Data for missing years were gap-filled with linear regressions using data from previous censuses and surrogate data relationships.

2.2.7. Landfill Stock Changes

Complete carbohydrate decomposition of food waste is unlikely to occur due to the presence of lignin (Barlaz, 1998). The residual carbon sequestration from food waste has been examined by Barlaz (1998) and (Staley & Barlaz, 2009). Here, we employ the methods presented in those studies to estimate the sequestration of food waste in landfills. Adapted from Barlaz (1998), we use the equation

$$\mathrm{C}_{\mathrm{seq}} = \mathrm{MSW}_{\mathrm{landfill}} \times F_{\mathrm{food}} \times F_{\mathrm{dry}} \times \mathrm{CSF}_m \tag{10}$$

where, $\mathrm{C}_{\mathrm{seq}}$ is carbon sequestration; $\mathrm{MSW}_{\mathrm{landfill}}$ is the mass of Municipal Solid Waste (MSW) buried in landfills; $\mathrm{F}_{\mathrm{food}}$ is the fraction of $\mathrm{MSW}_{\mathrm{landfill}}$ that is food waste (17.7% from Staley and Barlaz (2009)); F_{dry} is the dry fraction of food waste (30 % from Staley and Barlaz (2009)); CSF_m is the carbon storage factor (0.08 [kg C][dry kg refuse]$^{-1}$) from Barlaz (1998)).

MSW entering landfills is obtained from Table A-203 from Annex 3 of (EPA, 2023). Landfill MSW from 2017 to 2020 was averaged to 213.5 MMT of refuse, and the total MSW landfill between 1940 and 2020 was 13,150 MMT. We calculate the average sequestration over 2017–2020 to be:

$$C_{seq} = (213.5 \times 0.177) \times 0.30 \times 0.08 = 0.91 \text{ Tg C/yr}. \quad (11)$$

and sequestration since 1940 to be:

$$C_{seq} = (13,150 \times 0.177) \times 0.30 \times 0.08 = 55.9 \text{ Tg C}. \quad (12)$$

Due to a lack of state-level estimates, we assume that these residual emissions occur uniformly across the CONUS and calculate area-weighted partitioning for each state.

2.2.8. Residual Crop Emissions

Roughly 31% of food is lost due to food spoilage, plate waste, and other losses (USDA ERS, 2020). These losses occur throughout the lifecycle of agricultural products and are challenging to track directly. Here, we estimated residual emissions due to decomposition of agricultural products as the residual of crop harvest after adjusting for biofuel, trade, and respiration:

$$\text{Residual crop emissions} = \text{Harvestedcrop}_{adj} - \text{crop biofuel} - \text{Human Respiration} \\ - \text{Livestock Respiration} - \text{net crop trade} \quad (13)$$

2.3. Hydrologic-Cycle-Mediated Carbon Budget

Leaching and erosion from ecosystems results in riverine and lake emissions to the atmosphere, burial in terrestrial water bodies, and export to the ocean. All estimates used in this study were obtained from the Second State of the Carbon Cycle Report (SOCCR2) report (Butman et al., 2018). The net carbon burial in lakes and reservoirs (20.6 Tg C $year^{-1}$; 5% and 95%: 9.0, 65.1 Tg C $year^{-1}$) and coastal carbon export from inland waters to coastal waters (41.5 Tg C $year^{-1}$; 5% and 95%: 39.4, 43.5 Tg C $year^{-1}$) need to be considered in relating carbon stock changes to surface-atmosphere fluxes. We distribute the net lateral fluxes uniformly across CONUS. It is part of "other" in Figure 2b. The coastal export component from inland waters does not include any lateral transfers from estuaries, tidal wetlands, or blue carbon ecosystems to the open ocean. We also do not directly estimate carbon fluxes related to groundwater-surface water interactions.

2.4. Fossil Fuel Emissions

Fossil fuel emissions and industrial processes and product use (IPPU) emissions were obtained for the EPA state totals (EPA, 2022).

2.5. Top-Down Surface-Atmosphere Fluxes

Top-down NCE estimates were obtained from the v10 OCO-2 MIP (Byrne et al., 2023). This consists of an ensemble of 11 inversion systems that optimally estimate surface-atmosphere CO_2 fluxes with a top-down inversion approach assimilating atmospheric CO_2 observations. These estimates are performed for a series of experiments that assimilate different combinations of atmospheric CO_2 data, including: an experiment that assimilate in situ CO_2 measurements (IS); an experiment that assimilates OCO-2 land nadir and land glint X_{CO2} retrievals (LNLG); an experiment that assimilates both in situ data and OCO-2 land data (LNLGIS); and an experiment in situ data, OCO-2 land data ad OCO-2 ocean glint data (LNLGOGIS). See Byrne et al. (2023) for additional de tails on these inversion configurations.

3. Results

3.1. Incorporation of Lateral Fluxes to Inventories

The carbon budgets incorporating lateral movement and fluxes for forests, croplands and grasslands, and mediated by the water cycle are shown in Figure 1. The carbon stock change and lateral movements of harvested forest carbon are shown in Figure 1a. The total forest carbon stock change (ΔC_{forest}) is 257 Tg C yr^{-1}, while the lateral movement through harvest is 161 Tg C yr^{-1}, which is about 63% of the magnitude of forest carbon stock change. The annual total carbon uptake by the forest is the sum of carbon stock change and harvest, implying the critical role of accounting for harvest in comparing the inventory and top-down estimates of net carbon uptake. We obtain the adjusted harvest ($Harvest_{adj}$) after subtracting the net export of carbon and stock changes from HWPs within CONUS (Equation 4), which includes products in use and products in SWDS (32 Tg C yr^{-1}). This portion of the adjusted harvest (126 Tg C yr^{-1}) results in no net stock change over CONUS as the carbon is released back to the atmosphere over a short time period. Part of the emissions is through biofuel burning (59 Tg C yr^{-1}). After subtracting this, we have a residual imbalance of 67.7 Tg C $year^{-1}$ between the adjusted harvested carbon and the biofuel emissions, which we assume to be released back to the atmosphere through decomposition or combustion (Equation 5).

Most of the net carbon uptake in agricultural and grassland is harvested and transported to regions outside of where the carbon is absorbed. The annual carbon stock change ($\Delta C_{crop+grass}$) is only 11 Tg C $year^{-1}$, while the harvested carbon is 283 Tg C $year^{-1}$ (Figure 1b), indicating that 96% of annual carbon uptake over agricultural and grassland is lateral transport and released in other regions. Harvested agricultural and grassland carbon has a number of uses (Figure 1b) (Section 2.2). After subtracting the net accumulation in landfills and net exports, we obtain the amount of harvest crop product that is released back to the atmosphere over a short time period over CONUS, which is estimated at 232 Tg C $year^{-1}$. The majority of the adjusted harvest C is re-released to the atmosphere through biofuel combustion (30 Tg C $year^{-1}$) and respiration by humans (27 Tg C $year^{-1}$) or livestock (117 Tg C $year^{-1}$). We assume the residual carbon (58 Tg C $year^{-1}$) not accounted for in biofuel and respiration is lost to the atmosphere through decomposition of litter, as well as losses in transport, handling and processing of harvested biomass.

Water cycle-mediated carbon fluxes, obtained from the SOCCR2 report (Butman et al., 2018), are shown in Figure 1c. The total carbon leached to the water systems is 147 Tg C $year^{-1}$, which has a similar magnitude as forest harvest. Carbon leached from ecosystems is balanced by river and lake emissions (85 Tg C $year^{-1}$) to the atmosphere, coastal export (21 Tg C $year^{-1}$), and a net increase in buried carbon stocks (42 Tg C $year^{-1}$).

3.2. Regional Carbon Budgets

This compilation allows for constructing the complete surface-atmosphere CO_2 flux estimates—termed NCE at a regional level (Table S1 in Supporting Information S1) (Equation 1)—that facilitate direct comparisons with top-down atmospheric CO_2 inversion systems. Figure 2 and Table S1 in Supporting Information S1 show this complete regional carbon budget across CONUS. The annual total emission from FF and IPPU is 1,392 Tg C $year^{-1}$. We find that the integrated carbon stock change (ΔC_{Total}) for CONUS to be 323 Tg C $year^{-1}$, offsetting about 23% of FF emissions. The total change in carbon stocks (ΔC_{Total}) is the sum of ΔC_{forest}, $\Delta C_{grassland}$, $\Delta C_{cropland}$, wood products in use and solid waste disposal sites (PIC and SWDS), landfill stock changes from crops, and aquatic burial of carbon within the CONUS domain (see Table S1 in Supporting Information S1). The largest components of this net flux are 80% forest carbon stock (ΔC_{Forest}) increases, 10% wood products in use and solid waste disposal sites (PIC and SWDS), and 6% lake and river carbon burial (Figure 2a).

Figure 2b summarizes the regional carbon budgets for the National Climate Assessment regions. In Figure 2b, all Crop $harvest_{adj}$, wood $harvest_{adj}$, human and livestock respiration, biofuels, and others belong to the endpoint of the lateral C transfer and have an associated C flux. Wood $harvest_{adj}$ and crop $harvest_{adj}$ are calculated by Equations 4 and 8, respectively. Biofuels include both harvested wood and crops, and "others" include residual emissions from both wood and crops, net trade, and coastal carbon export (Equations 5 and 13). Figure 2b shows that component fluxes have regionally variable magnitudes (Figure 2b). While FF emissions are the largest single component flux for all regions, the second largest component fluxes differ by region. Fossil fuel emissions over the Southeast and Midwest have the largest and second largest magnitude among these seven regions, with 354 Tg C $year^{-1}$ and 311 Tg C $year^{-1}$ respectively. Crop harvests are found to be the second largest lateral movement of C in the Northern Great Plains and Midwest regions. The sum of crop harvests over these two regions represents 70% of total crop harvest in CONUS. ΔC_{Total}, representing the net carbon stock change, is the second largest component flux for all the other regions. Adjusted wood harvests contribute about half of ΔC_{Total} over the Southeast, representing 56% of the total adjusted wood harvest over CONUS. Respiration and biofuel emissions are found to be relatively evenly distributed across CONUS, although biofuel emissions are largest in the southeast.

The sum of lateral carbon fluxes and total carbon stock change represents all the carbon exchange between the atmosphere and land surface except FF emissions, which we call as Net Ecosystem Carbon Balance (Chapin

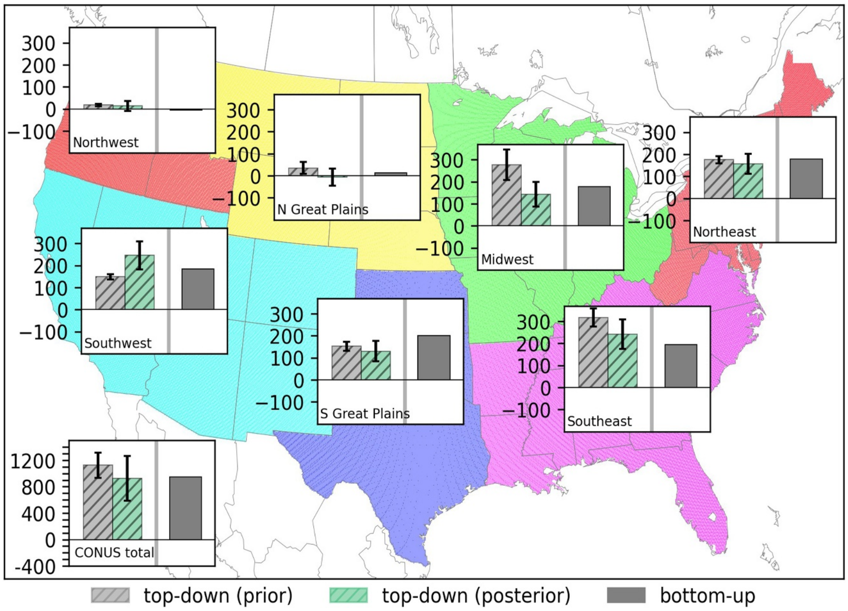

Figure 3. Regional net carbon exchange from the v10 OCO-2 MIP prior (unoptimized) and posterior (optimized) compared with the inventory estimates across U.S. Climate Assessment Regions.

et al., 2006). NCEB offsets FF emissions in all regions except Southwest. In northwest, NCEB has a similar magnitude as FF emissions, indicating that the net ecosystem uptake offsets all the FF emissions over the region. In the Northern Great Plains, the net ecosystem uptake offsets about 70% of FF emissions, while the carbon stock change is only 20% of FF emissions. The absolute ratio between the sum of all lateral carbon fluxes and carbon stock change (ΔC_{total}) ranges from 0.07 in the southeast to 2.6 over the North Great Plains with a mean value of 0.5 (Table S1 in Supporting Information S1), emphasizing the critical role of lateral fluxes in calculating regional carbon budgets and reconciling regional carbon budgets between top-down flux inversions and the inventories.

4. Comparison With Top-Down Estimates

We compare the NCE estimate from the regional inventory data set compiled for this study with top-down constraints provided by the v10 OCO-2 MIP (Byrne et al., 2023). The NCE inventory is calculated as the sum of FF emissions, ΔC_{total}, and the sum of all the lateral movement of carbon (Equation 1 and Table S1 in Supporting Information S1). Figure 3 compares the NCE from inventory estimates with the prior (unoptimized) and posterior NCE optimized by OCO-2 land column-averaged dry-air mole fractions (X_{CO2}) and in situ CO_2 data. Integrated across CONUS, we find that the posterior NCE (925 ± 339 Tg C year^{-1}) shows closer agreement with the inventory estimate (974 Tg C year^{-1}) than the prior (1,124 ± 191 Tg C year^{-1}).

This is the case for the Northwest, Northern Great Plains, Midwest, and Southeast regions, while the prior estimate shows closer agreement for the remaining regions. The largest disagreement between the top-down and inventory estimates is found for the Southwest region. This region experienced both the largest precipitation deficit and warmest temperature anomaly among all regions during 2015–2020 (Section 8.1 and Figure S1 in Supporting Information S1), such that it is possible that the top-down assessment captured a short-term biospheric carbon release that was not included in the inventory. Note that similar results are found for the other v10 OCO-2 MIP experiments assimilating different combinations of satellite and surface observations (Figure S2 in Supporting Information S1). Interestingly, although the statistical significance is limited by the small sample size, we find that the adjustment between the posterior and prior NCE is correlated with the net lateral C movement and associated fluxes across the regions (Figure 4). Lateral carbon fluxes have generally been neglected in the prior flux estimates used in the top-down flux inversions. Typically, prior biosphere-atmosphere fluxes are prescribed as the net ecosystem exchange from a terrestrial biosphere model combined with an estimate of fire emissions. These biosphere models often do not incorporate carbon removals through crop harvests, wood harvests, or water cycle-mediated carbon fluxes. The lateral release through respiration, biofuels and water bodies are also generally

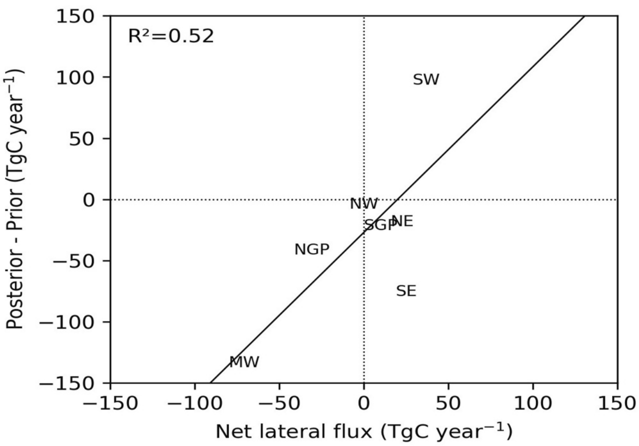

Figure 4. Difference between median posterior (LNLGIS) and prior net carbon exchange from the v10 OCO-2 MIP against the net lateral movement and associated flux for each CONUS region: NW: Northwest, NGP: Northern Great Plains, MW: Midwest, SW: Southwest, SGP: Southern Great Plain, SE: Southeast, and NE: Northeast.

not prescribed in the inversions. The correlation between net lateral movement of C and CO_2 fluxes and the top-down adjustment to the prior suggests that these fluxes may be the first-order correction occurring to annual net fluxes in these inversions.

Accounting for lateral transport and endpoint carbon emissions is essential in reconciling the top-down and inventory estimates at both CONUS and regional scales. Of the 974 Tg C year^{-1} NCE estimate over CONUS from the inventory, trade and coastal export account for 94.7 Tg C year^{-1}. This implies that the inventory NCE estimate would be 1,068.7 Tg C year^{-1} without accounting for the lateral carbon fluxes. It would be closer to the prior fluxes used in the flux inversion, instead of the posterior fluxes constrained by CO_2 observations. At regional scale, accounting for lateral transport is even more critical. For example, in Midwest, the NCE from inventory is 182.5 Tg C year^{-1}, within the uncertainty range of the top-down estimate of 142.5 ± 56.4. However, the NCE from the inventory would be 267.8 Tg C year^{-1} before accounting for lateral transport and endpoint emissions (Table S2 in Supporting Information S1), which is out of bounds of top-down flux inversion estimates. Averaged over the seven regions, accounting for lateral transport and endpoint carbon emissions decreases the mean absolute differences between inventory and top-down estimates from 58.2 Tg C year^{-1} to 40.5 Tg C year^{-1}, improving the consistency between the two types of estimates by 31%.

5. Conclusions and Discussion

To reconcile the regional carbon budget estimates between inventories and top-down flux inversions, we developed a comprehensive regional carbon budget for CONUS, including lateral movement and associated carbon fluxes due to forestry, agriculture, and the water cycle. We find that FF emissions drive net emissions across all regions except the Northwest. Increasing terrestrial carbon stocks counteract these emissions, primarily through increasing forest stocks across CONUS. The net ecosystem uptake over CONUS offsets 30% of FF emissions, but with various magnitudes across regions. The lateral fluxes are found to have significant regional magnitudes. The absolute ratio between lateral carbon fluxes and carbon stock change ranges from 0.07 in southeast to 2.6 over North Great Plains with a mean ratio of 0.5 averaged over the seven regions, reinforcing the importance of these lateral fluxes for carbon budgets (Casas-Ruiz et al., 2023).

We find that the inventory-based NCE reported here compares well with top-down NCE reported by the v10 OCO-2 MIP, after accounting for lateral carbon transport and endpoint emissions. Averaged over the seven regions, the lateral transport reduces the mean absolute differences between inventory and top-down estimates from 58.2 Tg C year^{-1} to 40.5 Tg C year^{-1}, improving the consistency between these two types of estimates by 31%. However, we also identify a correlation between the net regional lateral fluxes and the top-down adjustment in NCE informed by atmospheric CO_2 data. As the impact of lateral fluxes is generally not incorporated into the prior NCE, we suggest that correcting for these lateral fluxes is a significant component of the regional annual net flux updates in the inversions. This motivates future studies to incorporate these lateral fluxes into prior flux estimates for atmospheric CO_2 inversion analyses.

Even for this data-rich analysis for CONUS, there are several key data gaps in reconciling the top-down flux inversion results with inventory estimates at sub-national scale. First, the inventory estimates lack uncertainty quantification for sub-CONUS regions in almost all categories. Only cropland, grassland and forest land C stock changes have uncertainty estimates from a Monte Carlo method. Future research on rigorous uncertainty quantification for other components of the inventory is urgently needed to understand whether the differences between these two estimates are statistically significant. Second, several lateral carbon fluxes lack spatial granularity at subnational scale, such as hydrologic-cycle carbon fluxes and residual emissions. For those fluxes, we distributed them based on some proxy or uniformly across CONUS. In the future, developing lateral carbon fluxes at higher spatial resolution should be a priority. Third, both the wood and crop lateral fluxes had remaining budget imbalances, which were assumed to be missing respiration and combustion CO_2 released back to the atmosphere. This could occur in the form of respiration losses during transport, handling and processing of harvested biomass. However, more research is needed to understand if these sources could explain this missing residual.

Sub-national governments in the United States—such as states, provinces, and cities—are playing an increasingly important role in climate change mitigation by committing to ambitious emission reduction targets and implementing concrete actions. Even in countries where national climate policies formally apply across all provinces or states, developing consistent and transparent carbon budgets at the sub-national level remains essential. As nations and sub-national governments continue to advocate for nature-based climate solutions, comprehensive compilation of sub-national FF emissions and ecosystem system carbon balance provide the basis for tracking mitigation progress, identifying regional disparities, and designing tailored policies that account for local economic structures, energy use, and land management practices. Our study contributes to this effort by presenting a roadmap for reconciling the inventories and top-down atmospheric inversions at sub-national scale, thereby enabling a more robust assessment of progress toward climate targets and strengthening the alignment between local actions and national or global goals.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The Python code used to aggregate data and generate regional fluxes and plots is available at https://github.com/bkabyrne/TopDown_BottomUp_CONUS. The source data are also hosted in the same repository. The final data products used to generate the figures in this paper are archived at https://zenodo.org/records/15338225 (Brendan et al., 2025).

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