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## State of the science in reconciling top-down and bottom-up approaches for terrestrial CO<sub>2</sub> budget

Masayuki Kondo, Prabir Patra, Stephen Sitch, Pierre Friedlingstein, Benjamin Poulter, Frederic Chevallier, Philippe Ciais, Josep Canadell, Ana Bastos, Ronny Lauerwald, et al.

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## 18 **State of the science in reconciling top-down and bottom-up** 19 **approaches for terrestrial CO<sub>2</sub> budget**

20 **Running Title:** On reconciliation of CO<sub>2</sub> budgets

21

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73 **Abstract**

74 Robust estimates of CO<sub>2</sub> budget, CO<sub>2</sub> exchanged between the atmosphere and terrestrial biosphere, are  
75 necessary to better understand the role of the terrestrial biosphere in mitigating anthropogenic CO<sub>2</sub>  
76 emissions. Over the past decade, this field of research has advanced through understanding of the  
77 differences and similarities of two fundamentally different approaches: "top-down" atmospheric  
78 inversions and "bottom-up" biosphere models. Since the first studies were undertaken, these approaches  
79 have shown an increasing level of agreement, but disagreements in some regions still persist, in part  
80 because they do not estimate the same quantity of atmosphere-biosphere CO<sub>2</sub> exchange. Here we  
81 conducted a thorough comparison of CO<sub>2</sub> budgets at multiple scales and from multiple methods to  
82 assess the current state of the science in estimating CO<sub>2</sub> budgets. Our set of atmospheric inversions and  
83 biosphere models, which were adjusted for a consistent flux definition, showed a high level of  
84 agreement for global and hemispheric CO<sub>2</sub> budgets in the 2000s. Regionally, improved agreement in  
85 CO<sub>2</sub> budgets was notable for North America and Southeast Asia. However, large gaps between the two  
86 methods remained in East Asia and South America. In other regions, Europe, boreal Asia, Africa, South  
87 Asia, and Oceania, it was difficult to determine whether those regions act as a net sink or source because  
88 of the large spread in estimates from atmospheric inversions. These results highlight two research  
89 directions to improve the robustness of CO<sub>2</sub> budgets: (1) to increase representation of processes in  
90 biosphere models that could contribute to fill the budget gaps, such as forest regrowth and forest  
91 degradation, and (2) to reduce sink-source compensation between regions (dipoles) in atmospheric  
92 inversion so that their estimates become more comparable. Advancements on both research areas will  
93 increase the level of agreement between the top-down and bottom-up approaches and yield more robust  
94 knowledge of regional CO<sub>2</sub> budgets.

95  
96 **Keywords:** terrestrial CO<sub>2</sub> budget, net CO<sub>2</sub> flux, atmospheric inversion, biosphere model, carbon stock  
97 change, residual land uptake, land-use change emissions, riverine carbon export, CO<sub>2</sub> evasion

98 **1. INTRODUCTION**

99 Understanding the mitigation potential of the terrestrial biosphere against anthropogenic CO<sub>2</sub>  
100 emissions hinges upon accurate assessment of the net atmosphere-land CO<sub>2</sub> flux (net CO<sub>2</sub> flux, - for a  
101 net sink and + for a net source). Our ability to diagnose CO<sub>2</sub> sink-source patterns of the net CO<sub>2</sub> flux has  
102 progressed owing to the development of “top-down” atmospheric inversions (Peylin et al., 2013;  
103 Thompson et al., 2016) and “bottom-up” biosphere models (Sitch et al., 2008, 2015). Compared with  
104 early studies that varied by more than 3.0 Pg C yr<sup>-1</sup> in their estimates of northern and tropical CO<sub>2</sub> fluxes  
105 (e.g., Gurney et al., 2002; Jacobson, Fletcher, Gruber, Sarmiento, & Gloor, 2007; Peylin, Baker,  
106 Sarmiento, Ciais, & Bousquet, 2002; Rödenbeck, Houweling, Gloor, & Heimann, 2003), net CO<sub>2</sub> fluxes  
107 by current atmospheric inversions are converging around a sink of 1.0 to 2.0 Pg C yr<sup>-1</sup> in northern  
108 extratropical (NE) lands and a small net flux in southern–tropical (ST) lands, due to improvements in  
109 the transport processes modeling and abundance of aircraft and vessel observations, along with  
110 improved in situ CO<sub>2</sub> observation networks (Gaubert et al., 2019; Stephens et al., 2007). Likewise, net  
111 CO<sub>2</sub> fluxes simulated by biosphere models have become roughly consistent with this pattern, especially  
112 in ST lands, due to the offset of land-use change (LUC) emissions with enhanced CO<sub>2</sub> uptake by the  
113 stimulating effect of rising atmospheric CO<sub>2</sub> on plant photosynthesis (Schimel, Stephens, & Fisher,  
114 2015). However, disagreements in the CO<sub>2</sub> budgets between top-down and bottom-up approaches  
115 remain nontrivial at regional scales (Cervarich et al., 2016; Ciais et al., 2013; Kondo, Ichii, Takagi, &  
116 Sasakawa, 2015). In the fifth assessment report of Intergovernmental Panel on Climate Change (IPCC  
117 AR5), the sign and magnitude of regional CO<sub>2</sub> budget estimates were still contradictory between  
118 atmospheric inversions and biosphere models for some regions (Ciais et al., 2013).

119 These previous syntheses highlight the challenges of reconciling the top-down and bottom-up  
120 approaches and the importance of spatial scale in evaluating agreement and uncertainties. When  
121 comparing CO<sub>2</sub> budgets of multiple methods, understanding the definition of the net CO<sub>2</sub> flux and  
122 associated component fluxes that are included in developing the CO<sub>2</sub> budgets become increasingly  
123 important because these could lead to either a “total” or “partial” exchange of CO<sub>2</sub> between the  
124 atmosphere and land depending upon the methods employed. The former applies to methods that use  
125 atmospheric CO<sub>2</sub> concentrations as a basis for estimation such as atmospheric inversions (Peylin et al.,  
126 2013). The latter applies to methods that account for known processes in the carbon cycle interacting  
127 with the biosphere such as biosphere models (Sitch et al., 2015). Major terms that cause challenges in  
128 comparing atmospheric inversions and biosphere models at the time of the IPCC AR5 can be: (1)

129 hydrosphere fluxes, such as lateral riverine carbon export and CO<sub>2</sub> evasion from rivers and lakes,  
130 included in atmospheric inversions, but not simulated in biosphere models, and (2) the incomplete  
131 representation of CO<sub>2</sub> fluxes from land-use and management in biosphere models. Mitigating these  
132 differences in terminology will advance our understanding of net CO<sub>2</sub> flux at regional scales which so  
133 far has remained unresolved.

134 To address the current state of our knowledge on terrestrial CO<sub>2</sub> budgets and the level of  
135 reconciliation between current modeling methods, CO<sub>2</sub> budget assessments at global, hemispheric, and  
136 regional scales need to be reanalyzed with consistent datasets and definitions of the component fluxes  
137 that determine net CO<sub>2</sub> flux. Based on the net CO<sub>2</sub> flux defined as “the atmosphere-biosphere CO<sub>2</sub>  
138 exchange” (excluding hydrosphere fluxes), we investigate net CO<sub>2</sub> fluxes estimated for the decade of  
139 2000s (2000–2009) using fluxes adjusted around a consistent definition of the CO<sub>2</sub> exchange. These are  
140 compared with reproduced results of the IPCC AR5 obtained using inconsistent definitions, to determine  
141 how definitions play a role in reconciliation between the modeling methods. Aimed at serving as a  
142 useful reference, this study provides a thorough comparison between atmospheric inversions and  
143 biosphere models, and also among other existing estimates of global and regional CO<sub>2</sub> budgets based on  
144 forest inventories, remote sensing, atmospheric O<sub>2</sub> measurements, the residuals from non-terrestrial  
145 components of global CO<sub>2</sub> budgets, and previous regional budget assessments from the REgional  
146 Carbon Cycle Assessment and Processes (RECCAP, Canadell et al., 2011). Through these comparisons,  
147 we highlight potential difficulties faced by current CO<sub>2</sub> budget assessments, and suggests ways forward  
148 to increase the level of agreement between top-down and bottom-up approaches yielding more robust  
149 knowledge of CO<sub>2</sub> budgets.

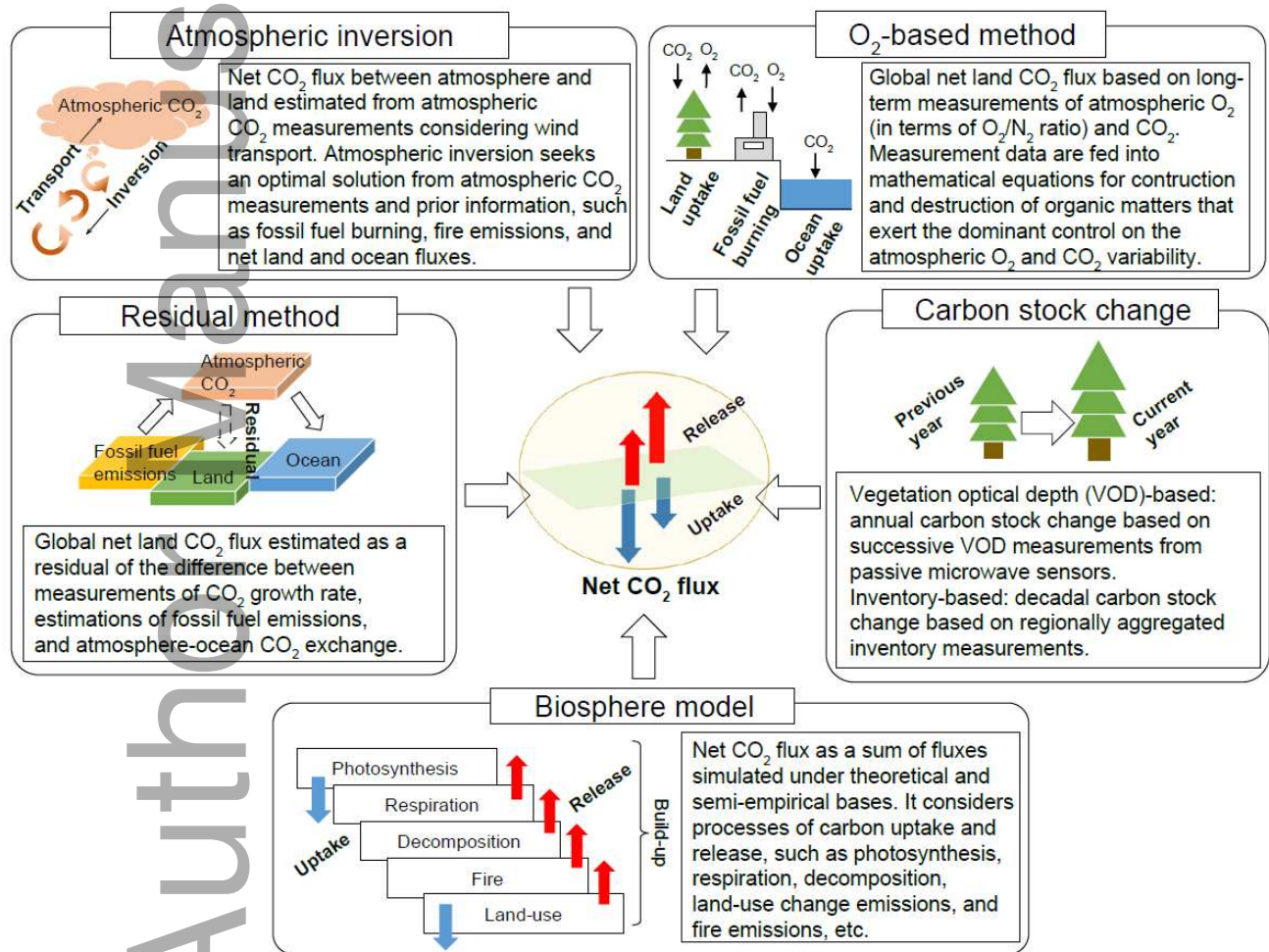
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## 151 **2. MATERIALS AND METHODS**

### 152 **2.1 Definition of net CO<sub>2</sub> flux**

153 We define the net CO<sub>2</sub> flux as the “atmosphere-biosphere CO<sub>2</sub> exchange”, comprising components  
154 such as photosynthesis, autotrophic and heterotrophic respirations, fire emissions, and CO<sub>2</sub> fluxes  
155 associated with land-use and land-cover changes. Adjustments based on the proposed definition of net  
156 CO<sub>2</sub> flux were applied to the methods described herein where relevant (Fig. 1; Spatial and temporal  
157 applicability of the methods is shown in Table S1). Biosphere models comply with this definition, as  
158 they consider numerous processes of atmosphere-land biogeochemistry, including LUC fluxes in the  
159 latest development (Le Quéré et al. 2018a). A method based on carbon stock changes from the

160 compilation of forest inventories ( $\Delta C_{IM}$ , Pan et al., 2011) also complies with this definition. The  
 161 Vegetation Optical Depth (VOD) derived from passive microwave sensors (e.g., Liu et al., 2015) is only  
 162 applicable to aboveground vegetation, but can be supplemented by inventories of missing belowground  
 163 components to represent the total stock change ( $\Delta C_{VOD}$ ). Methods that consider interactions beyond  
 164 those with the biosphere, such as atmospheric inversions, and global land uptake assessments based on a  
 165 residual of non-terrestrial components of global CO<sub>2</sub> budgets (residual method, Le Quéré et al., 2018a)  
 166 and based on decadal O<sub>2</sub> and CO<sub>2</sub> trends in the atmosphere (O<sub>2</sub>-based method, Keeling & Manning,  
 167 2014) can roughly comply with the proposed definition when the hydrosphere fluxes are excluded from  
 168 their budget estimates, as we discuss further in this paper.



169  
 170 **FIGURE 1.** Methods of terrestrial net CO<sub>2</sub> flux estimation.

171  
 172 **2.2 Independent methods of estimating net CO<sub>2</sub> flux**



174 **2.2.1 Atmospheric inversions**

175 The net CO<sub>2</sub> flux from atmospheric inversions was represented by eight inversions (Table 1). These  
176 inversions estimate net CO<sub>2</sub> flux through the assimilation of continuous or discrete atmospheric CO<sub>2</sub>  
177 measurements from global networks (e.g., World Data Centre for Greenhouse Gases, WDCGG; and the  
178 observation package (ObsPack) from the NOAA Earth System Research Laboratory, NOAA/ESRL) in  
179 transport model, with prior information (e.g., net land flux, net ocean flux, fire emissions, and fossil fuel  
180 emissions). The choices of CO<sub>2</sub> measurements and prior fluxes differ for each inversion system, as well  
181 as the spatial resolution and period of inverted fluxes (Table 1).

182 For each inversion, posterior land flux was adjusted by the difference between the respective fossil  
183 fuel emissions prescribed in the inversion and a reference emission estimate. This “fossil fuel  
184 adjustment” is a necessary procedure for reducing variability in posterior fluxes, as differences in  
185 prescribed fossil fuel emissions largely affect posterior fluxes (Peylin et al., 2013), especially for recent  
186 periods for which the uncertainty in fossil fuel emissions remains large (Ballantyne et al., 2015). We  
187 applied the fossil fuel adjustment using the emission dataset prescribed in ACTM (Table 1), showing a  
188 central tendency of global interannual variability among inversions, as the reference emission.

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189 **TABLE 1.** Configuration of the atmospheric CO<sub>2</sub> inversion systems used in this study.

Inversion system (in-text abbreviation)	No. of region	Time period	IAV prior <sup>#</sup>	No. of observations	Transport model	Meteorology	Prior fluxes				Reference
							Land	Ocean	Biomass Burning	Fossil fuel emissions	
ACTM (ACTM)	84	1990–2011	Yes: FF, LA No: SA	73 (GLOBALVIEW)	JAMSTEC's Atmospheric Chemistry-Transport Model (ACTM)	NCEP	Three-hourly flux from CASA	Monthly flux from the LDEO (Takahashi) Surface pCO <sub>2</sub> database	--	EDGAR v4.2 rescaled global total to CDIAC	Saeki & Patra (2017)
MIROC4-ACTM (MACTM)	84	1996–2015	Yes: FF, LA No: SA	42 sites (NOAA ESRL ObsPack & JMA)	Updated ACTM with MIROC4-ESM	JRA-55	Three-hourly flux from CASA	Monthly flux from the LDEO	--	EDGAR v4.3.2	Patra et al. (2018); Le Quéré et al. (2018b)
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)	ECMWF	Three-hourly flux from ORCHIDEE	Monthly flux from the LDEO (Takahashi) Surface pCO <sub>2</sub> database	GFAS	EDGAR v4.2 rescaled global total to CDIAC	Chevallier et al. (2010)
CCAM (CCAM)	94 land, 52 ocean	1993-2012	Yes: FF No: LA, SA	69 (GLOBALVIEW)	CSIRO Conformal-cubic Atmospheric Model (CCAM)	NCEP	Monthly flux from CASA	Monthly flux from the LDEO (Takahashi) Surface pCO <sub>2</sub> database	--	EDGAR v4.2 rescaled regionally to CDIAC	McGregor & Dix (2008)
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)	ECMWF and ERA	Monthly CASA flux downscaled to 90-minute flux	Ocean inversion fluxes and monthly flux from the LDEO Surface pCO <sub>2</sub> database	GFED4.1s and GFED_CM S	ODIAC2016 and Miller emissions datasets	Peters et al. (2007)
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	JCDAS	Daily flux from VISIT	Monthly flux from 4D-var + OTTM based on	GFED	ODIAC	Zhuravlev, Khattatov, & Kiryushov, &

								<i>p</i> CO <sub>2</sub> data			Maksyutov (2011)
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)	NCEP	Zero values	Monthly climatological flux based on an interpolation of <i>p</i> CO <sub>2</sub> data	--	Monthly values from CDIAC	Rödenbeck, Zaehle, Keeling, & Heimann (2018)
JMA2018 (JMA)	22	1985–2016	Yes: FF, SA No: LA	88 (WDCGG) 16 (aircraft observations), 59 (vessel observations)	JMA atmospheric transport model (based upon JMA global weather forecasting model)	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)

190 #Abbreviations: biomass burning emission (BB), fossil fuel emission (FF), land-air CO<sub>2</sub> exchange (LA), and sea-air CO<sub>2</sub> exchange (SA).

191

### 192 **2.2.2 Biosphere models**

193 Simulations from TRENDY v6 (Le Quéré et al., 2018a) represent the net CO<sub>2</sub> flux from the  
194 biosphere models of this study (Table 2). These simulations were prepared with a consistent forcing  
195 dataset: a global atmospheric CO<sub>2</sub> concentrations for 1860–2016 based on ice core measurements and  
196 stationary observations from NOAA, a gridded climate dataset (CRU-NCEP v8) for 1901–2016 (Viovy,  
197 2018), and a gridded annual land-use and land-cover change dataset for 1860–2016 (Hurtt et al., 2017;  
198 Klein Goldewijk, Beusen, Doelman, & Stehfest, 2017). The TRENDY models carried out three types of  
199 simulations: S1 that used varied atmospheric CO<sub>2</sub>, fixed climate (1901–1920) and fixed land-use and  
200 land-cover (1860), S2 that used varied CO<sub>2</sub> and climate (with fixed land-use and land-cover at 1860),  
201 and S3 that varied all three drivers. For each simulation, the models first established an equilibrium  
202 carbon balance by a spin-up run, forced with the 1860 CO<sub>2</sub> concentration (287.14 ppm), recycling  
203 climate variability from 1901–1920, and constant 1860 crop and pasture distributions.

204 Attributes of the net CO<sub>2</sub> flux (i.e. the effects of CO<sub>2</sub>, climate, and LUC) were extracted by  
205 separating flux signals in the S1, S2, and S3 simulations (Friedlingstein et al., 2006). The net CO<sub>2</sub> flux  
206 of S3 represented the estimate most closely matching observations, including the interactions between  
207 CO<sub>2</sub>, climate, and LUC effects on the ecosystem carbon cycling. Those from S1 and S2 represented  
208 partial contributions to the net CO<sub>2</sub> flux, isolating the CO<sub>2</sub> effect and CO<sub>2</sub>+climate effects on the net  
209 CO<sub>2</sub> flux, respectively. The LUC effect on the net CO<sub>2</sub> flux was extracted by subtracting estimates of S2  
210 from that of S3. Similarly, the effect of climate was extracted by subtracting the net CO<sub>2</sub> flux of S1 from  
211 that of S2.

212 **TABLE 2.** Configuration of the TRENDY models used in this study.

Biosphere model	Spatial resolution	Carbon-Nitrogen coupling	Fire simulation (including peat fire)	Age class	Land use change scheme					Reference
					Distinction between primary and secondary lands	Wood harvest	Shifting cultivation	Crop harvest (crop species: C, managed grassland :G)	Degradation	
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, & 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, & Yamagata (2013)

214

### 215 **2.2.3 Carbon stock changes, O<sub>2</sub>-based method, residual method, and RECCAP**

216 Inventory-based carbon stock changes ( $\Delta C_{IM}$ ) were estimated by incorporating information on forest  
217 area and biomass density obtained from (i) United Nations Global Forest Resources Assessment reports  
218 (Food and Agriculture Organization, 2006, 2010), (ii) deforestation and afforestation estimates from a  
219 book-keeping model (Houghton, 2007), and (iii) the observed carbon pools for regions around the  
220 globe. From these datasets, the sums of carbon stocks for intact and regrowth forests and soil carbon for  
221 2000 and 2007 were used to calculate regional carbon stock changes (Pan et al., 2011), except for South  
222 Asia where a missing estimate was supplemented by inventory and forest area data for 1992–2002 from  
223 Kaula, Dadhwal, and Mohren (2009). To estimate VOD-based carbon stock change ( $\Delta C_{VOD}$ ) for the  
224 2000s, we used the satellite-derived gridded aboveground biomass from Global Aboveground Biomass  
225 Carbon v1.0 (Liu et al., 2015). The VOD-based aboveground biomass is estimated based on an  
226 empirical relationship between the gridded aboveground biomass for tropical regions (Saatchi et al.,  
227 2011) and harmonized passive microwave observations. VOD only measures aboveground backscatter,  
228 therefore belowground biomass was estimated as a constant fraction of the estimated aboveground  
229 biomass (Liu et al., 2015). To provide more reliable estimates, we replaced this belowground biomass of  
230  $\Delta C_{VOD}$  with the data used for  $\Delta C_{IM}$ .

231 The O<sub>2</sub>-based method provides a mean annual global CO<sub>2</sub> budget for the land and ocean based on  
232 destructive and constructive O<sub>2</sub> and CO<sub>2</sub> processes (Keeling & Manning, 2014). This approach utilizes  
233 long-term measurements of CO<sub>2</sub> and the O<sub>2</sub>/N<sub>2</sub> molar ratio between a sample and a reference, expressed  
234 as  $\delta(O_2/N_2)$ , as changes in the global mean molar fraction of CO<sub>2</sub> and  $\delta(O_2/N_2)$  are related to the net  
235 sources and sinks of CO<sub>2</sub>, O<sub>2</sub>, and N<sub>2</sub> in the atmosphere. The budget used in this study was estimated for  
236 2000–2010 by Keeling and Manning (2014). The residual method from the Global Carbon Project (Le  
237 Quéré et al., 2018a) provided the global annual budget of land CO<sub>2</sub> uptake calculated as the difference  
238 between the other terms in the global carbon budget, i.e., fossil fuel emissions minus the CO<sub>2</sub> growth  
239 rate and the net ocean uptake simulated by biogeochemical models. The budget of this method for the  
240 2000s was calculated using the data of Le Quéré et al. (2018a). The RECCAP project quantified regional  
241 anthropogenic and biogenic CO<sub>2</sub> budgets by integrating CO<sub>2</sub> fluxes from multiple independent  
242 approaches, including biosphere models, atmospheric inversions, and inventories (Canadell et al., 2011).  
243 Based on the available major and minor fluxes and through consideration of the reliability of each of the

244 fluxes, the regional CO<sub>2</sub> budget was estimated for global regions. The regional budgets used in this  
245 study were from re-calculated estimates based on the RECCAP studies in Li et al. (2016).

246

### 247 **2.3 Adjustments for the atmosphere-biosphere CO<sub>2</sub> exchange estimation**

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

258 These data were also used to derive the atmosphere-biosphere CO<sub>2</sub> exchange for the O<sub>2</sub>-based  
259 method and RECCAP. The O<sub>2</sub>-based method and RECCAP account for lateral riverine exports as a part  
260 of the land biosphere flux. Thus, we excluded annual riverine DOC and DIC fluxes from the global  
261 budget estimates of both methods using the data described above. Global CO<sub>2</sub> uptake by the residual  
262 method includes only riverine carbon exports due to anthropogenic perturbations (Le Quéré et al.,  
263 2018b). To remove that flux from the residual method, an estimate of the anthropogenic component of  
264 river flux from Regnier et al. (2018) was used.

265

### 266 **2.4 A constraint for the global budget**

267 Owing to atmospheric observations, the CO<sub>2</sub> budget at the global scale is the best understood among  
268 those at other scales (Le Quéré et al., 2018a). To analyze CO<sub>2</sub> budgets at multiple scales, it is important  
269 to have consistent global CO<sub>2</sub> budgets so that results of hemispheric and regional budgets would not be  
270 misinterpreted due to outliers of global budget estimates. Therefore, we defined a criterion, based on the  
271 global CO<sub>2</sub> budget from the residual method and ±1.0 Pg C yr<sup>-1</sup> uncertainties, to constrain global CO<sub>2</sub>  
272 budgets from the top-down and bottom-up models for the 2000s. All eight atmospheric inversions of this  
273 study satisfied this criterion, since the atmospheric CO<sub>2</sub> growth rate was used to constraint atmospheric

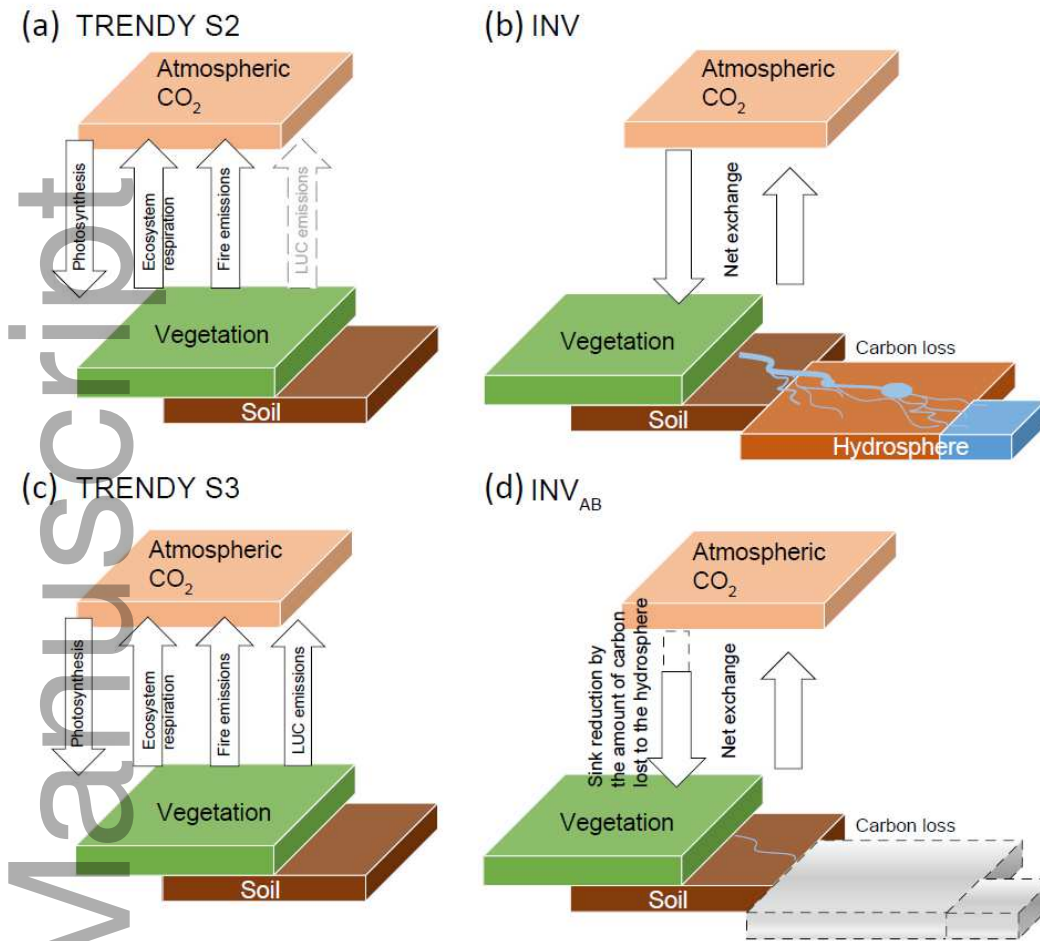
274 inversions. As for biosphere models, among the TRENDY models that provided net CO<sub>2</sub> fluxes of all  
275 three experiments, ten models satisfied this criterion (Table 2).

276

### 277 3. GLOBAL AND HEMISPHERIC BUDGETS

278 To articulate differences from results of the IPCC AR5, we compared experiments from TRENDY  
279 (S2: not including time-varying LUC simulation, and S3: including time-varying LUC simulation), and  
280 atmospheric inversions before (INV) and after correcting for the hydrosphere components (INV<sub>AB</sub>  
281 denotes inversions adjusted for the atmosphere-biosphere CO<sub>2</sub> exchange). TRENDY S3 and INV<sub>AB</sub>  
282 represented “best estimates” of the net CO<sub>2</sub> flux, and TRENDY S2 and INV represented estimates  
283 reproduced using the IPCC AR5 configuration (Fig. 2). As illustrated in Figure 3a, global CO<sub>2</sub> budgets  
284 by TRENDY S2 (-2.6 [-2.9, -2.1] Pg C yr<sup>-1</sup>: medians [lower, upper quartiles]) and INV (-2.3 [-2.5, -1.7]  
285 Pg C yr<sup>-1</sup>) largely overestimated the amount of CO<sub>2</sub> uptake compared with other independent estimates:  
286 ΔC<sub>VOID</sub> (-1.2 Pg C yr<sup>-1</sup>), ΔC<sub>IM</sub> (-1.2 Pg C yr<sup>-1</sup>), the residual method (-0.9 Pg C yr<sup>-1</sup>), O<sub>2</sub>-based method (-  
287 0.7 Pg C yr<sup>-1</sup>), and RECCAP (-1.3±0.6 Pg C yr<sup>-1</sup>, mean±1σ). This overestimated CO<sub>2</sub> uptake is likely a  
288 consequence of missing and excess components needed to satisfy the net CO<sub>2</sub> flux definition.  
289 Meanwhile, upward shifts in the net CO<sub>2</sub> flux caused by accounting for LUC emissions in the biosphere  
290 models and discounting the hydrosphere fluxes in the atmospheric inversions led to a close agreement in  
291 global CO<sub>2</sub> budgets with respect to the other independent estimates and with each other, where  
292 TRENDY S3 estimated -0.9 [-1.4, -0.8] Pg C yr<sup>-1</sup> and INV<sub>AB</sub> estimated -0.9 [-1.2, -0.4] Pg C yr<sup>-1</sup> (Fig.  
293 3a; interannual variability (IAV) shown in Fig. S1).





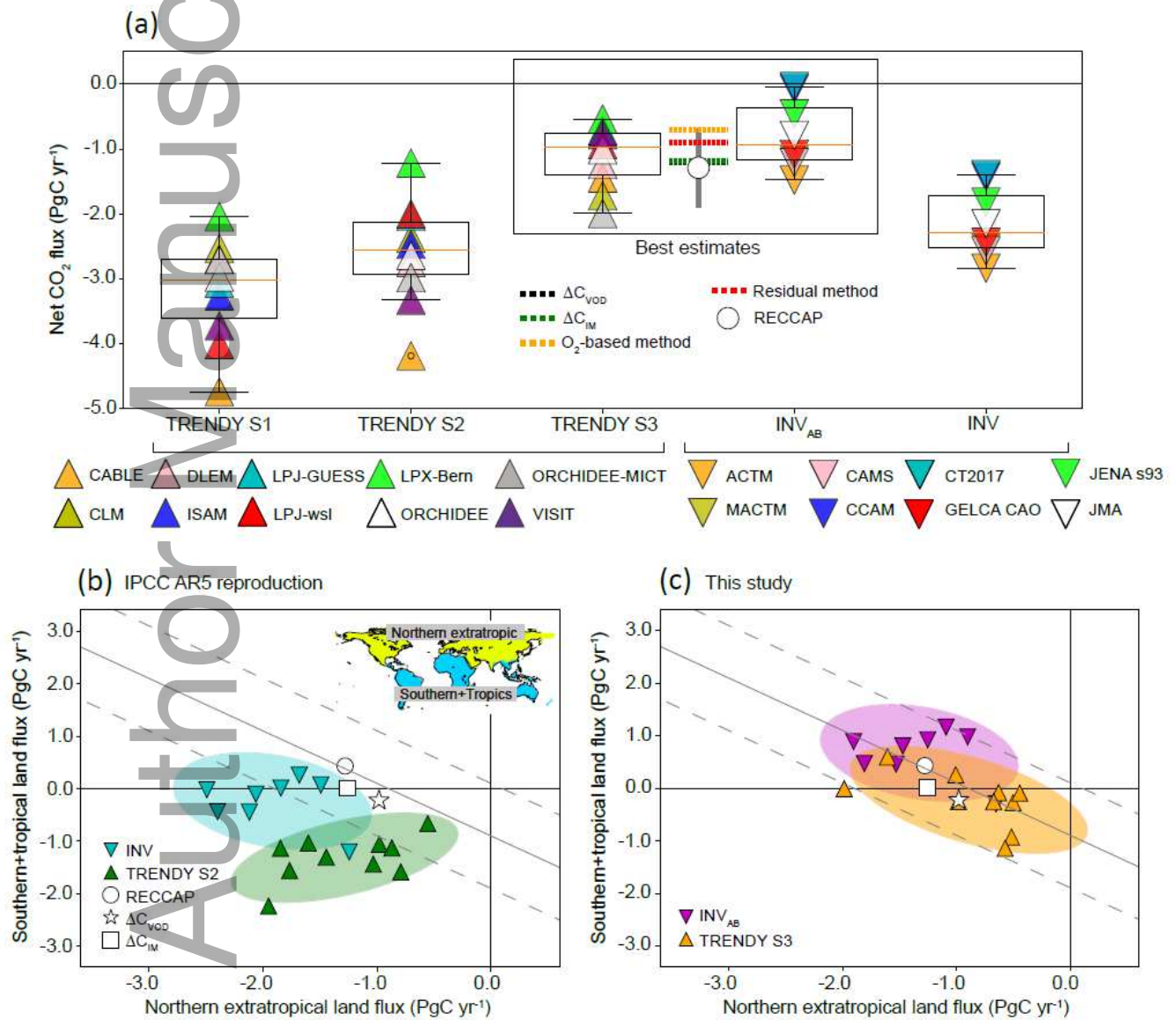
294

295 **FIGURE 2.** Differences in definition of the net CO<sub>2</sub> flux. Schematics show the components of the net CO<sub>2</sub> flux  
 296 considered in: **a)** TRENDY S2 (biosphere models without LUC), **b)** INV (atmospheric inversions including  
 297 hydrospheric components), **c)** TRENDY S3 (biosphere models including LUC), and **d)** INV<sub>AB</sub> (atmospheric  
 298 inversions excluding hydrospheric components).

299

300 The global CO<sub>2</sub> budget largely consists of fluxes from northern boreal-temperate and pantropical  
 301 ecosystems, with the former accounting for a large part of the global sink and the latter for a large part  
 302 of the global LUC emissions (Ciais et al., 2019; Le Quéré et al., 2018b). That is, the well-constrained  
 303 global CO<sub>2</sub> budgets among the methods should accompany a consistent budget partitioning between  
 304 those regions. To evaluate this aspect, we applied the so-called “diver down” plot of Schimel, Stephens,  
 305 and Fisher (2015) to better understand global CO<sub>2</sub> budget partitioning into NE and ST lands (Fig. 3b, c).  
 306 The reproduced IPCC AR5 results (TRENDY S2 and INV) exhibited limited overlap with each other  
 307 (Fig. 3b). INV produced relatively strong sinks of -1.2 to -2.5 Pg C yr<sup>-1</sup> in NE and a small net flux in ST

308 lands. With the absence of LUC emissions, TRENDY S2 resulted in a net sink for both NE and ST lands,  
 309 spanning approximately  $-1.0$  to  $-2.0$   $\text{Pg C yr}^{-1}$ . Including simulated LUC fluxes in biosphere models and  
 310 removing the hydrosphere fluxes from atmospheric inversions shifted the NE and ST land fluxes of the  
 311 two methods towards a reduced sink or net source, leading to an overlap between TRENDY S3 and  
 312  $\text{INV}_{\text{AB}}$  (Fig. 3c; IAV shown in Fig. S2) and with  $\Delta\text{C}_{\text{VOD}}$ ,  $\Delta\text{C}_{\text{IM}}$ , and RECCAP (Fig. 3c). However,  
 313 agreements between TRENDY S3 and  $\text{INV}_{\text{AB}}$  are not yet robust, as the distribution of  $\text{INV}_{\text{AB}}$  leans more  
 314 towards a net sink in NE lands ( $-2.2$  to  $-0.7$   $\text{Pg C yr}^{-1}$ ) and a net source in ST lands ( $-0.4$  to  $1.0$   $\text{Pg C yr}^{-1}$ )  
 315 than that of TRENDY S3:  $-2.0$  to  $-0.5$   $\text{Pg C yr}^{-1}$  in NE and  $-1.1$  to  $0.6$   $\text{Pg C yr}^{-1}$  in ST lands.

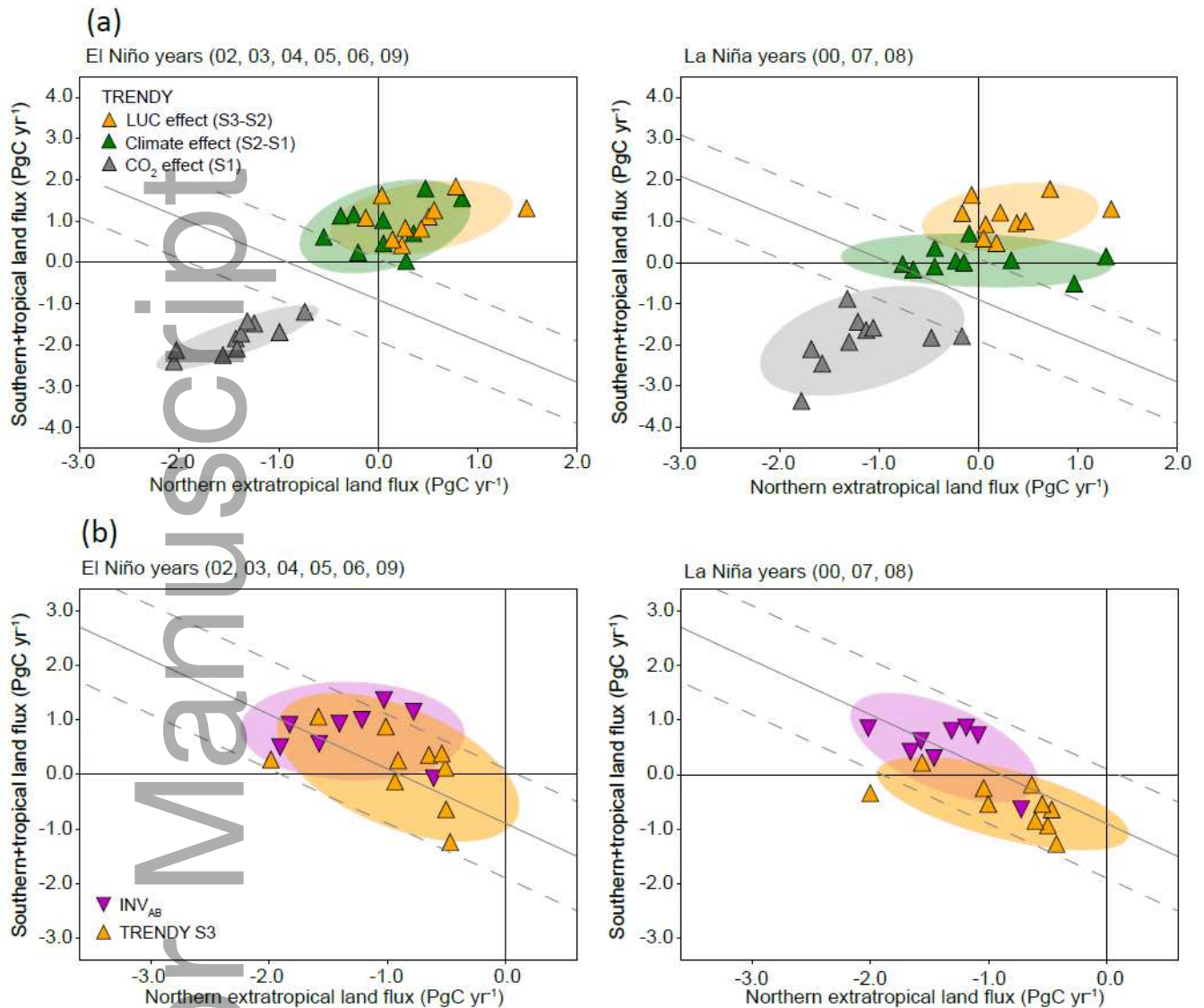


316  
 317 **FIGURE 3.** Improved agreement of global and hemispheric net  $\text{CO}_2$  flux estimates over the IPCC AR5. **a)** Global  
 318  $\text{CO}_2$  budgets for the 2000s from the biosphere models (upper triangles), atmospheric inversions (lower triangles),

319 carbon stock changes:  $\Delta C_{\text{VOD}}$  (black dashed line) and  $\Delta C_{\text{IM}}$  (green dashed line), O<sub>2</sub>-based method (yellow dashed  
320 line), residual method (red dashed line), and estimates from the RECCAP project (circle representing the mean  
321 value and bar representing the 1 $\sigma$  uncertainty). Box plots are shown for the biosphere models (three TRENDY  
322 simulations, S1, S2, and S3) and atmospheric inversions (INV and INV<sub>AB</sub>). Partitioning of the global CO<sub>2</sub> budget  
323 into northern extratropical (NE) and southern-tropical (ST) lands (diver-down plot) for **b**) TRENDY S2 and INV  
324 (IPCC AR5 reproduction), and **c**) TRENDY S3 and INV<sub>AB</sub> (results from this study). Gray lines are the constraint  
325 on global CO<sub>2</sub> budgets represented by the global budget estimate from the residual method, with  $\pm 1.0$  Pg C yr<sup>-1</sup>  
326 uncertainty. Results that fall within the constraints are combinations of NE and ST land budgets that preserve the  
327 reference value of global CO<sub>2</sub> budget. Individual model estimates and error ellipse of 2 $\sigma$  range are shown for  
328 TRENDY S2 and S3 (green and orange upper triangles, respectively), and INV and INV<sub>AB</sub> (cyan and purple lower  
329 triangles, respectively), along with the independent estimates from carbon stock changes:  $\Delta C_{\text{VOD}}$  and  $\Delta C_{\text{IM}}$  (star  
330 and square, respectively) and estimate from the RECCAP project (circle representing the mean value).

331

332 Figure 3c illustrates the results only of the net balance of CO<sub>2</sub> fluxes. To gain confidence in the  
333 overlapping pattern between the two methods, it is necessary to understand changes in the patterns of  
334 sinks and sources induced by the major processes governing the net CO<sub>2</sub> flux. The effect of increasing  
335 CO<sub>2</sub> concentration on photosynthesis (the CO<sub>2</sub> effect) is considered the dominant driver of current  
336 terrestrial CO<sub>2</sub> uptake (Keenan et al., 2016; Keenan & Williams, 2018; Kondo et al., 2018a; Schimel,  
337 Stephens, & Fisher, 2015), and LUC activities (the LUC effect) are the major net emissions source from  
338 ecosystems to the atmosphere (Arneeth et al., 2017; Kondo et al., 2018b). The net CO<sub>2</sub> flux of TRENDY  
339 S3 decomposed into three attributes confirms that the CO<sub>2</sub> and LUC effects are the major sink and  
340 source components in NE and ST lands, respectively (Fig. 4a). However, the climate effect should not  
341 be overlooked, as it induces substantial changes in sink-source patterns during El Niño and La Niña  
342 phases, especially in ST lands (Fig. 4a). Importantly, the overlap between TRENDY S3 and INV<sub>AB</sub>  
343 holds not only for the decadal mean (Fig. 3c), but also for the El Niño and La Niña phases during the  
344 2000s (Fig. 4b; IAV and seasonality of ST land fluxes shown in Fig. S3), indicating that large-scale flux  
345 changes in response to El Niño-Southern Oscillation (ENSO) are similar in the atmospheric inversions  
346 and biosphere models.



347

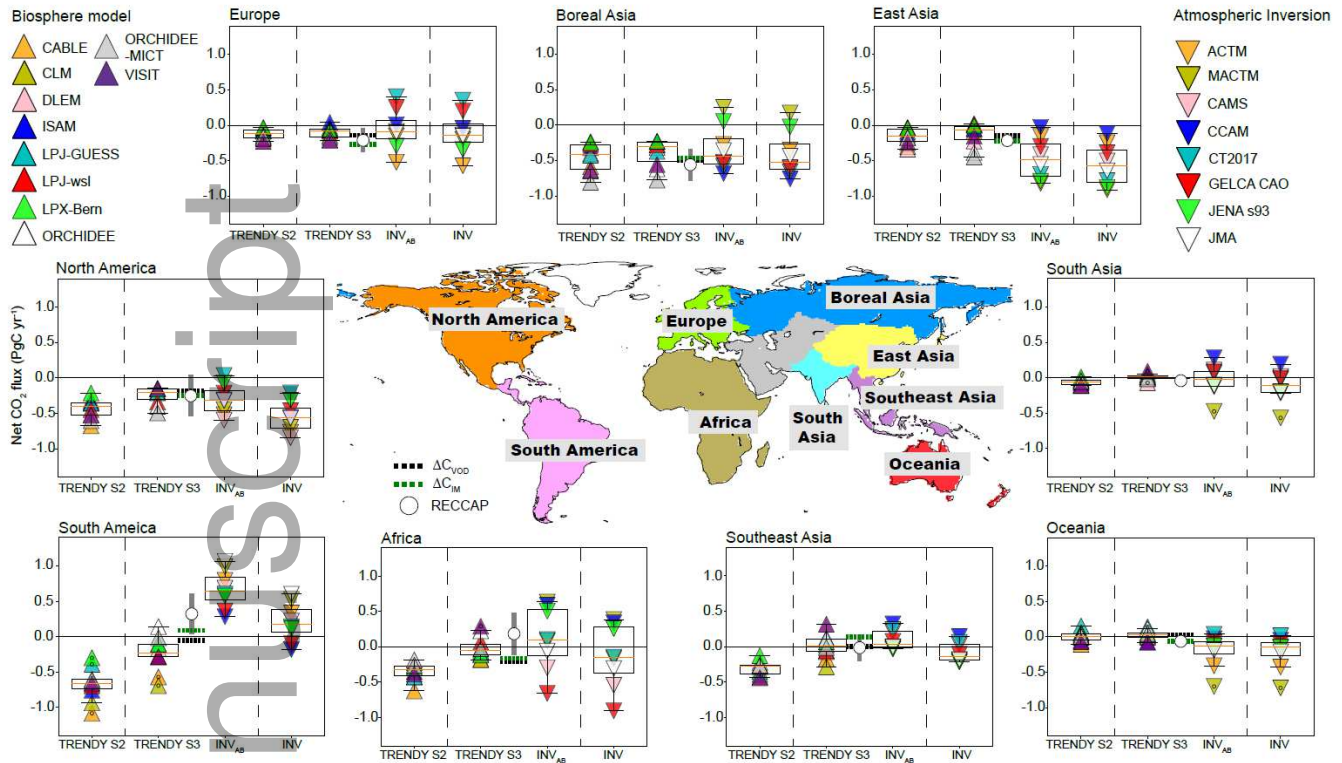
348 **FIGURE 4.** Patterns of global CO<sub>2</sub> budget partitioned into hemispheres under ENSO variability. Partitioning of  
 349 global CO<sub>2</sub> budget into NE and ST lands (diver-down plots), during El Niño years (2002, 03, 04, 05, 06, and 09)  
 350 and La Niña years (2000, 07, and 08) are shown for: **a)** each attribute of the net CO<sub>2</sub> flux by TRENDY S3, CO<sub>2</sub>  
 351 effect (TRENDY S1: grey upper triangles), climate effect (TRENDY S2-S1: green upper triangles), and LUC  
 352 effect (TRENDY S3-S2: orange upper triangles) and **b)** the net CO<sub>2</sub> fluxes of INV<sub>AB</sub> and TRENDY S3. El Niño  
 353 years are the years that have six-month averaged Multivariate ENSO Index (MEI) values >0.5 within a year, and  
 354 La Niña years are the years that have MEI values <-0.5 within a year. Gray lines represent the global budget  
 355 constraint and ±1.0 Pg C yr<sup>-1</sup> uncertainty same as in Figure 3c.

356

#### 357 4. REGIONAL BUDGETS

358 We further partitioned hemispheric budgets into nine regions. Regional CO<sub>2</sub> budgets were overall  
359 comparable between TRENDY S3 and INV<sub>AB</sub>, but the degree of agreement differed by region (Fig. 5;  
360 IAV shown in Fig. S4). Among the nine regions, the ranges of budget estimates were proximate among  
361 INV<sub>AB</sub>, TRENDY S3, and the other independent estimates for North America and Southeast Asia. A  
362 notable improvement was identified in Southeast Asia, where reduced CO<sub>2</sub> sinks by accounting for LUC  
363 fluxes in biosphere models and discounting for the hydrosphere fluxes from atmospheric inversions  
364 resulted in close agreement between INV<sub>AB</sub> (0.01 [-0.04, 0.20] Pg C yr<sup>-1</sup>) and TRENDY S3 (-0.01 [-0.06,  
365 0.10] Pg C yr<sup>-1</sup>). Budget estimates for Europe, boreal Asia, Africa, South Asia, and Oceania overlapped,  
366 but with a larger range in INV<sub>AB</sub> than in TRENDY S3 (Fig. 5). In Africa, adjustments for the missing  
367 and excess fluxes in the two modeling methods seemingly mitigated the gap between median INV and  
368 TRENDY S2 values; however, a range > 1.0 Pg C yr<sup>-1</sup> in the individual estimates of INV<sub>AB</sub> rendered  
369 comparison with TRENDY S3 difficult.

370 Budget estimates for East Asia and South America showed notable differences between INV<sub>AB</sub> and  
371 TRENDY S3 (Fig. 5). In East Asia, the budget estimates by both INV<sub>AB</sub> and TRENDY S3 indicated a  
372 net sink, but INV<sub>AB</sub> (-0.5 [-0.7, -0.3] Pg C yr<sup>-1</sup>) leaned towards a greater net sink than TRENDY S3 (-  
373 0.07 [-0.20, -0.01] Pg C yr<sup>-1</sup>). In South America, INV<sub>AB</sub> leaned towards a net source contrary to the net  
374 sink indicated by TRENDY S3. The gap in South America was the most notable, with budget estimates  
375 barely overlapping between INV<sub>AB</sub> (0.6 [0.5, 0.8] Pg C yr<sup>-1</sup>) and TRENDY S3 (-0.2 [-0.3, -0.1] Pg C yr<sup>-1</sup>).  
376 In this region, the flux adjustments did not reduce the gap in budgets. Importantly, these differences  
377 explained the minor deviation in the distributions of global budget partitioning into hemispheres  
378 between INV<sub>AB</sub> and TRENDY S3 (Fig. 3c). The differences between budget estimates for East Asia are  
379 largely responsible for INV<sub>AB</sub> indicating a stronger net sink in NE lands than TRENDY S3. Likewise,  
380 the differences in the estimates for South America are responsible for the INV<sub>AB</sub> indicating a stronger  
381 net source in ST lands than those of TRENDY S3. Thus, East Asia and South America are the regions  
382 where future model improvements are needed to generate CO<sub>2</sub> budgets that agree at the hemispheric and  
383 regional scales.



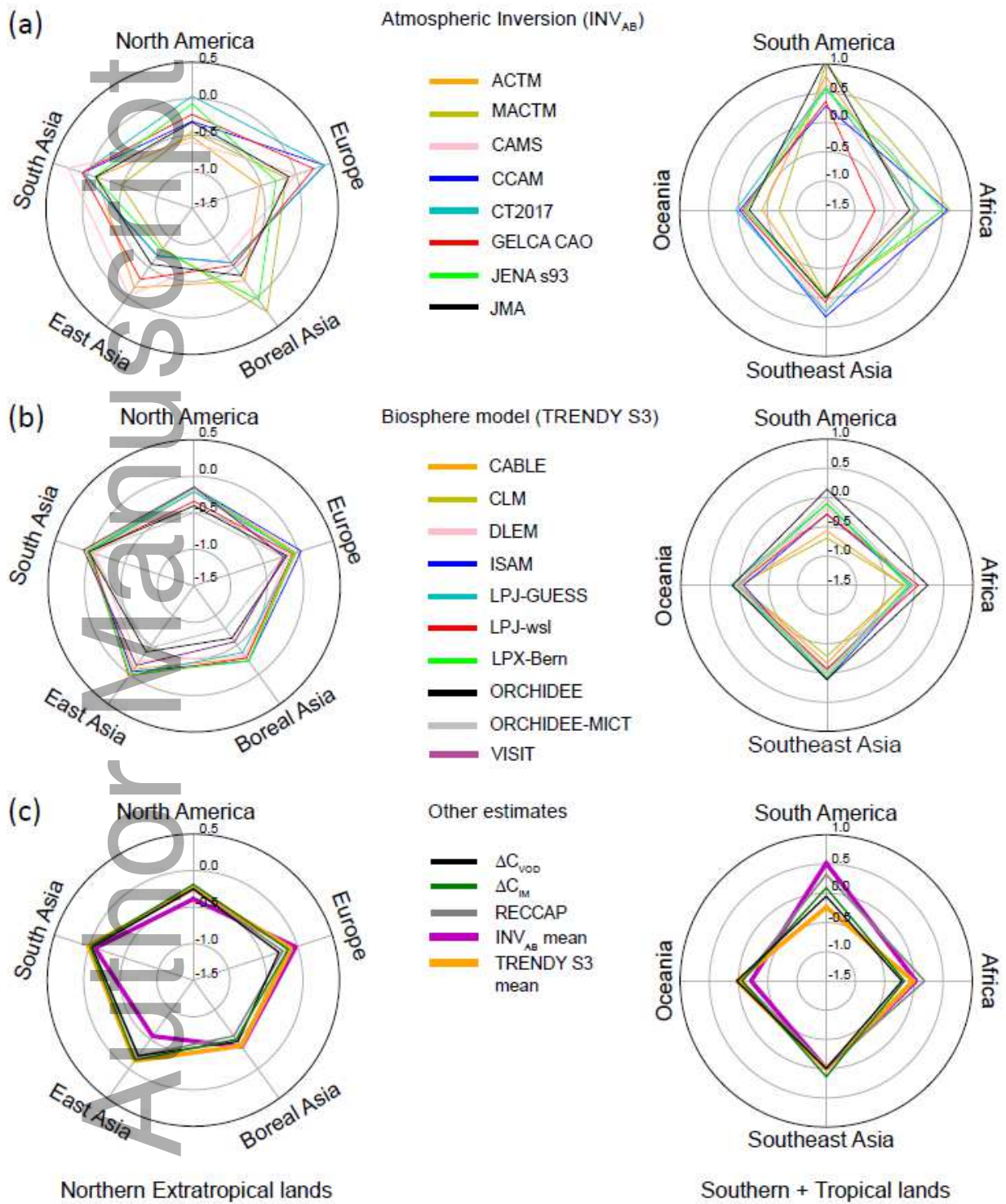
384

385 **FIGURE 5.** Consistency and inconsistency among the estimates of regional CO<sub>2</sub> budgets. Regional CO<sub>2</sub> budgets  
 386 for the 2000s by the biosphere models (TRENDY S2 and S3) and atmospheric inversions (INV and INV<sub>AB</sub>),  
 387 carbon stock changes ( $\Delta C_{VOD}$  and  $\Delta C_{IM}$ ), and RECCAP project. Regional classification is based on the RECCAP  
 388 studies. Colors and symbols are the same as in Figure 3a.

389

390 So far, we evaluated the regional CO<sub>2</sub> budgets in terms of the average patterns of the atmospheric  
 391 inversions and biosphere models. However, to derive robust budget agreements for all regions, the  
 392 means by which individual models partitioned hemispheric budgets into the nine regions must be further  
 393 investigated. Contrary to the consistent pattern found in the global budget partitioning, individual INV<sub>AB</sub>  
 394 results showed largely different patterns for the partitioning of NE and ST land budgets (Fig. 6a). Some  
 395 inversions showed a greater net source or reduced sink in Europe, corresponding to a greater net sink in  
 396 boreal Asia, while others showed the opposite pattern between these two regions. This sink-source  
 397 compensation was also identified between boreal Asia and East Asia, East Asia and South Asia, and  
 398 South America and Africa, with large variabilities in their patterns. These results suggest that differences  
 399 in the sink-source compensation are likely the major factor responsible for the large range found in  
 400 regional budget estimates by INV<sub>AB</sub> (Fig. 5). Although the magnitudes of budgets differed, the pattern of  
 401 NE and ST land budget partitioning was overall similar among the models of TRENDY S3 (Fig. 6b).

402 Additionally,  $\Delta C_{\text{VOD}}$ ,  $\Delta C_{\text{IM}}$ , and RECCAP showed close agreements in their patterns of partitioning (Fig.  
 403 6c), more closely resembling the average pattern of TRENDY S3 than that of  $\text{INV}_{\text{AB}}$ .



404  
 405 **FIGURE 6.** Multi-method comparison of hemispheric budget partitioning into regions. Partitioning of  
 406 hemispheric budgets into corresponding regions by **a)**  $\text{INV}_{\text{AB}}$ , **b)** TRENDY S3, and **c)** means of  $\text{INV}_{\text{AB}}$  and

407 TRENDY S3, and other independent estimates ( $\Delta C_{IM}$ ,  $\Delta C_{VOD}$ , and RECCAP). Partitioning of the NE land budget  
408 into five regions and the ST land budget into four regions are shown for each method. All figures are in units of  
409 Pg C yr<sup>-1</sup>.

410

## 411 **5. CHALLENGES FOR ESTIMATING REGIONAL CO<sub>2</sub> BUDGETS**

412 Schimel, Stephens, and Fisher (2015) demonstrated a rough agreement in the global budget  
413 partitioning between atmospheric inversions that are capable of reproducing the observed annual vertical  
414 gradients of atmospheric CO<sub>2</sub> and biosphere models that simulate offsets between the CO<sub>2</sub> and LUC  
415 effects. The results of our study revealed that agreements between the latest atmospheric inversions and  
416 biosphere models are more consistent under a unified definition of the net CO<sub>2</sub> flux (Fig. 3c), confirming  
417 the roles of NE and ST lands in the global carbon cycle (Gaubert et al., 2019; Schimel, Stephens, &  
418 Fisher, 2015; Stephens et al., 2007). However, our results also emphasize that this level of agreement is  
419 insufficient to fully reconcile regional CO<sub>2</sub> budgets, as illustrated in Figure 5. In addition, a meta-  
420 analysis of individual estimates from TRENDY S3 and INV<sub>AB</sub> indicates that the agreement between  
421 individual models found for particular regions does not necessarily hold true for the other regions (Fig.  
422 S5). This implies that we do not yet have an optimal combination of atmospheric inversions and  
423 biosphere models that is capable of producing consistent budget estimates for all global regions. To  
424 achieve consistent global, hemispheric, and regional CO<sub>2</sub> budgets between the two methods, we need to  
425 acknowledge some fundamental issues in modeling that should be resolved in future studies.

426 To produce regional CO<sub>2</sub> budgets with lower uncertainties, differences in the sink-source  
427 compensation (“the dipole effect”; Peylin, Baker, Sarmiento, Ciais, & Bousquet, 2002) among  
428 individual inversions need to be reduced. The dipole effect is intrinsic to the design of inversion systems,  
429 where the CO<sub>2</sub> budgets of neighboring regions connected via wind paths are tightly anti-correlated,  
430 because the sum of the regions is better constrained from the large-scale atmospheric signals than the  
431 individual regions. Europe and boreal Asia are a good example of this effect, with both exhibiting large  
432 variability, but a reverse order in the net sinks and sources of individual inversions (Fig. 6). While  
433 additional CO<sub>2</sub> observations could provide better constraints of the inversion system at global regions,  
434 this alone is unlikely to resolve the large variability among inversions. As notable variability was found  
435 in Europe, one of the regions characterized by a high density of in-situ CO<sub>2</sub> observations, we need to  
436 acknowledge a possibility that modeling issues are responsible for this variability. They include  
437 differences in prior datasets, model resolution, control vector size (a set of posterior CO<sub>2</sub> fluxes to be



438 estimated at given temporal and spatial resolutions), assimilation window length (the period during  
439 which data assimilation is conducted), transport rates (rates at which CO<sub>2</sub> is transported from a source  
440 region to neighboring regions through model atmosphere), and transport model errors (in particular  
441 concerning vertical mixing) among inversions. For example, the degree to which a regional budget  
442 reflects localized fossil fuel signals or CO<sub>2</sub> measurement signals varies with the resolution of the  
443 transport models and the size of the inversion control vector. These differences might have caused the  
444 large variability in the European CO<sub>2</sub> budgets, which then propagated into the budget estimates for  
445 boreal Asia via the dipole effect. Recent studies highlighted uncertainties in inter-hemispheric CO<sub>2</sub>  
446 transports as one of the causes behind the variability in zonal CO<sub>2</sub> budgets among inversions (Le Quéré  
447 et al., 2018b; Schuh et al., 2019). The variability co-occurring between neighboring regions indicates a  
448 possibility that a non-negligible level of uncertainties may exist in intra-hemispheric transports as well.

449 Contrary to atmospheric inversions, the biosphere models produced a relatively consistent pattern of  
450 hemispheric budget partitioning (Fig. 6b), however, this does not mean that the results are more reliable.  
451 Biosphere models still poorly represent certain processes, such as forest regrowth, cropland harvesting  
452 and management, shifting cultivation, wood harvesting, and degradation (Arneeth et al., 2017; Kondo et  
453 al., 2018b; Mitchard, 2018; Pugh et al. 2015, 2019; Williams, Gu, MacLean, Masek, & Collatz, 2016;  
454 Wolf et al., 2015), which could greatly affect regional budget estimates. For instance, a recent model  
455 that integrated the global forest age (the global forest age dataset (GFAD): Poulter et al., 2019)  
456 suggested the enhancement of CO<sub>2</sub> uptake (~0.45 Pg C yr<sup>-1</sup>) by regrowth of northern temperate and  
457 boreal forests (Pugh et al., 2019), compared with simulations without the age information. Although this  
458 alone may not resolve the issue, enhanced uptake by the age effect appears to play a role in filling the  
459 gap between the atmospheric inversions and biosphere models in East Asia (Fig. 5), as this region is one  
460 of the hot-spots of forest regrowth (Kondo et al., 2018a). In the case of South America, incomplete  
461 representations of shifting cultivation, wood harvesting, and forest degradation are potential causes for  
462 the biosphere models being inclined towards a net sink, opposite to the results based on atmospheric  
463 inversions (Fig. 5). Currently, there is limited spatiotemporal information available regarding forest  
464 degradation, but several studies have suggested that forest degradation is more important than other  
465 processes in tropical regions, potentially accounting for twice the carbon release of deforestation  
466 (Baccini et al., 2017; Mitchard, 2018; Ryan, Berry, & Joshi, 2014). Additional sinks and sources from  
467 these processes are expected to change the patterns of hemispheric budget partitioning and  
468 corresponding regional CO<sub>2</sub> budgets in the biosphere models of this study. Furthermore, although the

469 spread in regional budget estimates was smaller within the biosphere models than the atmospheric  
470 inversions, spread in seasonality of net CO<sub>2</sub> flux was larger within the biosphere models than the  
471 atmospheric inversions across global, hemispheric, and regional scales (Fig. S6). Thus, we cannot  
472 conclude that biosphere models are more reliable than atmospheric inversions based on the consistency  
473 of the hemispheric budget partition and regional budget estimates among models.

474 A tendency for  $\Delta C_{IM}$ ,  $\Delta C_{VOD}$ , and RECCAP results to agree more with biosphere models in  
475 estimates of regional budgets and partitioning than with atmospheric inversions may suggest that they  
476 capture common signals within the carbon cycle (Figs. 5, 6). However, we need to acknowledge the fact  
477 that carbon stock changes based on inventory measurements and VOD, as well as the statistical  
478 approaches of RECCAP have their own limitations. Both  $\Delta C_{IM}$  and  $\Delta C_{VOD}$  provide "forest-oriented"  
479 CO<sub>2</sub> budgets as available inventory data are of forests in large part and the conversion of VOD to  
480 biomass was based on an empirical relationship using ground measurements of forest biomass (Liu et al.,  
481 2015). These are considered insufficient to represent the diversity of terrestrial ecosystems, which  
482 include grasslands and croplands, and their associated carbon fluxes (King et al., 2015). Uncertainty in  
483 soil carbon stocks also affects the estimation of carbon stock changes. Even in the most extensive  
484 compilation of the inventory data, the global soil carbon stocks are likely underestimated, due to missing  
485 data of deep organic soils in ecosystems such as peatlands and mangroves (Pan et al., 2011). Despite  
486 efforts to integrate possible processes in the carbon cycle for each region, the regional CO<sub>2</sub> budgets from  
487 RECCAP are also influenced by the limitations in the independent CO<sub>2</sub> fluxes used for budget  
488 assessment, including the above-mentioned limitations in atmospheric inversions, biosphere models, and  
489 inventories. Thus, along with the modeling methods,  $\Delta C_{IM}$ ,  $\Delta C_{VOD}$ , and the statistical approaches of  
490 RECCAP should also be improved to serve as good references for future model improvements.

491 In addition to the above-mentioned issues of each method, further adjustments for the definition of  
492 the net CO<sub>2</sub> flux could reduce the gap in budget estimates between the modeling methods. For instance,  
493 lateral transports of harvested wood carbon via export and import affect regional CO<sub>2</sub> budget estimates  
494 (Peters, Davis, & Andrew, 2012), which is not well addressed in current biosphere models. Also,  
495 incorporation of bottom-up pathways of CO<sub>2</sub> resulting from oxidation of biogenetic volatile organic  
496 compounds (BVOC), CO, CH<sub>4</sub> (e.g., coming from biosphere, fire and fossil fuel emissions) could  
497 improve the gap in budget estimates. Despite recent progress aimed at filling the gaps between  
498 atmospheric inversions and biosphere models, our current level of modeling and process understanding  
499 is still insufficient to implement these factors into the multi-scale CO<sub>2</sub> budget comparison.

500

## 501 **6. CONCLUSIONS**

502 The aim of this study was to detail the current status of agreement between terrestrial CO<sub>2</sub> budgets  
503 derived from top-down and bottom-up approaches and to provide a pathway for future improvement of  
504 these methods. With comparisons under a consistent definition of net CO<sub>2</sub> flux, we illustrated different  
505 levels of consistency in the CO<sub>2</sub> budgets of atmospheric inversions and biosphere models at the global,  
506 hemispheric, and regional scales. The overlapping distributions of hemispheric budgets, and close  
507 agreement found for some regions (i.e., North America and Southeast Asia) are good indications of  
508 progress towards reconciliation of budget estimates, therefore, increasing robustness of our knowledge.  
509 However, further improvements are required to reach a more robust regional understanding.

510 First, differences in budget estimates between the modeling methods for East Asia and South  
511 America need to be reduced. To accomplish this, the impacts of physiological processes that contribute  
512 to net sinks or sources (e.g., age effects on regrowth, degradation, etc.) should be further investigated  
513 using biosphere models. Second, the large variability in the regional dipole effect within atmospheric  
514 inversions needs to be reduced for them to be more comparable with the estimates of biosphere models.  
515 This requires collective effort from the inverse modeling community to identify and resolve modeling  
516 issues at regional scales (e.g., detailed experiments on transport model and inversion performance,  
517 validation of fossil fuel and biogenetic flux partitioning using <sup>14</sup>CO<sub>2</sub> measurements, etc.). Given these  
518 findings, caution should be taken when interpreting regional CO<sub>2</sub> budgets estimated using only either  
519 atmospheric inversions or biosphere models, or individual models from these approaches, unless  
520 regional applications have been properly parameterized and benchmarked with regional observations.

521 The terrestrial biosphere plays a major role in mitigating CO<sub>2</sub> emitted by human activities (Le Quéré  
522 et al., 2018b). While the partitioning of the sink between the northern hemisphere and pantropic is  
523 increasingly better constrained, we have yet to establish confidence in the roles of global regions  
524 because of the uncertainties remaining in current models. Those uncertainties continue to limit our  
525 ability to project the mitigation potential by the terrestrial biosphere (Hoffman et al., 2014), and require  
526 continuous international and multidisciplinary efforts to resolve such as those under the umbrella of the  
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528

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552

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555 inversion data are available from the web sites (CAMS: [https://apps.ecmwf.int/datasets/data/cams-ghg-](https://apps.ecmwf.int/datasets/data/cams-ghg-inversions/)  
556 [inversions/](https://apps.ecmwf.int/datasets/data/cams-ghg-inversions/), CT2017: <https://www.esrl.noaa.gov/gmd/ccgg/carbontracker/>, JENA: [http://www.bgc-](http://www.bgc-jena.mpg.de/CarboScope/)  
557 [jena.mpg.de/CarboScope/](http://www.bgc-jena.mpg.de/CarboScope/)). ACTM, MACTM, CCAM, and GELCA CAO inversion data are available  
558 by contacting Dr. Prabir K. Patra (prabir@jamstec.go.jp). JMA inversion data are available by  
559 contacting Dr. Takashi Maki (tmaki@mri-jma.go.jp). Global above-ground biomass carbon (v1.0) is  
560 available from the web site ([http://wald.anu.edu.au/data\\_services/data/global-above-ground-biomass-](http://wald.anu.edu.au/data_services/data/global-above-ground-biomass-)

561 carbon-v1-0/). Flux data of Global Carbon Project are available from the web site  
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563

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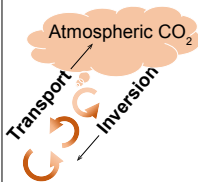
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## Atmospheric inversion

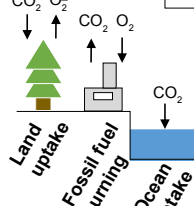
Net CO<sub>2</sub> flux between atmosphere and land estimated from atmospheric CO<sub>2</sub> measurements considering wind transport. Atmospheric inversion seeks an optimal solution from atmospheric CO<sub>2</sub> measurements and prior information, such as fossil fuel burning, fire emissions, and net land and ocean fluxes.



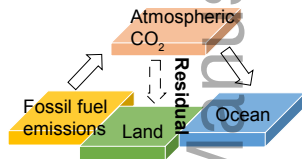
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## O<sub>2</sub>-based method

Global net land CO<sub>2</sub> flux based on long-term measurements of atmospheric O<sub>2</sub> (in terms of O<sub>2</sub>/N<sub>2</sub> ratio) and CO<sub>2</sub>. Measurement data are fed into mathematical equations for construction and destruction of organic matters that exert the dominant control on the atmospheric O<sub>2</sub> and CO<sub>2</sub> variability.

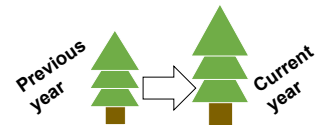


## Residual method



Global net land CO<sub>2</sub> flux estimated as a residual of the difference between measurements of CO<sub>2</sub> growth rate, estimations of fossil fuel emissions, and atmosphere-ocean CO<sub>2</sub> exchange.

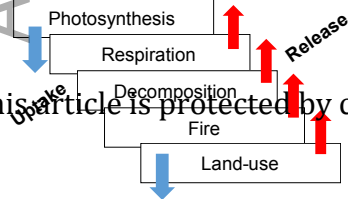
## Carbon stock change



Vegetation optical depth (VOD)-based: annual carbon stock change based on successive VOD measurements from passive microwave sensors.  
Inventory-based: decadal carbon stock change based on regionally aggregated inventory measurements.

Net CO<sub>2</sub> flux

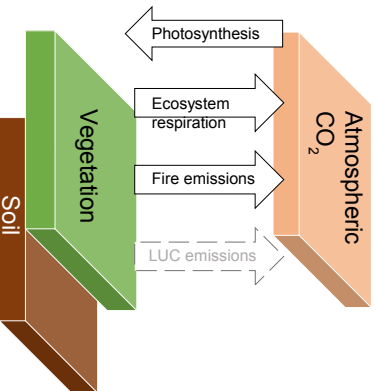
## Biosphere model



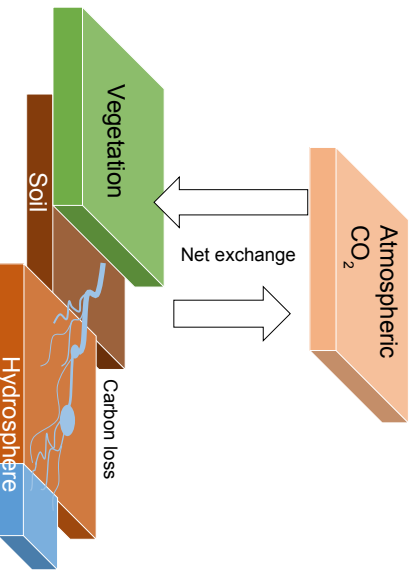
Net CO<sub>2</sub> flux as a sum of fluxes simulated under theoretical and semi-empirical bases. It considers processes of carbon uptake and release, respiration, decomposition, land-use change emissions, and fire emissions, etc.

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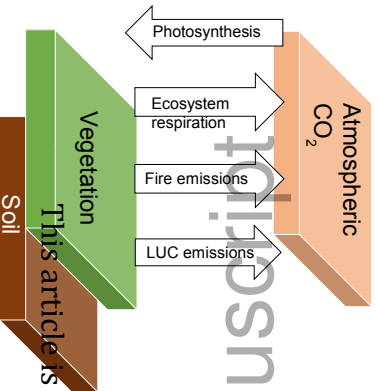
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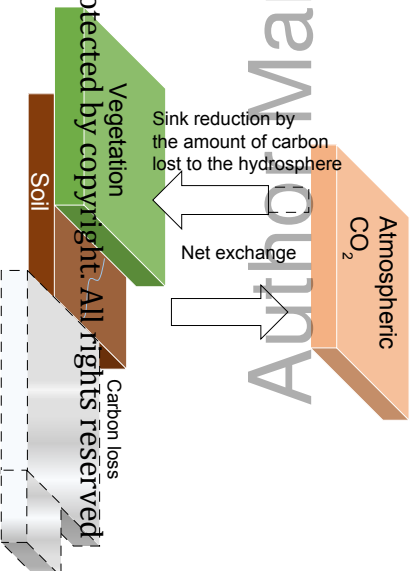
(b) INV



(c) TRENDY S3



(d) INV<sub>AB</sub>

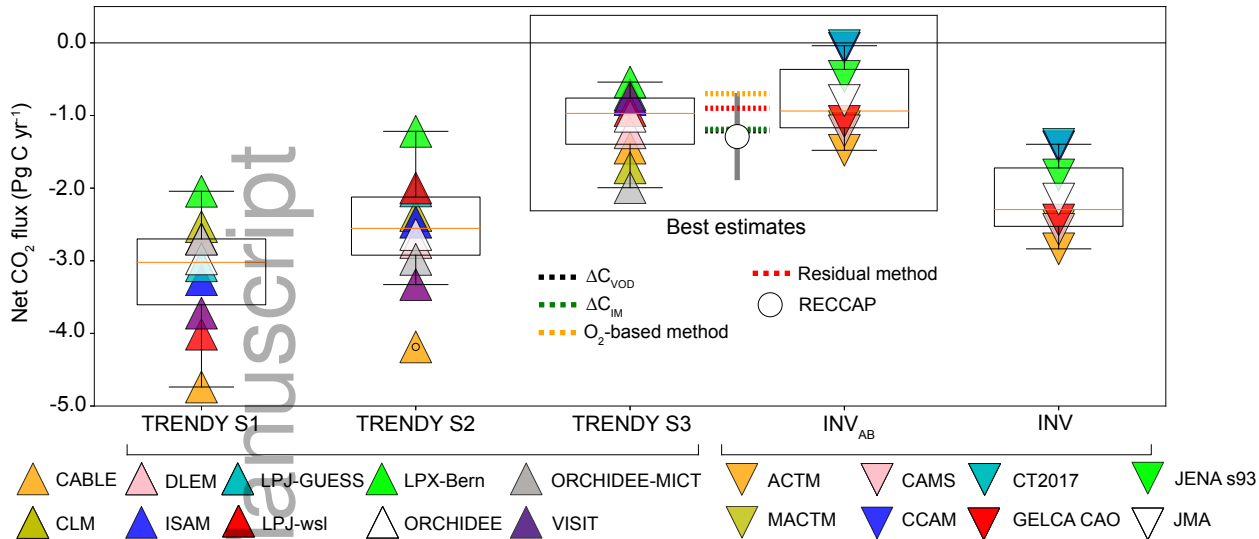


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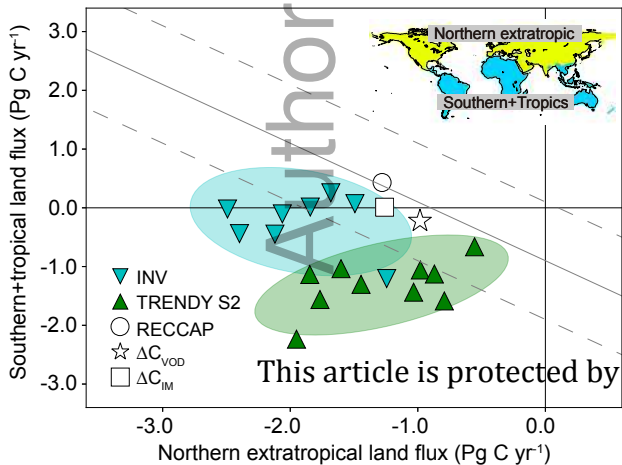
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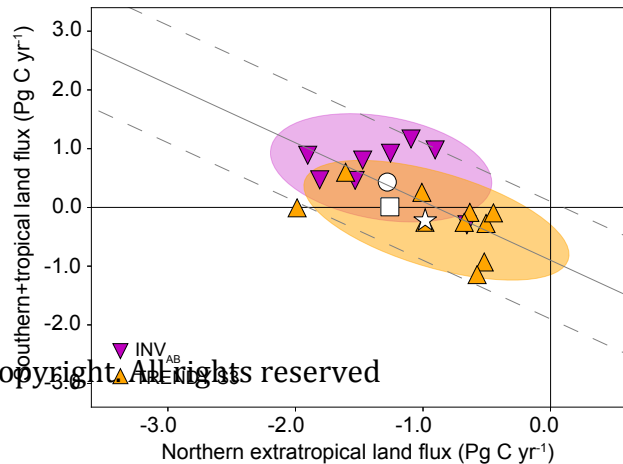
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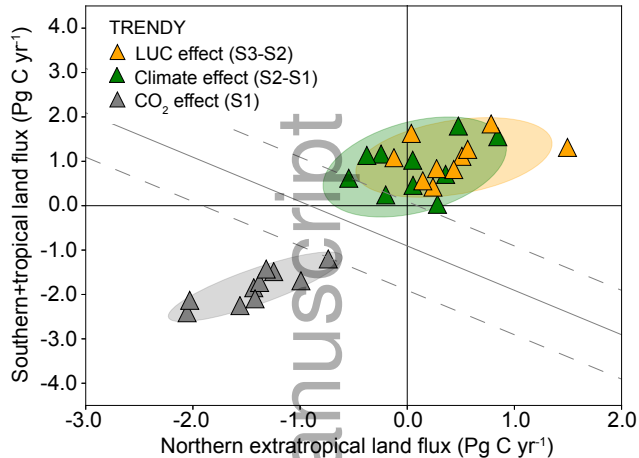


(c) This study

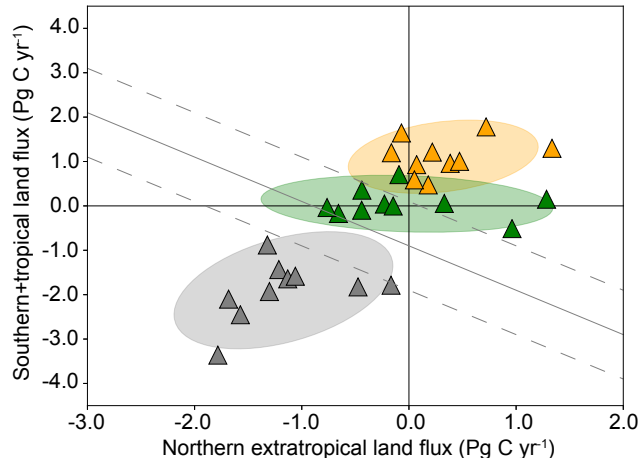


(a)

El Niño years (02, 03, 04, 05, 06, 09)

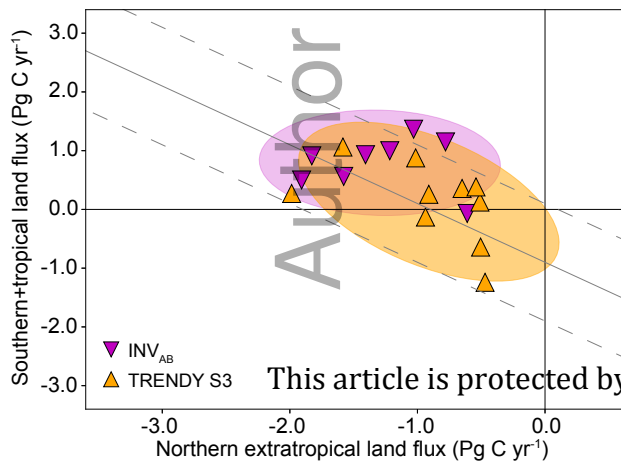


La Niña years (00, 07, 08)

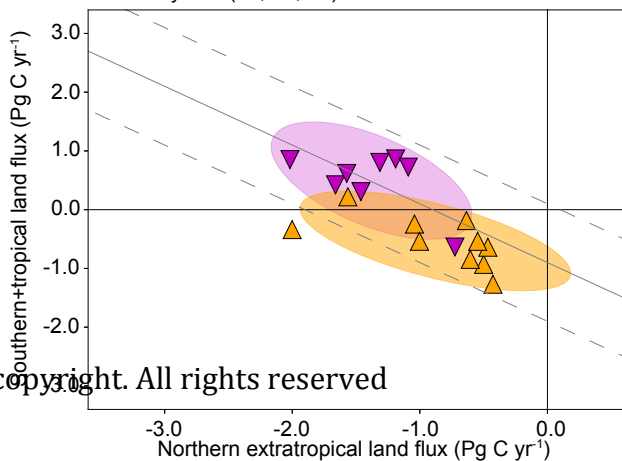


(b)

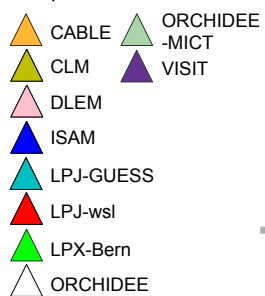
El Niño years (02, 03, 04, 05, 06, 09)



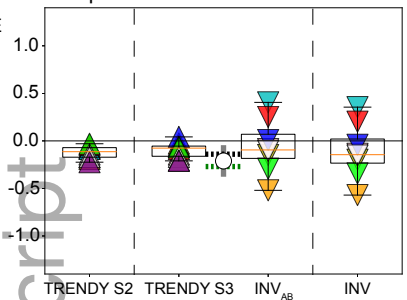
La Niña years (00, 07, 08)



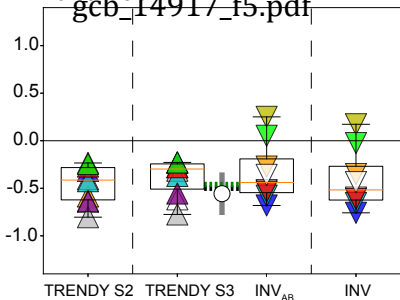
Biosphere model



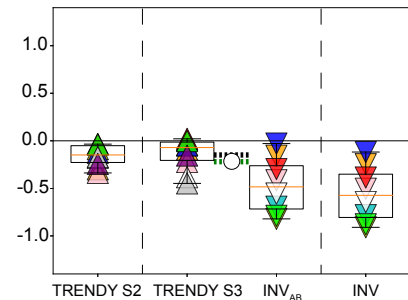
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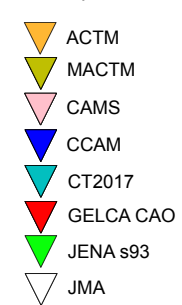
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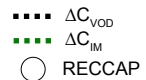
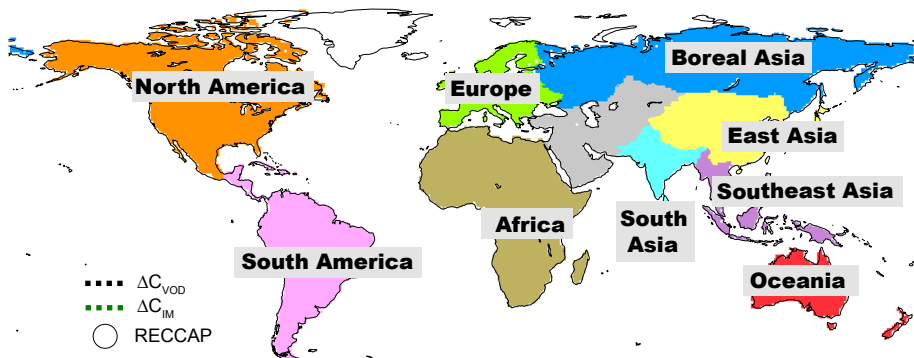
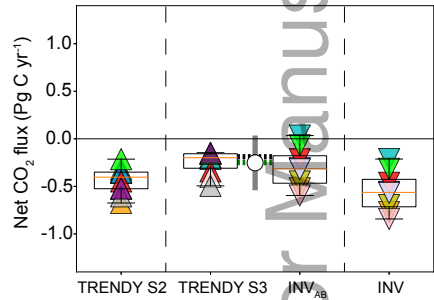
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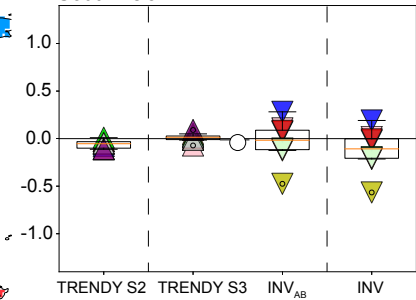
Atmospheric Inversion



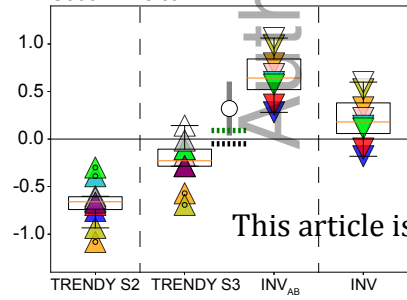
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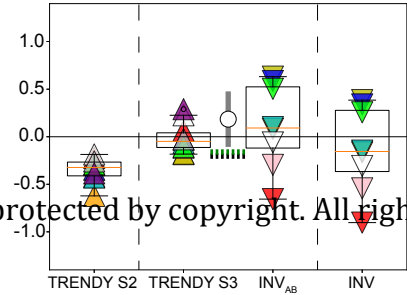
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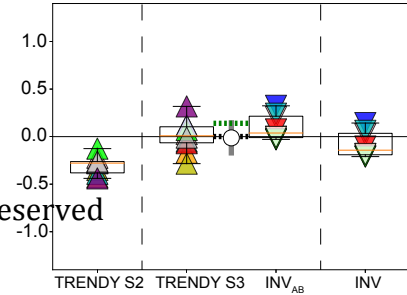
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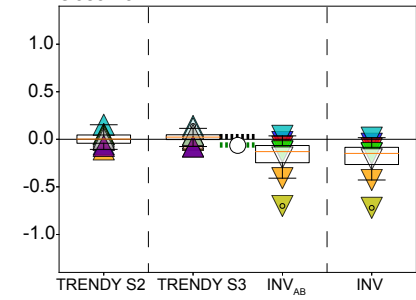
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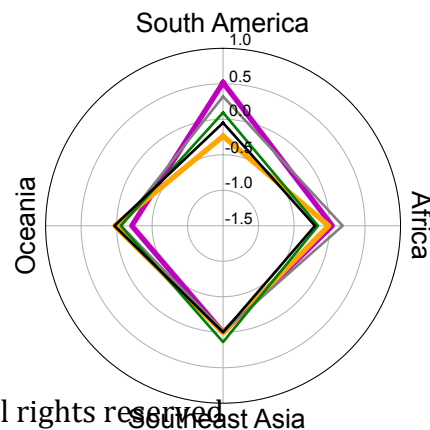
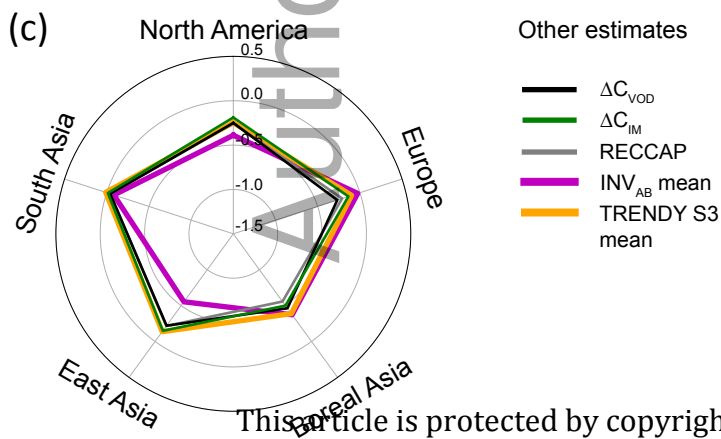
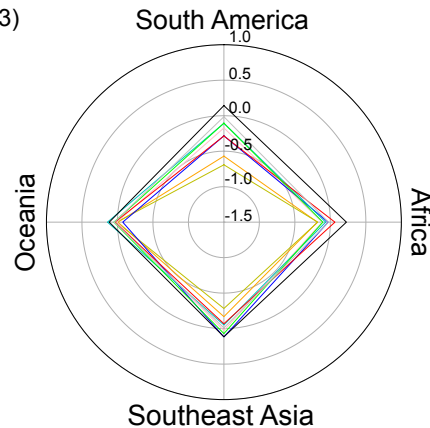
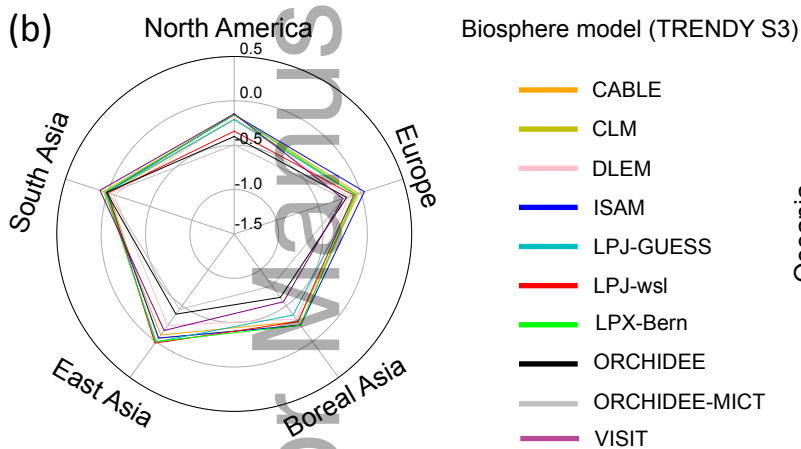
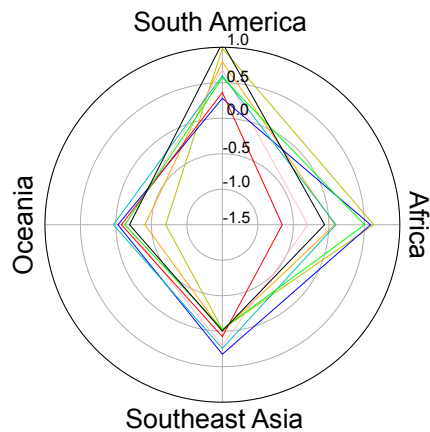
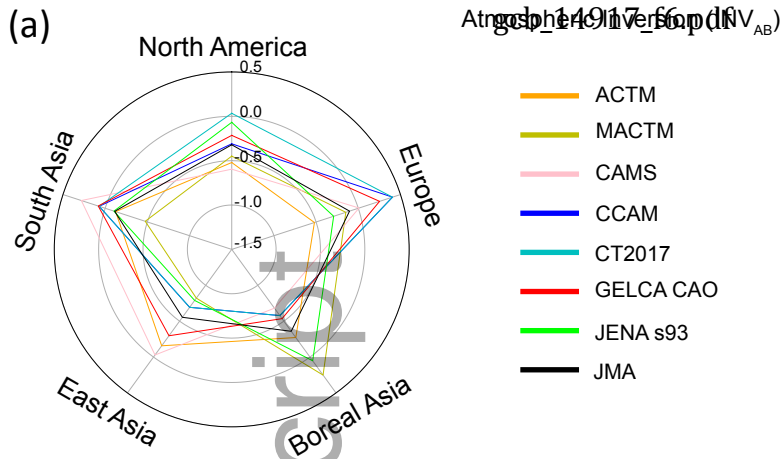
Southeast Asia



Oceania



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Northern extratropical lands

Southern+Tropical lands

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