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OPINION

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State of the science in reconciling top-down and bottom-up approaches for terrestrial CO_2 budget

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Abstract

Robust estimates of CO_2 budget, CO_2 exchanged between the atmosphere and terrestrial biosphere, are necessary to better understand the role of the terrestrial biosphere in mitigating anthropogenic CO_2 emissions. Over the past decade, this field

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of research has advanced through understanding of the differences and similarities of two fundamentally different approaches: “top-down” atmospheric inversions and “bottom-up” biosphere models. Since the first studies were undertaken, these approaches have shown an increasing level of agreement, but disagreements in some regions still persist, in part because they do not estimate the same quantity of atmosphere–biosphere CO_2 exchange. Here, we conducted a thorough comparison of CO_2 budgets at multiple scales and from multiple methods to assess the current state of the science in estimating CO_2 budgets. Our set of atmospheric inversions and biosphere models, which were adjusted for a consistent flux definition, showed a high level of agreement for global and hemispheric CO_2 budgets in the 2000s. Regionally, improved agreement in CO_2 budgets was notable for North America and Southeast Asia. However, large gaps between the two methods remained in East Asia and South America. In other regions, Europe, boreal Asia, Africa, South Asia, and Oceania, it was difficult to determine whether those regions act as a net sink or source because of the large spread in estimates from atmospheric inversions. These results highlight two research directions to improve the robustness of CO_2 budgets: (a) to increase representation of processes in biosphere models that could contribute to fill the budget gaps, such as forest regrowth and forest degradation; and (b) to reduce sink–source compensation between regions (dipoles) in atmospheric inversion so that their estimates become more comparable. Advancements on both research areas will increase the level of agreement between the top-down and bottom-up approaches and yield more robust knowledge of regional CO_2 budgets.

KEYWORDS
atmospheric inversion, biosphere model, carbon stock change, CO_2 evasion, land-use change emissions, net CO_2 flux, residual land uptake, riverine carbon export, terrestrial CO_2 budget

1 | INTRODUCTION

Understanding the mitigation potential of the terrestrial biosphere against anthropogenic CO_2 emissions hinges upon accurate assessment of the net atmosphere–land CO_2 flux (net CO_2 flux, − for a net sink and + for a net source). Our ability to diagnose CO_2 sink–source patterns of the net CO_2 flux has progressed owing to the development of “top-down” atmospheric inversions (Peylin et al., 2013; Thompson et al., 2016) and “bottom-up” biosphere models (Sitch et al., 2008, 2015). Compared with early studies that varied by more than 3.0 Pg C/year in their estimates of northern and tropical CO_2 fluxes (e.g., Gurney et al., 2002; Jacobson, Fletcher, Gruber, Sarmiento, & Gloor, 2007; Peylin, Baker, Sarmiento, Ciais, & Bousquet, 2002; Rödenbeck, Houweling, Gloor, & Heimann, 2003), net CO_2 fluxes by current atmospheric inversions are converging around a sink of 1.0–2.0 Pg C/year in northern extratropical (NE) lands and a small net flux in southern tropical (ST) lands, due to improvements in the transport processes modeling and abundance of aircraft and vessel observations, along with improved in situ CO_2 observation networks (Gaubert et al., 2019; Stephens et al., 2007). Likewise, net CO_2 fluxes simulated by biosphere models have become roughly consistent with this pattern, especially in ST lands, due to the offset of land-use change (LUC) emissions with enhanced CO_2 uptake by the stimulating effect of rising atmospheric CO_2 on plant photosynthesis (Schimel, Stephens, & Fisher, 2015). However, disagreements in the CO_2 budgets between top-down and bottom-up approaches remain nontrivial at regional scales (Cervarich et al., 2016; Ciais et al., 2013; Kondo, Ichii, Takagi, & Sasakawa, 2015). In the fifth assessment report of Intergovernmental Panel on Climate Change (IPCC AR5), the sign and magnitude of regional CO_2 budget estimates were still contradictory between atmospheric inversions and biosphere models for some regions (Ciais et al., 2013).

These previous syntheses highlight the challenges of reconciling the top-down and bottom-up approaches and the importance of spatial scale in evaluating agreement and uncertainties. When comparing CO_2 budgets of multiple methods, understanding the definition of the net CO_2 flux and associated component fluxes that are included in developing the CO_2 budgets become increasingly important because these could lead to either a “total” or “partial” exchange of CO_2 between the atmosphere and land depending on the methods employed. The former applies to methods that use atmospheric CO_2 concentrations as a basis for estimation such as atmospheric inversions

(Peylin et al., 2013). The latter applies to methods that account for known processes in the carbon cycle interacting with the biosphere such as biosphere models (Sitch et al., 2015). Major terms that cause challenges in comparing atmospheric inversions and biosphere models at the time of the IPCC AR5 can be: (a) hydrosphere fluxes, such as lateral riverine carbon export and CO_2 evasion from rivers and lakes, included in atmospheric inversions, but not simulated in biosphere models; and (b) the incomplete representation of CO_2 fluxes from land-use and management in biosphere models. Mitigating these differences in terminology will advance our understanding of net CO_2 flux at regional scales which so far has remained unresolved.

To address the current state of our knowledge on terrestrial CO_2 budgets and the level of reconciliation between current modeling methods, CO_2 budget assessments at global, hemispheric, and regional scales need to be reanalyzed with consistent datasets and definitions of the component fluxes that determine net CO_2 flux. Based on the net CO_2 flux defined as "the atmosphere–biosphere CO_2 exchange" (excluding hydrosphere fluxes), we investigate net CO_2 fluxes estimated for the decade of 2000s (2000–2009) using fluxes adjusted around a consistent definition of the CO_2 exchange. These are compared with reproduced results of the IPCC AR5 obtained using inconsistent definitions, to determine how definitions play a role in reconciliation between the modeling methods. Aimed at serving as a useful reference, this study provides a thorough comparison between atmospheric inversions and biosphere models, and also among other existing estimates of global and regional CO_2 budgets based on forest inventories, remote sensing, atmospheric O_2 measurements, the residuals from non-terrestrial components of global CO_2 budgets, and previous regional budget assessments from the REgional Carbon Cycle Assessment and Processes (RECCAP; Canadell et al., 2011). Through these comparisons, we highlight potential difficulties faced by current CO_2 budget assessments, and suggest ways forward to increase the level of agreement between top-down and bottom-up approaches yielding more robust knowledge of CO_2 budgets.

2 | MATERIALS AND METHODS

2.1 | Definition of net CO_2 flux

We define the net CO_2 flux as the "atmosphere–biosphere CO_2 exchange," comprising components such as photosynthesis, autotrophic

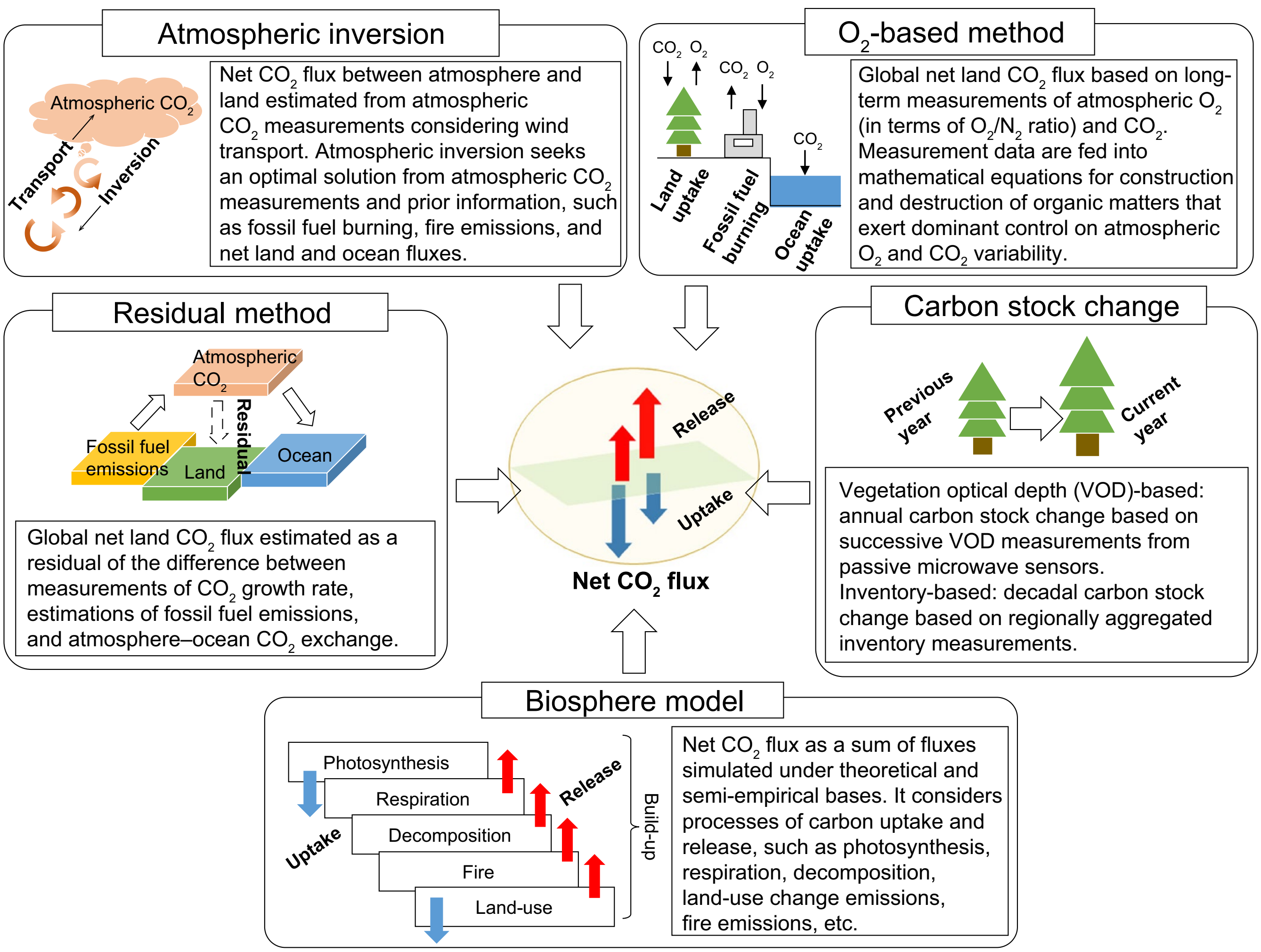

FIGURE 1 Methods of terrestrial net CO_2 flux estimation

TABLE 1 Configuration of the atmospheric CO_2 inversion systems used in this study

Inversion system (in-text abbreviation)	No. of regions	Time period	IAV prior	No. of observations	Transport model
ACTM (ACTM)	84	1990–2011	Yes: FF, LA No: SA	73 (GLOBALVIEW)	JAMSTEC's Atmospheric Chemistry-Transport Model (ACTM)
MIROC4-ACTM (MACTM)	84	1996–2015	Yes: FF, LA No: SA	42 sites (NOAA ESRL ObsPack and JMA)	Updated ACTM with MIROC4-ESM
CAMS v18r1 (CAMS)	Grid cells (3.75° × 2.5°)	1979–2015	Yes: FF No: BB, LA, SA	81 (NOAA ESRL ObsPack)	Tracer Transport Model version 5 (TM5)
CCAM (CCAM)	94 land, 52 ocean	1993–2012	Yes: FF No: LA, SA	69 (GLOBALVIEW)	CSIRO Conformal-cubic Atmospheric Model (CCAM)
Carbon Tracker2017 (CT2017)	Grid cells (1.0° × 1.0°)	2000–2016	Yes: FF, BB, LA, SA	254 (from 55 institutions)	Tracer Transport Model version 5 (TM5)
GELCA_CAO (GELCA CAO)	Grid cells (1.0° × 1.0°)	2000–2013	Yes: FF, BB. LA, SA	NOAA ESRL ObsPack	Coupled GELCA-NIES 08.1 Eulerian model
JENA s93_v4.2 (JENA s93)	Grid-cells (about 4.0° × 5.0°)	1993–2016	Yes: FF No: LA, SA	35 (from various institutions)	Tracer Transport Model version 3 (TM3)
JMA2018 (JMA)	22	1985–2016	Yes: FF, SA No: LA	88 (WDCGG) 16 (aircraft observations), 59 (vessel observations)	JMA atmospheric transport model (based on JMA global weather forecasting model)

Abbreviations: BB, biomass burning emission; FF, fossil fuel emission; IAV, interannual variability; LA, land–air CO_2 exchange; SA, sea–air CO_2 exchange.

and heterotrophic respirations, fire emissions, and CO_2 fluxes associated with land-use and land-cover changes. Adjustments based on the proposed definition of net CO_2 flux were applied to the methods described herein where relevant (Figure 1; spatial and temporal applicability of the methods is shown in Table S1). Biosphere models comply with this definition, as they consider numerous processes of atmosphere–land biogeochemistry, including LUC fluxes in the latest development (Le Quéré, Andrew, Friedlingstein, Sitch, Pongratz, et al., 2018). A method based on carbon stock changes from the compilation of forest inventories (ΔC_{IM}; Pan et al., 2011) also complies with this definition. The vegetation optical depth (VOD) derived from passive microwave sensors (e.g., Liu et al., 2015) is only applicable to aboveground vegetation, but can be supplemented by inventories of missing belowground components to represent the total stock change (ΔC_{VOD}). Methods that consider interactions beyond those with the biosphere, such as atmospheric inversions, and global land uptake assessments based on a residual of non-terrestrial components of global CO_2 budgets (residual method; Le Quéré, Andrew, Friedlingstein, Sitch, Pongratz, et al., 2018) and based on decadal O_2 and CO_2 trends in the atmosphere (O_2-based method; Keeling & Manning, 2014) can roughly comply with the proposed definition when the hydrosphere fluxes are excluded from their budget estimates, as we discuss further in this paper.

2.2 | Independent methods of estimating net CO_2 flux

2.2.1 | Atmospheric inversions

The net CO_2 flux from atmospheric inversions was represented by eight inversions (Table 1). These inversions estimate net CO_2 flux through the assimilation of continuous or discrete atmospheric CO_2 measurements from global networks (e.g., World Data Centre for Greenhouse Gases; and the observation package from the NOAA Earth System Research Laboratory) in transport model, with prior information (e.g., net land flux, net ocean flux, fire emissions, and fossil fuel emissions). The choices of CO_2 measurements and prior fluxes differ for each inversion system, as well as the spatial resolution and period of inverted fluxes (Table 1).

For each inversion, posterior land flux was adjusted by the difference between the respective fossil fuel emissions prescribed in

Meteorology	Prior fluxes: Land	Ocean	Biomass burning	Fossil fuel emissions	Reference
NCEP	Three-hourly flux from CASA	Monthly flux from the LDEO (Takahashi) surface *p*CO_2 database	—	EDGAR v4.2 rescaled global total to CDIAC	Saeki and Patra (2017)
JRA-55	Three-hourly flux from CASA	Monthly flux from the LDEO	—	EDGAR v4.3.2	Patra et al. (2018), Le Quéré, Andrew, Friedlingstein, Sitch, Hauck, et al. (2018)
ECMWF	Three-hourly flux from ORCHIDEE	Monthly flux from the LDEO (Takahashi) surface *p*CO_2 database	GFAS	EDGAR v4.2 rescaled global total to CDIAC	Chevallier et al. (2010)
NCEP	Monthly flux from CASA	Monthly flux from the LDEO (Takahashi) surface pCO_2 database	—	EDGAR v4.2 rescaled regionally to CDIAC	McGregor and Dix (2008)
ECMWF and ERA	Monthly CASA flux downscaled to 90 min flux	Ocean inversion fluxes and monthly flux from the LDEO surface *p*CO_2 database	GFED4.1s and GFED_CMS	ODIAC2016 and Miller emissions datasets	Peters et al. (2007)
JCDAS	Daily flux from VISIT	Monthly flux from 4D-var + OTTM based on *p*CO_2 data	GFED	ODIAC	Zhuravlev, Khattatov, Kiryushov, and Maksyutov (2011)
NCEP	Zero values	Monthly climatological flux based on an interpolation of *p*CO_2 data	—	Monthly values from CDIAC	Rödenbeck, Zaehle, Keeling, and Heimann (2018)
JRA-55	Monthly flux from CASA	Monthly flux from the JMA (Iida et al., 2015)	—	CDIAC2016 rescaled global total to Global Carbon Budget (2017v1.2)	Update of Maki et al. (2010)

the inversion and a reference emission estimate. This "fossil fuel adjustment" is a necessary procedure for reducing variability in posterior fluxes, as differences in prescribed fossil fuel emissions largely affect posterior fluxes (Peylin et al., 2013), especially for recent periods for which the uncertainty in fossil fuel emissions remains large (Ballantyne et al., 2015). We applied the fossil fuel adjustment using the emission dataset prescribed in Atmospheric Chemistry-Transport Model (Table 1), showing a central tendency of global interannual variability (IAV) among inversions, as the reference emission.

2.2.2 | Biosphere models

Simulations from TRENDY v6 (Le Quéré, Andrew, Friedlingstein, Sitch, Pongratz, et al., 2018) represent the net CO_2 flux from the biosphere models of this study (Table 2). These simulations were prepared with a consistent forcing dataset: global atmospheric CO_2 concentrations for 1860–2016 based on ice core measurements and stationary observations from NOAA, a gridded climate dataset (CRU-NCEP v8) for 1901–2016 (Viovy, 2018), and a gridded annual land-use and land-cover change dataset for 1860–2016 (Hurtt et al., 2017; Klein Goldewijk, Beusen, Doelman, & Stehfest, 2017). The TRENDY models carried out three types of simulations: S1 that used varied atmospheric CO_2, fixed climate (1901–1920), and fixed land-use and land-cover (1860), S2 that used varied CO_2 and climate (with fixed land-use and land-cover at 1860), and S3 that varied all three drivers. For each simulation, the models first established an equilibrium carbon balance by a spin-up run, forced with the 1860 CO_2 concentration (287.14 ppm), recycling climate variability from 1901 to 1920, and constant 1860 crop and pasture distributions.

Attributes of the net CO_2 flux (i.e., the effects of CO_2, climate, and LUC) were extracted by separating flux signals in the S1, S2, and S3 simulations (Friedlingstein et al., 2006). The net CO_2 flux of S3 represented the estimate most closely matching observations, including the interactions between CO_2, climate, and LUC effects on the ecosystem carbon cycling. Those from S1 and S2 represented partial contributions to the net CO_2 flux, isolating the CO_2 effect and CO_2 + climate effects on the net CO_2 flux, respectively. The LUC effect on the net CO_2 flux was extracted by subtracting estimates of S2 from that of S3. Similarly, the effect

TABLE 2 Configuration of the TRENDY models used in this study

					Land-use change scheme					
Biosphere model	Spatial resolution	Carbon–nitrogen coupling	Fire simulation (including peat fire)	Age class	Distinction between primary and secondary lands	Wood harvest	Shifting cultivation	Crop harvest (crop species: C, managed grassland: G)	Degradation	Reference
CABLE	0.5° × 0.5°	Yes	No	Yes	Yes	Yes	Yes	Yes: G	No	Haverd et al. (2018)
CLM	1.9° × 2.5°	Yes	Yes (yes)	No	Yes	Yes	Yes	Yes: G	No	Oleson et al. (2013)
DLEM	0.5° × 0.5	Yes	No	No	Yes	Yes	No	Yes: G	No	Tian et al. (2015)
ISAM	0.5° × 0.5°	Yes	No	No	Yes	Yes	No	Yes: G	No	Jain, Meiyappan, Song, and House (2013)
LPJ-GUESS	0.5° × 0.5°	Yes	Yes (no)	No	Yes	Yes	Yes	Yes: C	No	Smith et al. (2014)
LPJ-wsl	0.5° × 0.5°	No	Yes (no)	No	Yes	No	No	Yes: G	No	Sitch et al. (2003)
LPX-Bern	1.0° × 1.0°	Yes	Yes (no)	No	No	No	No	Yes: G	No	Keller et al. (2017)
ORCHIDEE	0.5° × 0.5°	No	No	No	Yes	Yes	No	Yes: G	No	Krinner et al. (2005)
ORCHIDEE-MICT	1.0° × 1.0°	No	Yes (no)	No	Yes	No	No	Yes: C	No	Guimberteau et al. (2018)
VISIT	0.5° × 0.5°	No	Yes (no)	No	Yes	Yes	Yes	Yes: G	No	Kato, Kinoshita, Ito, Kawamiya, and Yamagata (2013)

of climate was extracted by subtracting the net CO_2 flux of S1 from that of S2.

2.2.3 | Carbon stock changes, O_2-based method, residual method, and RECCAP

Inventory-based carbon stock changes (ΔC_{IM}) were estimated by incorporating information on forest area and biomass density obtained from (a) United Nations Global Forest Resources Assessment reports (Food & Agriculture Organization, 2006, 2010); (b) deforestation and afforestation estimates from a book-keeping model (Houghton, 2007); and (c) the observed carbon pools for regions around the globe. From these datasets, the sums of carbon stocks for intact and regrowth forests and soil carbon for 2000 and 2007 were used to calculate regional carbon stock changes (Pan et al., 2011), except for South Asia where a missing estimate was supplemented by inventory and forest area data for 1992–2002 from Kaula, Dadhwal, and Mohren (2009). To estimate VOD-based carbon stock change (ΔC_{VOD}) for the 2000s, we used the satellite-derived gridded aboveground biomass from Global Aboveground Biomass Carbon v1.0 (Liu et al., 2015). The VOD-based aboveground biomass is estimated based on an empirical relationship between the gridded aboveground biomass for tropical regions (Saatchi et al., 2011) and harmonized passive microwave observations. VOD only measures aboveground backscatter; therefore, belowground biomass was estimated as a constant fraction of the estimated aboveground biomass (Liu et al., 2015). To provide more reliable estimates, we replaced this belowground biomass of ΔC_{VOD} with the data used for ΔC_{IM}.

The O_2-based method provides a mean annual global CO_2 budget for the land and ocean based on destructive and constructive O_2 and CO_2 processes (Keeling & Manning, 2014). This approach utilizes long-term measurements of CO_2 and the O_2/N_2 molar ratio between a sample and a reference, expressed as $\delta(O_2/N_2)$, as changes in the global mean molar fraction of CO_2 and $\delta(O_2/N_2)$ are related to the net sources and sinks of CO_2, O_2, and N_2 in the atmosphere. The budget used in this study was estimated for 2000–2010 by Keeling and Manning (2014). The residual method from the Global Carbon Project (Le Quéré, Andrew, Friedlingstein, Sitch, Pongratz, et al., 2018) provided the global annual budget of land CO_2 uptake calculated as the difference between the other terms in the global carbon budget, that is, fossil fuel emissions minus the CO_2 growth rate and the net ocean uptake simulated by biogeochemical models. The budget of this method for the 2000s was calculated using the data of Le Quéré, Andrew, Friedlingstein, Sitch, Pongratz, et al. (2018). The RECCAP project quantified regional anthropogenic and biogenic CO_2 budgets by integrating CO_2 fluxes from multiple independent approaches, including biosphere models, atmospheric inversions, and inventories (Canadell et al., 2011). Based on the available major and minor fluxes and through consideration of the reliability of each of the fluxes, the regional CO_2 budget was estimated for global regions. The regional budgets used in this study were from recalculated estimates based on the RECCAP studies in Li et al. (2016).

2.3 | Adjustments for the atmosphere–biosphere CO_2 exchange estimation

To yield the atmosphere–biosphere CO_2 exchange, global gridded data of lateral riverine carbon export and CO_2 evasion from rivers and lakes were used to remove the hydrosphere components from the fossil fuel-adjusted CO_2 budgets of the atmospheric inversions. Global lateral riverine carbon including dissolved organic and inorganic carbon (DOC and DIC, respectively) was obtained from the multiform model of nutrient exports by NEWS 2 (Mayorga et al., 2010). Global river CO_2 evasion was derived from the empirical river water pCO_2 model and global maps of stream surface area and gas exchange velocities (Lauerwald, Laruelle, Hartmann, Ciais, & Regnier, 2015). Global lake CO_2 evasion was estimated based on lake pCO_2, total lake/reservoir surface area, and total CO_2 evasions for 231 coastal regions (Raymond et al., 2013), subsequently downscaled to a continuous grid scale via the Global Lakes and Wetland Database (Zscheischler et al., 2017).

These data were also used to derive the atmosphere–biosphere CO_2 exchange for the O_2-based method and RECCAP. The O_2-based method and RECCAP account for lateral riverine exports as a part of the land biosphere flux. Thus, we excluded annual riverine DOC and DIC fluxes from the global budget estimates of both methods using the data described above. Global CO_2 uptake by the residual method includes only riverine carbon exports due to anthropogenic perturbations (Le Quéré, Andrew, Friedlingstein, Sitch, Hauck, et al., 2018). To remove that flux from the residual method, an estimate of the anthropogenic component of river flux from Regnier et al. (2013) was used.

2.4 | A constraint for the global budget

Owing to atmospheric observations, the CO_2 budget at the global scale is the best understood among those at other scales (Le Quéré, Andrew, Friedlingstein, Sitch, Pongratz, et al., 2018). To analyze CO_2 budgets at multiple scales, it is important to have consistent global CO_2 budgets so that results of hemispheric and regional budgets would not be misinterpreted due to outliers of global budget estimates. Therefore, we defined a criterion, based on the global CO_2 budget from the residual method and ±1.0 Pg C/year uncertainties, to constrain global CO_2 budgets from the top-down and bottom-up models for the 2000s. All eight atmospheric inversions of this study satisfied this criterion, since the atmospheric CO_2 growth rate was used to constraint atmospheric inversions. As for biosphere models, among the TRENDY models that provided net CO_2 fluxes of all three experiments, 10 models satisfied this criterion (Table 2).

3 | GLOBAL AND HEMISPHERIC BUDGETS

To articulate differences from results of the IPCC AR5, we compared experiments from TRENDY (S2: not including time-varying LUC simulation, and S3: including time-varying LUC simulation), and atmospheric inversions before (INV) and after correcting for the hydrosphere components (INV_{AB} denotes inversions adjusted for the atmosphere–biosphere CO_2 exchange). TRENDY S3 and INV_{AB} represented "best estimates" of the net CO_2 flux, and TRENDY S2 and INV represented estimates reproduced using the IPCC AR5 configuration (Figure 2). As illustrated in Figure 3a, global CO_2 budgets by TRENDY S2 (−2.6 [−2.9, −2.1] Pg C/year: medians [lower, upper quartiles]) and INV (−2.3 [−2.5, −1.7] Pg C/year) largely overestimated the amount of CO_2 uptake compared with other independent estimates: ΔC_{VOD} (−1.2 Pg C/year), ΔC_{IM} (−1.2 Pg C/year), the residual method (−0.9 Pg C/year), O_2-based method (−0.7 Pg C/year), and RECCAP (−1.3 ± 0.6 Pg C/year, mean ± 1σ). This overestimated CO_2 uptake is likely a consequence of missing and excess components needed to satisfy the net CO_2 flux definition. Meanwhile, upward shifts in the net CO_2 flux caused by accounting for LUC emissions in the biosphere models and discounting the hydrosphere fluxes in the atmospheric inversions led to a close agreement in global CO_2 budgets with respect to the other independent estimates and with each other, where TRENDY S3 estimated −0.9 [−1.4, −0.8] Pg C/year and INV_{AB} estimated −0.9 [−1.2, −0.4] Pg C/year (Figure 3a; IAV shown in Figure S1).

The global CO_2 budget largely consists of fluxes from northern boreal-temperate and pantropical ecosystems, with the former accounting for a large part of the global sink and the latter for a large part of the global LUC emissions (Ciais et al., 2019; Le Quéré, Andrew, Friedlingstein, Sitch, Hauck, et al., 2018). That is, the well-constrained global CO_2 budgets among the methods should accompany a consistent budget partitioning between those regions. To evaluate this aspect, we applied the so-called "diver down" plot of Schimel et al. (2015) to better understand global CO_2 budget partitioning into NE and ST lands (Figure 3b,c). The reproduced IPCC AR5 results (TRENDY S2 and INV) exhibited limited overlap with each other (Figure 3b). INV produced relatively strong sinks of −1.2 to −2.5 Pg C/year in NE and a small net flux in ST lands. With the absence of LUC emissions, TRENDY S2 resulted in a net sink for both NE and ST lands, spanning approximately −1.0 to −2.0 Pg C/year. Including simulated LUC fluxes in biosphere models and removing the hydrosphere fluxes from atmospheric inversions shifted the NE and ST land fluxes of the two methods toward a reduced sink or net source, leading to an overlap between TRENDY S3 and INV_{AB} (Figure 3c; IAV shown in Figure S2) and with ΔC_{VOD}, ΔC_{IM}, and RECCAP (Figure 3c). However, agreements between TRENDY S3 and INV_{AB} are not yet robust, as the distribution of INV_{AB} leans more toward a net sink in NE lands (−2.2 to −0.7 Pg C/year) and a net source in ST lands (−0.4 to 1.0 Pg C/year) than that of TRENDY S3: −2.0 to −0.5 Pg C/year in NE and −1.1 to 0.6 Pg C/year in ST lands.

Figure 3c illustrates the results only of the net balance of CO_2 fluxes. To gain confidence in the overlapping pattern between the two methods, it is necessary to understand changes in the patterns of sinks and sources induced by the major processes governing

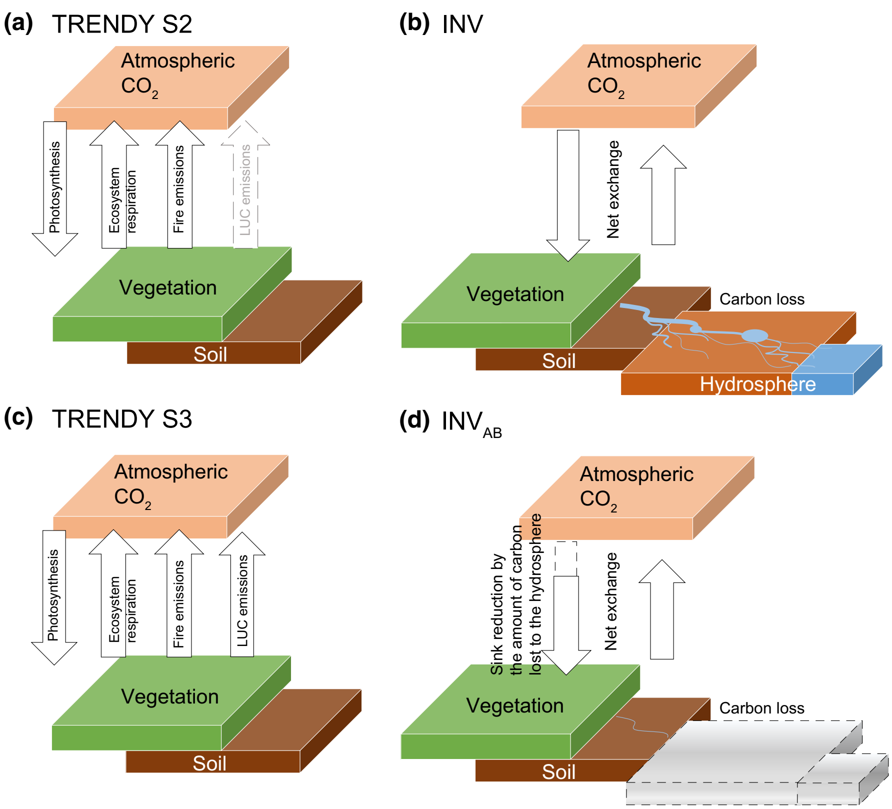

FIGURE 2 Differences in definition of the net CO_2 flux. Schematics show the components of the net CO_2 flux considered in: (a) TRENDY S2 (biosphere models without land-use change [LUC]), (b) INV (atmospheric inversions including hydrospheric components), (c) TRENDY S3 (biosphere models including LUC), and (d) INV_{AB} (atmospheric inversions excluding hydrospheric components)

the net CO_2 flux. The effect of increasing CO_2 concentration on photosynthesis (the CO_2 effect) is considered the dominant driver of current terrestrial CO_2 uptake (Keenan et al., 2016; Keenan & Williams, 2018; Kondo, Ichii, Patra, Poulter, et al., 2018; Schimel et al., 2015), and LUC activities (the LUC effect) are the major net emissions source from ecosystems to the atmosphere (Arneth et al., 2017; Kondo, Ichii, Patra, Canadell, et al., 2018). The net CO_2 flux of TRENDY S3 decomposed into three attributes confirms that the CO_2 and LUC effects are the major sink and source components in NE and ST lands, respectively (Figure 4a). However, the climate effect should not be overlooked, as it induces substantial changes in sink–source patterns during El Niño and La Niña phases, especially in ST lands (Figure 4a). Importantly, the overlap between TRENDY S3 and INV_{AB} holds not only for the decadal mean (Figure 3c) but also for the El Niño and La Niña phases during the 2000s (Figure 4b; IAV and seasonality of ST land fluxes shown in Figure S3), indicating that large-scale flux changes in response to El Niño-Southern Oscillation are similar in the atmospheric inversions and biosphere models.

4 | REGIONAL BUDGETS

We further partitioned hemispheric budgets into nine regions. Regional CO_2 budgets were overall comparable between TRENDY S3 and INV_{AB}, but the degree of agreement differed by region (Figure 5; IAV shown in Figure S4). Among the nine regions, the ranges of budget estimates were proximate among INV_{AB}, TRENDY S3, and the other independent estimates for North America and Southeast Asia. A notable improvement was identified in Southeast Asia, where reduced CO_2 sinks by accounting for LUC fluxes in biosphere models and discounting for the hydrosphere fluxes from atmospheric inversions resulted in close agreement between INV_{AB} (0.01 [−0.04, 0.20] Pg C/year) and

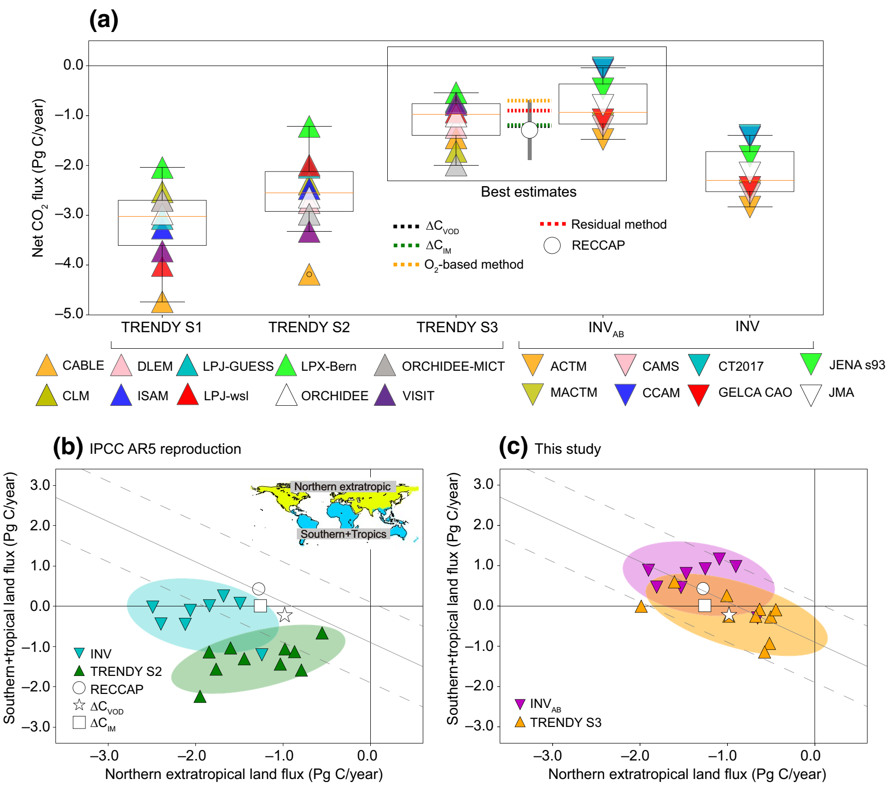

FIGURE 3 Improved agreement of global and hemispheric net CO_2 flux estimates over the IPCC AR5. (a) Global CO_2 budgets for the 2000s from the biosphere models (upper triangles), atmospheric inversions (lower triangles), carbon stock changes: ΔC_{VOD} (black dashed line) and ΔC_{IM} (green dashed line), O_2-based method (yellow dashed line), residual method (red dashed line), and estimates from the REgional Carbon Cycle Assessment and Processes (RECCAP) project (circle representing the mean value and bar representing the 1σ uncertainty). Box plots are shown for the biosphere models (three TRENDY simulations, S1, S2, and S3) and atmospheric inversions (INV and INV_{AB}). Partitioning of the global CO_2 budget into northern extratropical (NE) and southern tropical (ST) lands (diver-down plot) for (b) TRENDY S2 and INV (IPCC AR5 reproduction), and (c) TRENDY S3 and INV_{AB} (results from this study). Gray lines are the constraint on global CO_2 budgets represented by the global budget estimate from the residual method, with ±1.0 Pg C/year uncertainty. Results that fall within the constraints are combinations of NE and ST land budgets that preserve the reference value of global CO_2 budget. Individual model estimates and error ellipse of 2σ range are shown for TRENDY S2 and S3 (green and orange upper triangles, respectively), and INV and INV_{AB} (cyan and purple lower triangles, respectively), along with the independent estimates from carbon stock changes: ΔC_{VOD} and ΔC_{IM} (star and square, respectively) and estimate from the RECCAP project (circle representing the mean value)

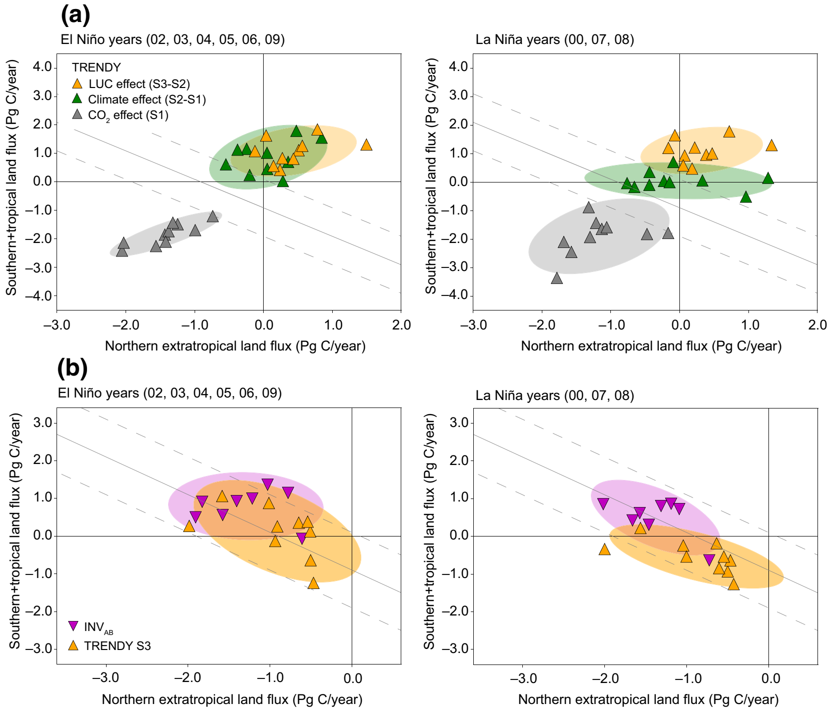

FIGURE 4 Patterns of global CO_2 budget partitioned into hemispheres under El Niño-Southern Oscillation (ENSO) variability. Partitioning of global CO_2 budget into northern extratropical and southern tropical lands (diver-down plots), during El Niño years (2002, 2003, 2004, 2005, 2006, and 2009) and La Niña years (2000, 2007, and 2008) are shown for: (a) each attribute of the net CO_2 flux by TRENDY S3, CO_2 effect (TRENDY S1: gray upper triangles), climate effect (TRENDY S2–S1: green upper triangles), and land-use change (LUC) effect (TRENDY S3–S2: orange upper triangles) and (b) the net CO_2 fluxes of INV_{AB} and TRENDY S3. El Niño years are the years that have 6 month averaged Multivariate ENSO Index (MEI) values >0.5 within a year, and La Niña years are the years that have MEI values <−0.5 within a year. Gray lines represent the global budget constraint and ±1.0 Pg C/year uncertainty same as in Figure 3c

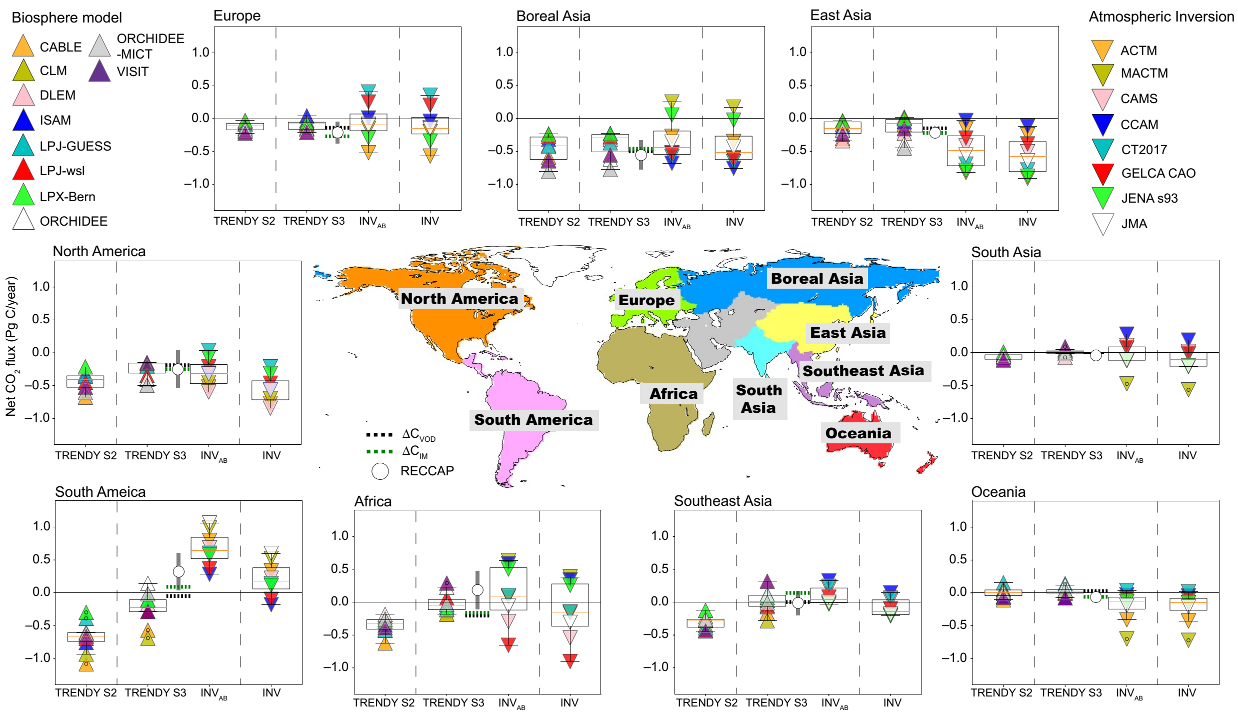

FIGURE 5 Consistency and inconsistency among the estimates of regional CO_2 budgets. Regional CO_2 budgets for the 2000s by the biosphere models (TRENDY S2 and S3) and atmospheric inversions (INV and INV_{AB}), carbon stock changes (ΔC_{VOD} and ΔC_{IM}), and REgional Carbon Cycle Assessment and Processes (RECCAP) project. Regional classification is based on the RECCAP studies. Colors and symbols are the same as in Figure 3a

TRENDY S3 (−0.01 [−0.06, 0.10] Pg C/year). Budget estimates for Europe, boreal Asia, Africa, South Asia, and Oceania overlapped, but with a larger range in INV_{AB} than in TRENDY S3 (Figure 5). In Africa, adjustments for the missing and excess fluxes in the two modeling methods seemingly mitigated the gap between median INV and TRENDY S2 values; however, a range >1.0 Pg C/year in the individual estimates of INV_{AB} rendered comparison with TRENDY S3 difficult.

Budget estimates for East Asia and South America showed notable differences between INV_{AB} and TRENDY S3 (Figure 5). In East Asia, the budget estimates by both INV_{AB} and TRENDY S3 indicated a net sink, but INV_{AB} (−0.5 [−0.7, −0.3] Pg C/year) leaned toward a greater net sink than TRENDY S3 (−0.07 [−0.20, −0.01] Pg C/year). In South America, INV_{AB} leaned toward a net source contrary to the net sink indicated by TRENDY S3. The gap in South America was the most notable, with budget estimates barely overlapping between INV_{AB} (0.6 [0.5, 0.8] Pg C/year) and TRENDY S3 (−0.2 [−0.3, −0.1] Pg C/year). In this region, the flux adjustments did not reduce the gap in budgets. Importantly, these differences explained the minor deviation in the distributions of global budget partitioning into hemispheres between INV_{AB} and TRENDY S3 (Figure 3c). The differences between budget estimates for East Asia are largely responsible for INV_{AB} indicating a stronger net sink in NE lands than TRENDY S3. Likewise, the differences in the estimates for South America are responsible for the INV_{AB} indicating a stronger net source in ST lands than those of TRENDY S3. Thus, East Asia and South America are the regions where future model improvements are needed to generate CO_2 budgets that agree at the hemispheric and regional scales.

So far, we evaluated the regional CO_2 budgets in terms of the average patterns of the atmospheric inversions and biosphere models. However, to derive robust budget agreements for all regions, the means by which individual models partitioned hemispheric budgets into the nine regions must be further investigated. Contrary to the consistent pattern found in the global budget partitioning, individual INV_{AB} results showed largely different patterns for the partitioning of NE and ST land budgets (Figure 6a). Some inversions showed a greater net source or reduced sink in Europe, corresponding to a greater net sink in boreal Asia, while others showed the opposite pattern between these two regions. This sink–source compensation was also identified between boreal Asia and East Asia, East Asia and South Asia, and South America and Africa, with large variabilities in their patterns. These results suggest that differences in the sink–source compensation are likely the major factor responsible for the large range found in regional budget estimates by INV_{AB} (Figure 5). Although the magnitudes of budgets differed, the pattern of NE and ST land budget partitioning was overall similar among the models of TRENDY S3 (Figure 6b). Additionally, ΔC_{VOD}, ΔC_{IM}, and RECCAP showed close agreements in their patterns of partitioning (Figure 6c), more closely resembling the average pattern of TRENDY S3 than that of INV_{AB}.

5 | CHALLENGES FOR ESTIMATING REGIONAL CO_2 BUDGETS

Schimel et al. (2015) demonstrated a rough agreement in the global budget partitioning between atmospheric inversions that are capable of reproducing the observed annual vertical gradients of atmospheric CO_2 and biosphere models that simulate offsets between the CO_2 and LUC effects. The results of our study revealed that agreements between the latest atmospheric inversions and biosphere models are more consistent under a unified definition of the net CO_2 flux (Figure 3c), confirming the roles of NE and ST lands in the global carbon cycle (Gaubert et al., 2019; Schimel et al., 2015; Stephens et al., 2007). However, our results also emphasize that this level of agreement is insufficient to fully reconcile regional CO_2 budgets, as illustrated in Figure 5. In addition, a meta-analysis of individual estimates from TRENDY S3 and INV_{AB} indicates that the agreement between individual models found for particular regions does not necessarily hold true for the other regions (Figure S5). This implies that we do not yet have an optimal combination of atmospheric inversions and biosphere models that is capable of producing consistent budget estimates for all global regions. To achieve consistent global, hemispheric, and regional CO_2 budgets between the two methods, we need to acknowledge some fundamental issues in modeling that should be resolved in future studies.

To produce regional CO_2 budgets with lower uncertainties, differences in the sink–source compensation ("the dipole effect"; Peylin et al., 2002) among individual inversions need to be reduced. The dipole effect is intrinsic to the design of inversion systems, where the CO_2 budgets of neighboring regions connected via wind paths are tightly anticorrelated, because the sum of the regions is better constrained from the large-scale atmospheric signals than the individual regions. Europe and boreal Asia are a good example of this effect, with both exhibiting large variability, but a reverse order in the net sinks and sources of individual inversions (Figure 6). While additional CO_2 observations could provide better constraints of the inversion system at global regions, this alone is unlikely to resolve the large variability among inversions. As notable variability was found in Europe, one of the regions characterized by a high density of in situ CO_2 observations, we need to acknowledge a possibility that modeling issues are responsible for this variability. They include differences in prior datasets, model resolution, control vector size (a set of posterior CO_2 fluxes to be estimated at given temporal and spatial resolutions), assimilation window length (the period during which data assimilation is conducted), transport rates (rates at which CO_2 is transported from a source region to neighboring regions through model atmosphere), and transport model errors (in particular concerning vertical mixing) among inversions. For example, the degree to which a regional budget reflects localized fossil fuel signals or CO_2 measurement signals varies with the resolution of the transport models and the size of the inversion control vector. These differences might have caused the large variability in the European CO_2 budgets, which then propagated into the budget estimates for boreal Asia via the dipole effect. Recent studies highlighted uncertainties

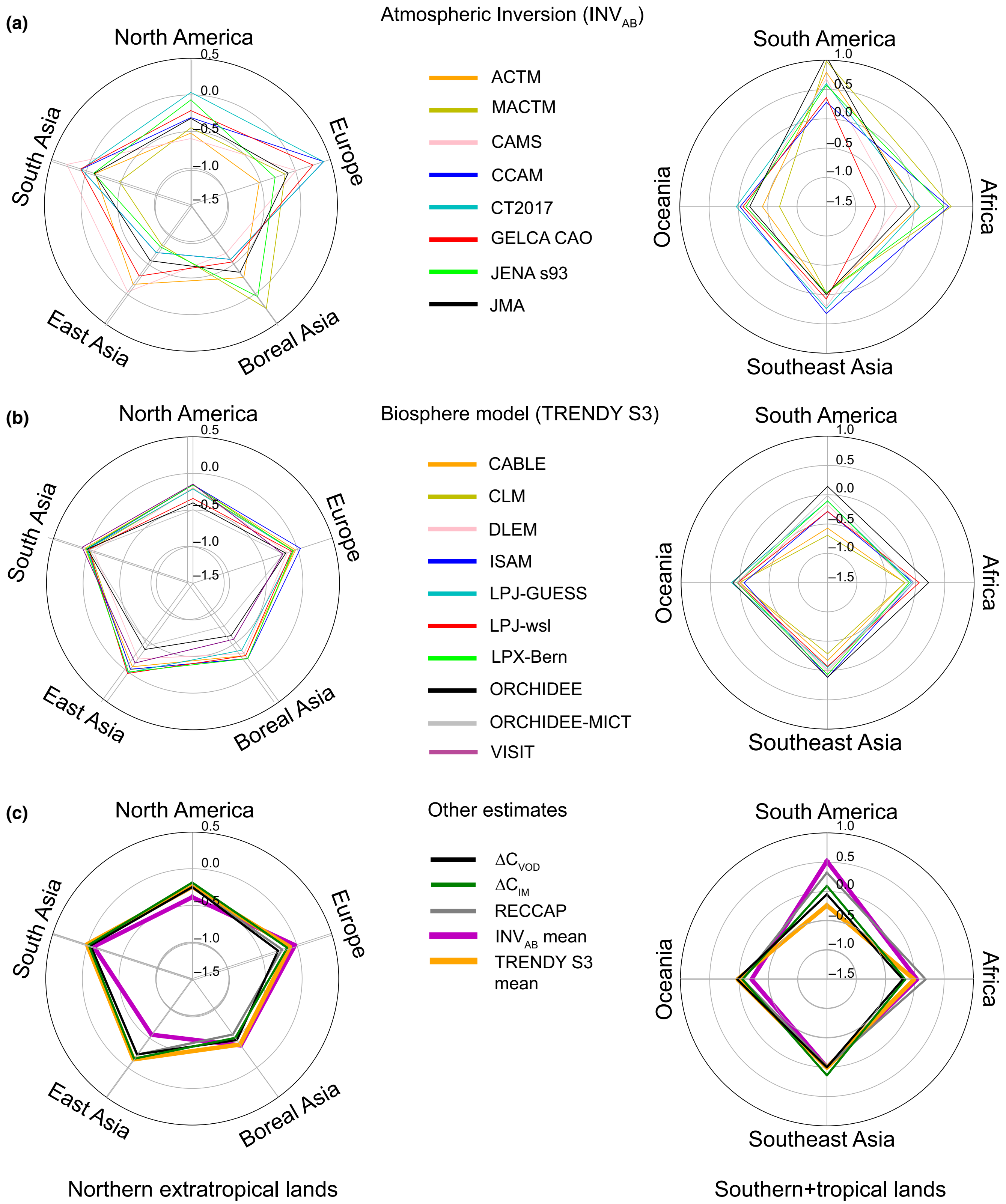

FIGURE 6 Multimethod comparison of hemispheric budget partitioning into regions. Partitioning of hemispheric budgets into corresponding regions by (a) INV_{AB}, (b) TRENDY S3, and (c) means of INV_{AB} and TRENDY S3, and other independent estimates (ΔC_{IM}, ΔC_{VOD}, and RECCAP). Partitioning of the northern extratropical land budget into five regions and the southern tropical land budget into four regions are shown for each method. All figures are in units of Pg C/year. INV, inversions; RECCAP, REgional Carbon Cycle Assessment and Processes

in inter-hemispheric CO_2 transports as one of the causes behind the variability in zonal CO_2 budgets among inversions (Le Quéré, Andrew, Friedlingstein, Sitch, Hauck, et al., 2018; Schuh et al., 2019). The variability co-occurring between neighboring regions indicates a possibility that a non-negligible level of uncertainties may exist in intra-hemispheric transports as well.

Contrary to atmospheric inversions, the biosphere models produced a relatively consistent pattern of hemispheric budget partitioning (Figure 6b); however, this does not mean that the results are more reliable. Biosphere models still poorly represent certain processes, such as forest regrowth, cropland harvesting and management, shifting cultivation, wood harvesting, and degradation (Arneth et al., 2017; Kondo, Ichii, Patra, Canadell, et al., 2018; Mitchard, 2018; Pugh et al., 2015, 2019; Williams, Gu, MacLean, Masek, & Collatz, 2016; Wolf et al., 2015), which could greatly affect regional budget estimates. For instance, a recent model that integrated the global forest age (the global forest age dataset; Poulter et al., 2019) suggested the enhancement of CO_2 uptake (~0.45 Pg C/year) by regrowth of northern temperate and boreal forests (Pugh et al., 2019), compared with simulations without the age information. Although this alone may not resolve the issue, enhanced uptake by the age effect appears to play a role in filling the gap between the atmospheric inversions and biosphere models in East Asia (Figure 5), as this region is one of the hotspots of forest regrowth (Kondo, Ichii, Patra, Poulter, et al., 2018). In the case of South America, incomplete representations of shifting cultivation, wood harvesting, and forest degradation are potential causes for the biosphere models being inclined toward a net sink, opposite to the results based on atmospheric inversions (Figure 5). Currently, there is limited spatiotemporal information available regarding forest degradation, but several studies have suggested that forest degradation is more important than other processes in tropical regions, potentially accounting for twice the carbon release of deforestation (Baccini et al., 2017; Mitchard, 2018; Ryan, Berry, & Joshi, 2014). Additional sinks and sources from these processes are expected to change the patterns of hemispheric budget partitioning and corresponding regional CO_2 budgets in the biosphere models of this study. Furthermore, although the spread in regional budget estimates was smaller within the biosphere models than the atmospheric inversions, spread in seasonality of net CO_2 flux was larger within the biosphere models than the atmospheric inversions across global, hemispheric, and regional scales (Figure S6). Thus, we cannot conclude that biosphere models are more reliable than atmospheric inversions based on the consistency of the hemispheric budget partition and regional budget estimates among models.

A tendency for ΔC_{IM}, ΔC_{VOD}, and RECCAP results to agree more with biosphere models in estimates of regional budgets and partitioning than with atmospheric inversions may suggest that they capture common signals within the carbon cycle (Figures 5 and 6). However, we need to acknowledge the fact that carbon stock changes based on inventory measurements and VOD, as well as the statistical approaches of RECCAP have their own limitations. Both ΔC_{IM} and ΔC_{VOD} provide "forest-oriented" CO_2 budgets as available inventory data are of forests in large part and the conversion of VOD to biomass was based on an empirical relationship using ground measurements of forest biomass (Liu et al., 2015). These are considered insufficient to represent the diversity of terrestrial ecosystems, which include grasslands and croplands, and their associated carbon fluxes (King et al., 2015). Uncertainty in soil carbon stocks also affects the estimation of carbon stock changes. Even in the most extensive compilation of the inventory data, the global soil carbon stocks are likely underestimated, due to missing data of deep organic soils in ecosystems such as peatlands and mangroves (Pan et al., 2011). Despite efforts to integrate possible processes in the carbon cycle for each region, the regional CO_2 budgets from RECCAP are also influenced by the limitations in the independent CO_2 fluxes used for budget assessment, including the above-mentioned limitations in atmospheric inversions, biosphere models, and inventories. Thus, along with the modeling methods, ΔC_{IM}, ΔC_{VOD}, and the statistical approaches of RECCAP should also be improved to serve as good references for future model improvements.

In addition to the above-mentioned issues of each method, further adjustments for the definition of the net CO_2 flux could reduce the gap in budget estimates between the modeling methods. For instance, lateral transports of harvested wood carbon via export and import affect regional CO_2 budget estimates (Peters, Davis, & Andrew, 2012), which is not well addressed in current biosphere models. Also, incorporation of bottom-up pathways of CO_2 resulting from oxidation of biogenetic volatile organic compounds, CO, CH_4 (e.g., coming from biosphere, fire and fossil fuel emissions) could improve the gap in budget estimates. Despite recent progress aimed at filling the gaps between atmospheric inversions and biosphere models, our current level of modeling and process understanding is still insufficient to implement these factors into the multiscale CO_2 budget comparison.

6 | CONCLUSIONS

The aim of this study was to detail the current status of agreement between terrestrial CO_2 budgets derived from top-down and bottom-up approaches and to provide a pathway for future improvement of these methods. With comparisons under a consistent definition of net CO_2 flux, we illustrated different levels of consistency in the CO_2 budgets of atmospheric inversions and biosphere models at the global, hemispheric, and regional scales. The overlapping distributions of hemispheric budgets, and close agreement found for some regions (i.e., North America and Southeast Asia) are good indications of progress toward reconciliation of budget estimates, therefore, increasing robustness of our knowledge. However, further improvements are required to reach a more robust regional understanding.

First, differences in budget estimates between the modeling methods for East Asia and South America need to be reduced. To accomplish this, the impacts of physiological processes that contribute to net sinks or sources (e.g., age effects on regrowth, degradation, etc.) should be further investigated using biosphere models. Second, the large variability in the regional dipole effect within atmospheric inversions needs to be reduced for them to be more comparable with the estimates of biosphere models. This requires collective effort from the inverse modeling community to identify and resolve modeling issues at regional scales (e.g., detailed experiments on transport model and inversion performance, validation of fossil fuel and biogenetic flux partitioning using $^{14}CO_2$ measurements, etc.). Given these findings, caution should be taken when interpreting regional CO_2 budgets estimated using only either atmospheric inversions or biosphere models, or individual models from these approaches, unless regional applications have been properly parameterized and benchmarked with regional observations.

The terrestrial biosphere plays a major role in mitigating CO_2 emitted by human activities (Le Quéré, Andrew, Friedlingstein, Sitch, Hauck, et al., 2018). While the partitioning of the sink between the northern hemisphere and pantropic is increasingly better constrained, we have yet to establish confidence in the roles of global regions because of the uncertainties remaining in current models. Those uncertainties continue to limit our ability to project the mitigation potential by the terrestrial biosphere (Hoffman et al., 2014), and require continuous international and multidisciplinary efforts to resolve such as those under the umbrella of the Global Carbon Project.

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CONFLICT OF INTEREST

The authors declare that there are no competing financial interests.

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DATA AVAILABILITY STATEMENT

TRENDY data are available via Profs. Stephen Sitch and Pierre Friedlingstein, Exeter University (s.a.sitch@exeter.ac.uk; p.friedlingstein@exeter.ac.uk). CAMS, CT2017, JENA inversion data are available from the websites (CAMS: https://apps.ecmwf.int/datasets/data/cams-ghg-inversions/, CT2017: https://www.esrl.noaa.gov/gmd/ccgg/carbontracker/, JENA: http://www.bgc-jena.mpg.de/CarboScope/). ACTM, MACTM, CCAM, and GELCA CAO inversion data are available by contacting Dr. Prabir K. Patra (prabir@jamstec.go.jp). JMA inversion data are available by contacting Dr. Takashi Maki (tmaki@mri-jma.go.jp). Global aboveground biomass carbon (v1.0) is available from the website (http://wald.anu.edu.au/data_services/data/global-above-ground-biomass-carbon-v1-0/). Flux data of Global Carbon Project are available from the website (https://www.globalcarbonproject.org/carbonbudget/18/data.htm).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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