

1 **The terrestrial biosphere as a net source of greenhouse gases to the atmosphere**

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13 **The terrestrial biosphere can release or absorb the greenhouse gases, carbon dioxide (CO₂),**
14 **methane (CH₄) and nitrous oxide (N₂O) and therefore plays an important role in regulating**
15 **atmospheric composition and climate¹. Anthropogenic activities such as land use change,**
16 **agricultural and waste management have altered terrestrial biogenic greenhouse gas fluxes**
17 **and the resulting increases in methane and nitrous oxide emissions in particular can**
18 **contribute to climate warming^{2,3}. The terrestrial biogenic fluxes of individual greenhouse**
19 **gases have been studied extensively⁴⁻⁶, but the net biogenic greenhouse gas balance as a**
20 **result of anthropogenic activities and its effect on the climate system remains uncertain.**
21 **Here we use bottom-up (BU: e.g., inventory, statistical extrapolation of local flux**
22 **measurements, process-based modeling) and top-down (TD: atmospheric inversions)**
23 **approaches to quantify the global net biogenic greenhouse gas balance between 1981-2010**
24 **as a result of anthropogenic activities and its effect on the climate system. We find that the**
25 **cumulative warming capacity of concurrent biogenic CH₄ and N₂O emissions is about a**
26 **factor of 2 larger than the cooling effect resulting from the global land CO₂ uptake in the**
27 **2000s. This results in a net positive cumulative impact of the three GHGs on the planetary**
28 **energy budget, with a best estimate of 3.9±3.8 Pg CO₂ eq/yr (TD) and 5.4±4.8 Pg CO₂ eq/yr**
29 **(BU) based on the GWP 100 metric (global warming potential on a 100-year time horizon).**
30 **Our findings suggest that a reduction in agricultural CH₄ and N₂O emissions in particular**
31 **in Southern Asia may help mitigate climate change.**

32 The concentration of atmospheric CO₂ has increased by nearly 40% since the start of the
33 industrial era, while CH₄ and N₂O concentrations have increased by 150% and 20%,
34 respectively^{3,7,8}. Although thermogenic sources (e.g., fossil fuel combustion and usage, cement
35 production, geological and industrial processes) represent the single largest perturbation of

36 climate forcing, biogenic sources and sinks also account for a significant portion of the land-
37 atmosphere exchange of these gases. Land biogenic GHG fluxes are those originating from
38 plants, animals, and microbial communities, with changes driven by both natural and
39 anthropogenic perturbations (see *Methods*). Although the biogenic fluxes of CO₂, CH₄ and N₂O
40 have been individually measured and simulated at various spatial and temporal scales, an overall
41 GHG balance of the terrestrial biosphere is lacking³. Simultaneous quantification of the fluxes of
42 these three gases is needed, however, for developing effective climate change mitigation
43 strategies^{9,10}.

44 In the analysis that follows, we use a dual-constraint approach from 28 bottom-up (BU)
45 studies and 13 top-down (TD) atmospheric inversion studies to constrain biogenic fluxes of the
46 three gases. We generate decadal mean estimates and 1-sigma standard deviations of CO₂, CH₄
47 and N₂O fluxes (mean ± SD with SD being the square root of quadratic sum of standard
48 deviations reported by individual studies) in land biogenic sectors by using the BU and TD
49 ensembles as documented in *Extended Data Table 1* and *Table S2* in *Supplementary Information*
50 (SI). Grouping GHG fluxes by sector may not precisely separate the contributions of human
51 activities from natural components. For instance, wetland CH₄ emission is composed of a natural
52 component (background emissions) and an anthropogenic contribution (e.g., emissions altered by
53 land use and climate change). Therefore, in this study, the anthropogenic contribution to the
54 biogenic flux of each GHG is distinguished by removing modeled pre-industrial emissions from
55 contemporary GHG estimates. To quantify the human-induced net biogenic balance of these
56 three GHGs and its impact on climate system, we use CO₂ equivalent units (CO₂-eq) based on
57 the global warming potentials (GWP) on a 100-year time horizon⁷. This choice has been driven
58 by the policy options being considered when dealing with biogenic GHG emissions and sinks^{7,11}.

59 To address the changing relative importance of each gas as a function of the selected time frame,
60 a supplemental calculation based on GWP metrics for a 20-year time horizon is also provided
61 (Table 1 and *Methods*).

62 We first examine the overall biogenic fluxes of all three gases in the terrestrial biosphere
63 during the period 2000-2009 (Figure 1). The overall land biogenic CH₄ emissions estimated by
64 TD and BU are very similar, 325 ± 39 Tg C/yr and 326 ± 43 Tg C/yr (1 Tg = 10^{12} g),
65 respectively. Among the multiple land biogenic CH₄ sources (*Extended Data Table 1*), natural
66 wetlands were the largest contributor, accounting for 40-50% of total CH₄ emissions during the
67 2000s, while rice cultivation contributed about 10%. The remaining CH₄ emissions were from
68 ruminants (~20%), landfills and waste (~14%), biomass burning (~4-5%), manure management
69 (~2%), and termites, wild animals and others (~6-10%). Both TD and BU results suggest a
70 global soil CH₄ sink that offsets approximately 10% of global biogenic CH₄ emissions, but this
71 flux is poorly constrained, especially by atmospheric inversions, given its distributed nature and
72 small magnitude.

73 Global biogenic N₂O emissions were estimated to be 12.6 ± 0.7 Tg N/yr and 15.2 ± 1.0
74 Tg N/yr by TD and BU methods, respectively. Natural ecosystems were a major source,
75 contributing ~55-60% of all land biogenic N₂O emissions during the 2000s, the rest being from
76 agricultural soils (~25-30%), biomass burning (~5%), indirect emissions (~5%), manure
77 management (~2%), and human sewage (~2%).

78 The estimates of the global terrestrial CO₂ sink in the 2000s are -1.6 ± 0.9 Pg C/yr (TD)
79 and -1.5 ± 1.2 Pg C/yr (BU). This estimate is comparable with the most recent estimates⁴, but
80 incorporates more data sources (Table S1 in *SI*).

81 Some CH₄ and N₂O emissions were present during pre-industrial times, while the global
82 land CO₂ uptake was approximately in balance with the transport of carbon by rivers to the ocean
83 and a compensatory ocean CO₂ source¹². Thus, the net land-atmosphere CO₂ flux reported here
84 represents fluxes caused by human activities. In contrast, for CH₄ and N₂O only the difference
85 between current and pre-industrial emissions represents net drivers of anthropogenic climate
86 change. When subtracting modeled pre-industrial biogenic CH₄ and N₂O emissions of 125±14
87 TgC/yr and 7.4±1.3TgN/yr, respectively, from the contemporary estimates (see *Methods*), we
88 find the heating capacity of human-induced land biogenic CH₄ and N₂O emissions is opposite in
89 sign and equivalent in magnitude to 1.7 (TD) and 2.0 (BU) times that of the current (2000s)
90 global land CO₂ sink using 100-year GWPs (Figure 1, Table 1). Hence there is a net positive
91 cumulative impact of the three GHGs on the planetary energy budget, with our “best estimate”
92 being 3.9±3.8 Pg CO₂ eq/yr (TD) and 5.4±4.8 Pg CO₂ eq/yr (BU). An alternative GWP metric
93 (e.g., GWP20 instead of GWP100) changes the relative importance of each gas, and gives a
94 different view of the potential of various mitigation options¹¹. Using GWP20 values, the
95 radiative forcing of contemporary (2000s) human-induced biogenic CH₄ emission alone is 3.8
96 (TD) or 4.2 (BU) times that of the land CO₂ sink in magnitude but opposite in sign, much larger
97 than its role using GWP100 metric (Table 1). Therefore, cutting CH₄ emissions is an effective
98 pathway for rapidly reducing GHG-induced radiative forcing and the rate of climate warming in
99 a short time frame^{8,11}.

100 On a 100-year time horizon, the cumulative radiative forcing of agricultural and waste
101 emissions alone, including CH₄ from paddy fields, manure management, ruminants, and landfill
102 and waste, along with N₂O emissions from crop cultivation, manure management, human sewage
103 and indirect emissions, are estimated to be 7.9±0.5 (BU) and 8.2±1.0 Pg CO₂ eq/yr (TD) for the

104 2000s, offsetting the human-induced land CO₂ sink by 1.4 to 1.5 times, respectively. In other
105 words, agriculture represents the largest contributor to this twofold offset of the land CO₂ sink.

106 We further examine the change of human-induced biogenic GHG fluxes over past three
107 decades (Figure 2, Table 1). The net biogenic GHG source shows a decreasing trend of 2.0 Pg
108 CO₂ eq/yr per decade ($p < 0.05$), primarily due to an increased CO₂ sink (2.2 (TD) and 2.0 (BU)
109 Pg CO₂ eq/yr per decade, $p < 0.05$), as driven by a combination of increasing atmospheric CO₂
110 concentrations, forest regrowth, and nitrogen deposition³. The net emissions of CO₂ from tropical
111 deforestation, included in the above net land CO₂ sink estimates, were found to decline or remain
112 stable due to reduced deforestation and increased forest regrowth¹³. However, one recent study
113 based on satellite observations¹⁴ suggests that the decreased deforestation in Brazil has been
114 offset by an increase in deforestation in other tropical countries during 2000-2012. There is no
115 clear decadal trend in total global biogenic CH₄ emissions from 1980 to 2010⁵. Since 2007,
116 increased CH₄ emissions seem to result in a renewed and sustained increase of atmospheric CH₄,
117 although the relative contribution of anthropogenic and natural sources is still uncertain¹⁵⁻¹⁷. The
118 BU estimates suggest an increase in human-induced biogenic N₂O emissions since 1980, at a rate
119 of 0.25 Pg CO₂ eq/yr per decade ($p < 0.05$), mainly due to increasing nitrogen deposition and
120 nitrogen fertilizer use, as well as climate warming¹⁸. With preindustrial emissions removed, the
121 available TD estimates of N₂O emissions during 1995-2008 reflect a similar positive trend,
122 although they cover a shorter period¹⁹.

123 The human-induced biogenic GHG fluxes vary by region (Figure 3). Both TD and BU
124 approaches indicate that human-caused biogenic fluxes of CO₂, CH₄, and N₂O in the biosphere
125 of Southern Asia (Figure 3) lead to a large net climate warming effect, because the 100-year
126 cumulative effects of CH₄ and N₂O emissions significantly exceed that of the terrestrial CO₂ sink.

127 Southern Asia has about 90% of global rice fields²⁰ and represents over 60% of the world's
128 nitrogen fertilizer consumption²¹, with 64-81% of CH₄ emissions and 36-52% of N₂O emissions
129 derived from the agriculture and waste sectors (Table S3 in *SI*). Given the large footprint of
130 agriculture in Southern Asia, improved fertilizer use efficiency, rice management and animal
131 diets could substantially reduce global agricultural N₂O and CH₄ emissions^{22,23}.

132 Africa is estimated to be a small terrestrial biogenic CO₂ sink (BU) or a CO₂-neutral
133 region (TD), but it slightly warms the planet when accounting for human-induced biogenic
134 emissions of CH₄ and N₂O, which is consistent with the finding of a recent study²⁴. South
135 America is estimated to be neutral or a small sink of human-induced biogenic GHGs, because
136 most current CH₄ and N₂O emissions in this region were already present during the pre-industrial
137 period, and therefore do not represent new emissions since the pre-industrial era. Using the
138 GWP100 metric, CO₂ uptake in North America and Northern Asia is almost equivalent in
139 magnitude or even larger than human-caused biogenic CH₄ and N₂O emissions but opposite in
140 sign, implying a small but significant role of the land biosphere in mitigating climate warming.
141 Europe's land ecosystem is found to play a neutral role, similar to a previous synthesis study⁹
142 using both BU and TD approaches.

143 Compared to global estimations, much more work on regional GHG budgets is
144 needed^{18,19}, particularly for tropical areas, as large uncertainty is revealed in both TD and BU-
145 derived GHG estimations. TD methods are subject to large uncertainties in their regional
146 attribution of GHG fluxes to different types of sources. Furthermore, some TD estimates used
147 BU values as priors, and may be heavily influenced by these assumed priors in regions where
148 atmospheric observations are sparse. In contrast, BU approaches are able to consider region-
149 specific disturbances and drivers (e.g., insects and disease outbreaks) that are important at

150 regional scale but negligible at global scale. However, the shortcoming of BU estimates is that
151 they may not be consistent with the well-observed global atmospheric growth rates of GHGs.
152 Also, accurate BU assessments are hindered by our limited understanding of microbial and
153 belowground processes and the lack of spatially-explicit, time-series datasets of drivers (e.g.,
154 wildfire, peatland drainage, wetland extent). The magnitude of human-induced CH₄ and N₂O
155 emissions reported here is more uncertain than the total emissions of these gases because it
156 contains both the uncertainty of pre-industrial emission and contemporary emission estimates
157 (see *Methods* for additional discussion).

158 This study highlights the importance of including all three major GHGs in global and
159 regional climate impact assessments, mitigation option and climate policy development. We
160 should be aware of the likely countervailing impacts of mitigation efforts, such as enhanced N₂O
161 emissions with soil C sequestration²⁵, increased CO₂ and N₂O emissions with paddy-drying to
162 reduce CH₄ emissions²⁶, enhanced CH₄ emissions with peatland fire suppression and rewetting to
163 reduce CO₂ and N₂O emissions²⁷, and increased indirect emissions from biofuel production²⁸.
164 The future role of the biosphere as a source or sink of GHGs will depend on future land use
165 intensification pathways and on the evolution of the land CO₂ sinks²⁹. If the latter continues
166 increasing as observed in the last three decades⁴, the overall biospheric GHG balance could be
167 reversed. However, the evolution of the land CO₂ sink remains uncertain, with some projections
168 showing an increasing sink in the coming decades³, while others showing a weakening sink due
169 to the saturation of the CO₂ fertilization effect and positive carbon-climate feedbacks^{3,30}.
170 Increasing land-use intensification using today's practices to meet food and energy demands will
171 likely increase anthropogenic GHG emissions²³. However, the results of this study suggest that

172 adoption of best practices to reduce GHG emissions from human-impacted land ecosystems
173 could reverse the biosphere's current warming role.

174

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265

266 **Author Contributions:** H.T. initiated this research and was responsible for the integrity of the
267 work as a whole. H.T. and C.L. performed analysis, calculations and drafted the manuscript. P.C.,
268 A.M. and J.C. contributed to data synthesis and manuscript development. B.Z., J.Y., G.C. and
269 S.P. contributed to data collection and analysis. E.S., D.H., K.G., S.S., P.B., L.B., E.D., P. F.,
270 J.M., B.P., R.P., M.S., C.S, and S.W. contributed to data provision, data processing, or
271 interpretation. All authors discussed and commented on the manuscript.

272

273 **Figure Legends:**

274 **Figure 1. The overall biogenic greenhouse gas (GHG) balance of the terrestrial biosphere in**
275 **the 2000s.** Top-Down (TD) and Bottom-Up (BU) approaches are used to estimate land CO₂ sink,
276 CH₄ and N₂O fluxes for four major categories merged from 14-sectors (*Extended Data Table 1*).
277 Global warming potential (GWP 100) is calculated after removing pre-industrial biogenic
278 emissions of CH₄ (125 ±14 TgC/yr) and N₂O (7.4 ±1.3 Tg N/yr). Negative values indicate GHG
279 sinks and positive values indicate GHG sources. *TD estimates of agricultural CH₄ and N₂O
280 emissions include CH₄ source from landfill and waste, and N₂O source from human sewage,
281 respectively.

282
283 **Figure 2. Changes in the decadal balance of human-induced biogenic greenhouse gases**
284 **(GHG) in the past three decades (GWP 100).** TD and BU denote Top-Down and Bottom-Up
285 estimates, respectively. Data points show individual gases (blue for CO₂, yellow for CH₄, and red
286 for N₂O) and human-induced GHG balance (black dots) derived from biogenic sources with pre-
287 industrial biogenic CO₂ sink, and CH₄ and N₂O emissions removed. Error bars show standard
288 deviation calculated from various estimate ensembles.

289
290 **Figure 3. The balance of human-induced biogenic greenhouse gases (GHG) for different**
291 **continents in the 2000s (GWP 100).** TD and BU denote Top-Down and Bottom-Up estimates,
292 respectively. Blue bars represent CO₂ flux, yellow for CH₄, and red for N₂O. Black dots indicate
293 net human-induced GHG balance and error bars are standard deviation of estimate ensembles.

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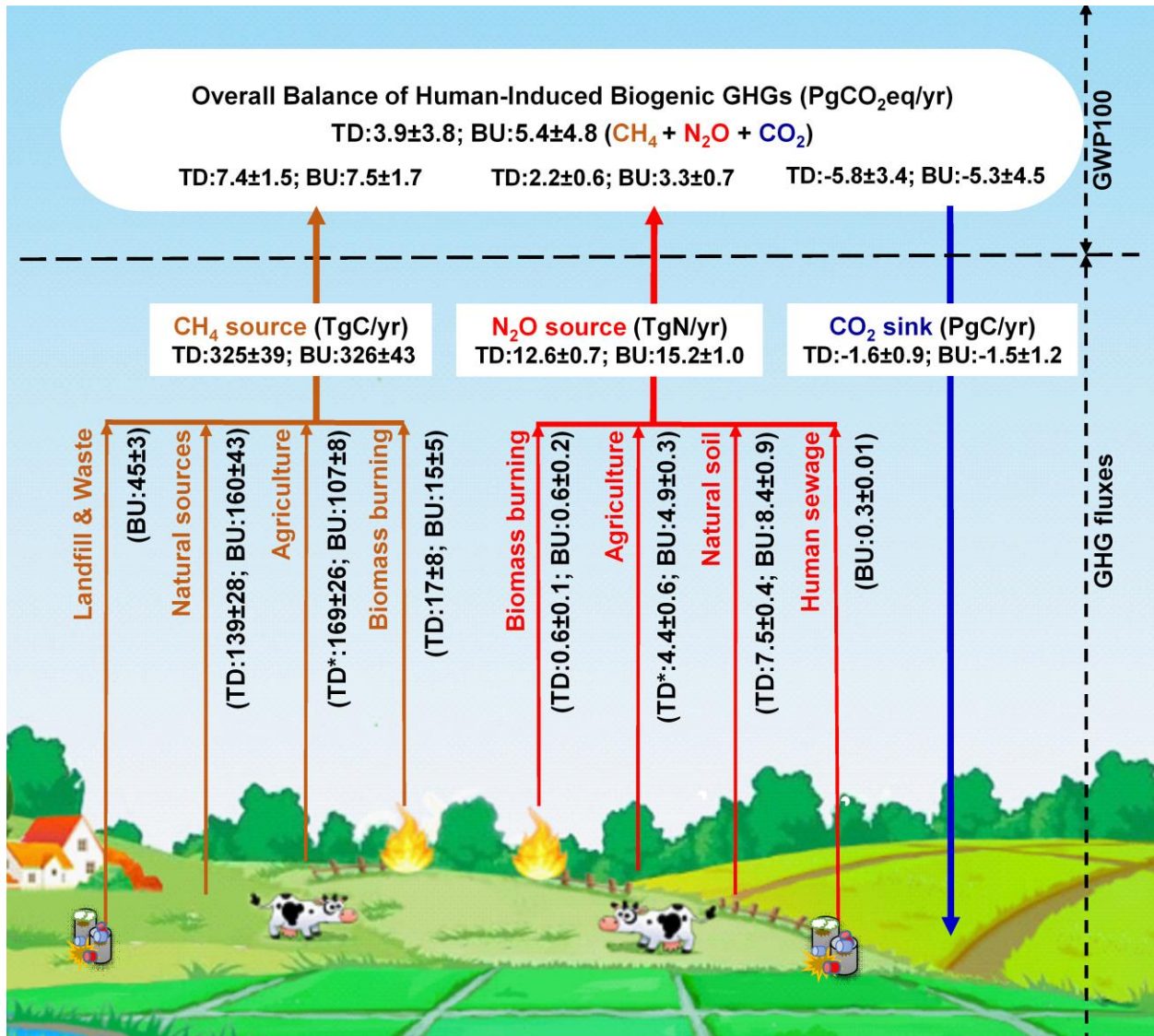
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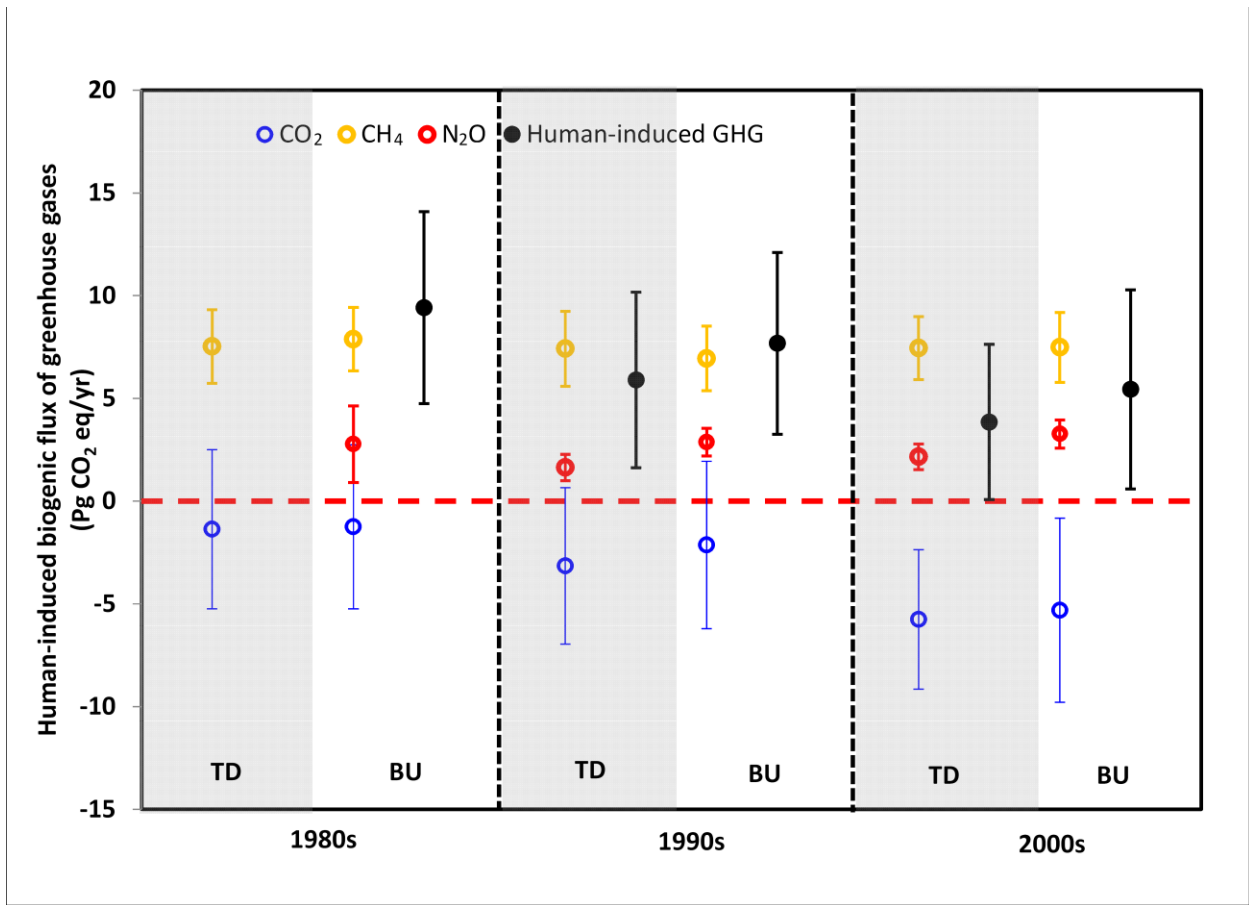
Table 1 Three-decadal estimates of human-induced biogenic GHGs in the terrestrial biosphere by using GWP100 and GWP20 metrics.

Human-Induced GHG (Pg CO ₂ eq/year)		1980s		1990s		2000s	
		TD	BU	TD	BU	TD	BU
GWP100	CO ₂ sink	-1.4 (3.9)	-1.2 (4.0)	-3.2 (3.8)	-2.1 (4.1)	-5.8 (3.4)	-5.3 (4.5)
	CH ₄ source	7.5 (1.8)	7.9 (1.5)	7.4 (1.8)	6.9 (1.6)	7.4 (1.5)	7.5 (1.7)
	N ₂ O source		2.8 (1.9)	1.6 (0.6)	2.9 (0.7)	2.2 (0.6)	3.3 (0.7)
	Overall GHG Balance		9.4 (4.7)	5.9 (4.3)	7.7 (4.4)	3.9 (3.8)	5.4 (4.8)
	Proportion of land CO ₂ sink being offset		-855%	-287%	-460%	-167%	-202%
GWP20	CO ₂ sink	-1.4 (3.9)	-1.2 (4.0)	-3.2 (3.8)	-2.1 (4.1)	-5.8 (3.4)	-5.3 (4.5)
	CH ₄ source	22.6 (5.4)	23.6 (4.6)	22.2 (5.5)	20.8 (4.7)	22.3 (4.6)	22.5 (5.1)
	N ₂ O source		2.8 (1.9)	1.6 (0.6)	2.9 (0.7)	2.2 (0.6)	3.3 (0.7)
	Overall GHG Balance		25.2 (6.4)	20.7 (6.7)	21.5 (6.3)	18.7 (5.8)	20.4 (6.8)
	Proportion of land CO ₂ sink being offset		-2118%	-757%	-1110%	-425%	-484%

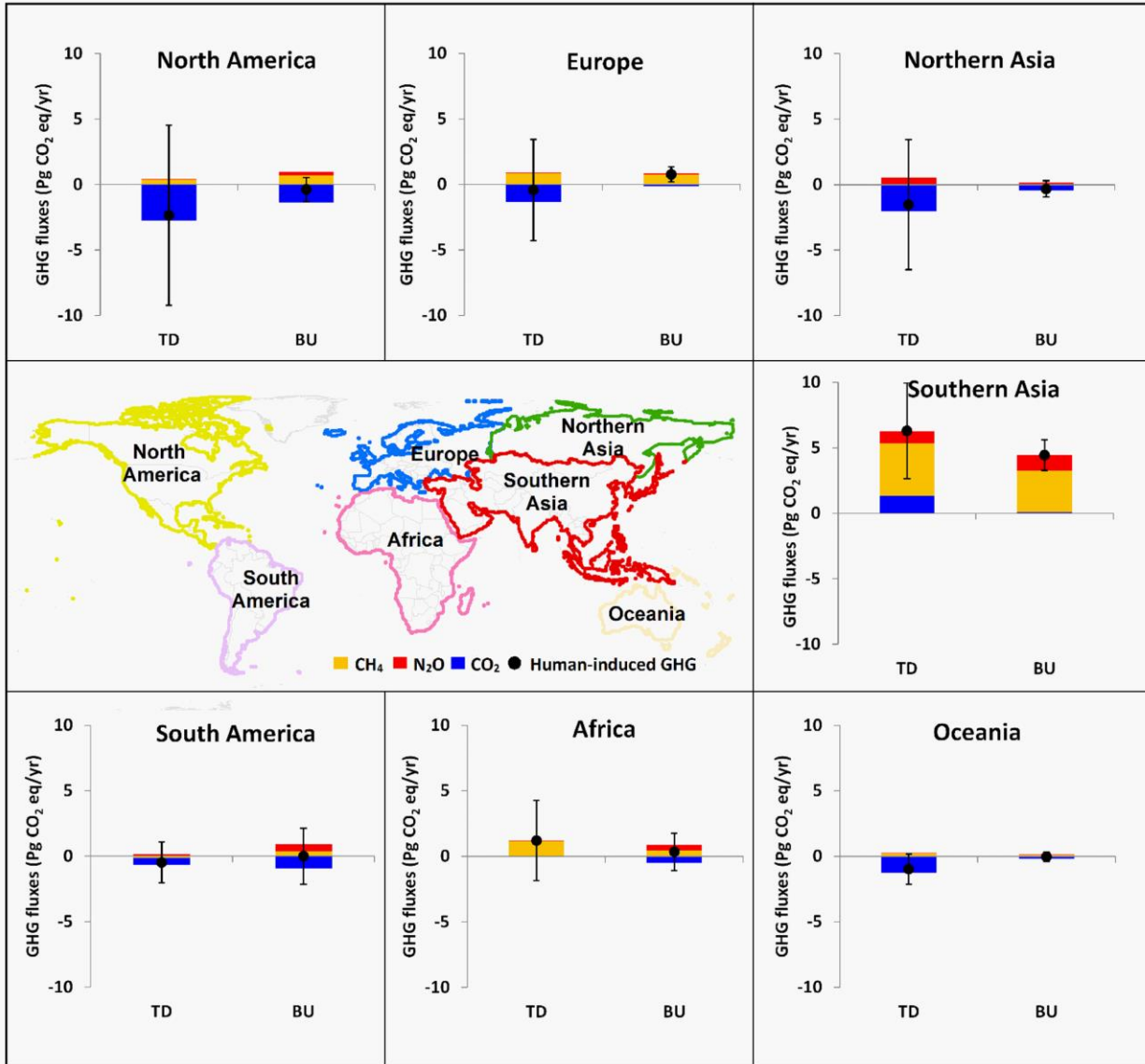
302 Note: Estimated human-induced biogenic fluxes of CO₂, CH₄ and N₂O in the terrestrial biosphere for the
303 1980s, 1990s, and 2000s based on global warming potential (GWP) on 20-, and 100-year time horizons.
304 Numbers in parenthesis represent 1-sigma standard deviations. TD and BU stand for top-down and
305 bottom-up estimates, respectively. The percentage numbers represent the proportion of land CO₂ sink that
306 has been offset by human-induced CH₄ and N₂O emissions in the terrestrial biosphere. Detailed data
307 sources and literature cited are provided in *SI*.

308
309
310





314



316 **Methods**

317 **Definition of biogenic GHG fluxes**

318 In this study, we define land biogenic GHG fluxes as those originating from plants, animals, and
319 microbial communities, with changes driven by both natural and anthropogenic perturbations.
320 For example, this analysis considers the biosphere-atmosphere CO₂ flux resulting from the direct
321 and indirect effects of anthropogenic activities, such as land use and management, climate
322 warming, rising atmospheric CO₂, and nitrogen deposition, but excludes CO₂ emissions due to
323 geological processes (e.g., volcanic eruption, weathering), fossil fuel combustion, and cement
324 production. Biogenic CH₄ fluxes include land-atmosphere CH₄ emissions by natural wetlands,
325 rice cultivation, biomass burning, manure management, ruminants, termites, landfills and waste,
326 as well as soil CH₄ uptake. Biogenic N₂O emissions include those released from agricultural
327 ecosystems (i.e., fertilized soil emission, manure management, human sewage, and indirect N₂O
328 emission from manure and synthetic nitrogen fertilizer use), natural ecosystems (i.e., soil
329 emissions and emissions from nitrogen re-deposition), and biomass burning.

330

331 **Data sources and calculation**

332 We synthesized estimates of biogenic CO₂, CH₄ and N₂O fluxes in the terrestrial biosphere
333 derived from 28 bottom-up (BU) studies and 13 top-down (TD) atmospheric inversion studies
334 for two spatiotemporal domains (global scale during 1981-2010 and continental scale during the
335 2000s). The first level data sets meeting our criteria are the most recent estimates of individual
336 GHG gases from multi-model inter-comparison projects (e.g., Atmospheric Tracer Transport
337 Model Inter-comparison Project-TransCom³¹, Trends in net land atmosphere carbon exchanges –
338 Trendy³², and Multi-scale Synthesis and Terrestrial Model Inter-comparison Project –
339 MsTMIP³³). Second, the estimate ensembles included the published global synthesis results that

340 report decadal land-atmosphere GHG exchange during 1981-2010⁴⁻⁶. Third, for those items that
341 lack detailed information from the above estimations (e.g., continental estimate of CH₄ emission
342 from rice fields and soil CH₄ sink, Table S1 in *SI*), we use multi-source published estimates and
343 a recent process-based modeling result¹⁸. We limit literature reporting the continental GHG
344 estimate to those studies that have close boundary delineation with our definition, and that have
345 gas flux estimates covering all continents. Only part of global studies we used has provided
346 continental estimates (Details on data sources can be found in Table S1 and S3 in *SI*).

347

348 In Le Quéré et al. (2014)⁴, net land CO₂ flux is the sum of carbon emission due to land use
349 change (E_{LUC}) and the residual terrestrial carbon sink (S_{LAND}). Estimates of budget residual, as
350 one of top-down approaches, are calculated as the sum of E_{LUC} and S_{LAND} (cited from Table 7 of
351 Le Quéré et al., 2014⁴). Land CO₂ sink estimated by the TRENDY model inter-comparison
352 project³² does not account for land use effects on terrestrial carbon dynamics, and we therefore
353 add land-use-induced carbon fluxes as estimated by IPCC AR5³ (Table 6.3) to obtain the net land
354 carbon sink estimates. However, land CO₂ sink estimated by MsTMIP project³⁴ is derived from
355 model simulations considering climate variability, atmospheric CO₂ concentration, nitrogen
356 deposition, as well as land use change. We directly use its model ensemble estimates in this
357 study. In addition, BU estimates of land CO₂ sink^{4,34} have been adjusted by removing the CO₂
358 emissions from drained peatland globally^{13,35}, because global land ecosystem models usually
359 overlook this part of carbon loss.

360

361 We include TD and BU estimates of CH₄ and N₂O emission from biomass burning. TD approach
362 (e.g., CarbonTracker-CH₄, Bruhwiler et al., 2014³⁶) considers all the emission sources and

363 growth rate in atmospheric concentration. For BU estimation (e.g., DLEM simulation, Tian et al.,
364 2012³⁷), we use historical fire data that is developed from satellite image and historical record, to
365 drive a process-based land ecosystem model, so the change in fire occurrence is naturally
366 considered. Other BU estimates, e.g., GFED (Van der Werf et al., 2010³⁸) and EDGAR (2014)³⁹
367 all include peatland fire emissions. We remove preindustrial CH₄ and N₂O emission that includes
368 source from biomass burning to estimate human-caused gas fluxes in the terrestrial biosphere.
369 The role of peatland fire in estimated CO₂ flux is similar to CH₄ and N₂O estimation: fire
370 emission is included in TD approach and historical fire is included as one of input drivers (or
371 counted as part of land use change in most BU models, e.g., fire occurrence in deforestation and
372 cropland expansion) in some models. Although peatland fire emission caused by human
373 activities is counted in our analysis, like other sectors, we cannot distinguish how much peat fire
374 is caused by human activity since no specific information is available on pre-industrial peatland
375 fire emission.

376
377 In summary, this study provides multi-level estimates on biogenic GHG fluxes, including global
378 biogenic fluxes of CO₂, CH₄, and N₂O during 1981-2010, continental-level estimates on biogenic
379 fluxes of CO₂, CH₄ and N₂O over the 2000s, and sector-based estimates on biogenic CH₄ and
380 N₂O fluxes over the 2000s. Extended Data Table 1 shows our estimates on biogenic CH₄ fluxes
381 for 8 sectors and N₂O fluxes for 6 sectors. These sectors are further merged into four major
382 categories for CH₄ and N₂O fluxes, respectively (Figure 1).

383

384 All the raw data and relevant calculation can be found in supplementary Table S2. Human-
385 induced biogenic CH₄ and N₂O emissions are calculated by subtracting the pre-industrial
386 emissions as estimated below.

387

388 **Pre-industrial biogenic GHG estimations**

389 Here we provide a description of how we estimated the pre-industrial GHG emissions. For CO₂
390 flux, since terrestrial ecosystem models assume the net land-air carbon flux in the pre-industrial
391 era is zero and the modeled C sink is solely human-driven, in order to make TD estimates
392 comparable to BU estimates, the CO₂ sink from TransCom simulations³¹ has been adjusted by
393 removing the natural CO₂ sink (0.45 Pg C/yr)¹² due to riverine transport from land to ocean. This
394 CO₂ sink of 0.45 Pg C/yr was allocated to each continent by using continental-scale estimates of
395 riverine carbon export by Ludwig et al. (2011)⁴⁰ and assuming 100 Tg C/yr of organic carbon is
396 buried and 50% of DIC export is degassing⁴¹.

397

398 Human-induced biogenic CH₄ and N₂O emissions are calculated by subtracting the pre-industrial
399 emissions. We define pre-industrial emissions as the GHG source under pre-industrial
400 environmental conditions and land-use patterns, including CH₄ and N₂O emissions from both
401 managed (e.g., crop cultivation) and non-managed ecosystems (e.g., natural wetlands, forests,
402 grassland, shrublands etc.). Preindustrial CH₄ estimate (125.4 ± 14.4 Tg C/yr) is composed of
403 CH₄ emission from natural wetland and vegetation (99.2 ± 14.3 Tg C/yr derived from Houweling
404 et al. (2008)⁴², Basu et al. (2014)⁴³ and unpublished result from DLEM model simulation with
405 potential vegetation map (excluding cropland cultivation and other anthropogenic activities)),
406 termites (15 Tg C/yr, Dlugokencky et al. (2011)⁴⁴), and wildfire and wild animal (3.75-7.5 Tg

407 C/yr each, Dlugokencky et al. (2011)⁴⁴). Preindustrial N₂O emission (7.4 ± 1.3 Tg N/yr) is
408 derived from the estimate of terrestrial N₂O emission (6.6 ± 1.4 Tg N/yr) by Davidson and
409 Kanter (2014)⁶, and DLEM simulation (8.1 ± 1.2 Tg N/yr) driven by environmental factors at
410 preindustrial level and potential vegetation map.

411

412 **Calculation and interpretation of global warming potential (GWP)**

413 GWP is used to define the cumulative impacts that the emission of 1 gram CH₄ or N₂O could
414 have on planetary energy budget relative to 1 gram reference CO₂ gas over a certain period (e.g.,
415 GWP100 and GWP20 for 100 or 20 years). To calculate CO₂ equivalents of the human-induced
416 biogenic GHG balance, we adopt 100-year GWPs of 28 and 265 for CH₄ and N₂O, respectively,
417 and 20-year GWPs of 84 and 264, respectively⁷. These values of GWP 20 and 100 used in this
418 study do not include carbon-climate feedbacks. The different contributions of each gas to the net
419 GHG balance will vary using different GWP time horizons (e.g., GWP20 versus GWP100, see
420 Table 1). In this study, we applied the following equation to calculate the human-induced
421 biogenic GHG balance:

422

$$GHG = F_{CO_2-C} \frac{44}{12} + F_{CH_4-C} \frac{16}{12} \times GWP_{CH_4} + F_{N_2O-N} \frac{44}{28} \times GWP_{N_2O}$$

423

424 Where F_{CO_2-C} , F_{CH_4-C} and F_{N_2O-N} are annual exchanges (unit: Pg C/yr or Pg N/yr) of
425 human-induced biogenic CO₂, CH₄ and N₂O between terrestrial ecosystems and the atmosphere
426 based on mass of C and N, respectively. The fractions $44/12$, $16/12$ and $44/28$ were used to
427 convert the mass of CO₂-C, CH₄-C and N₂O-N into CO₂, CH₄ and N₂O. GWP_{CH_4} (Pg CO₂ eq/Pg

428 CH₄) and GWP_{N_2O} (Pg CO₂ eq/Pg N₂O) are constants indicating integrated radiative forcing of
429 CH₄ and N₂O in terms of a CO₂ equivalent unit.
430
431 Nevertheless, it is noted that adoption of GWP100 to calculate CO₂ equivalent is not
432 fundamentally scientific but depends on a policy perspective. The relative importance of each
433 gas at a certain time period and likely mitigation option could change due to GWP metrics at
434 different time horizon (e.g., GWP20 and GWP100 according to Myhre et al., 2013⁷, Table 1).
435 For example, CH₄ has a shorter lifetime (~9 years), and its cumulative radiative forcing is
436 equivalent to 84 times same amount of CO₂ over 20 years, and 28 times same amount of CO₂
437 over 100 years. At a 20-year time horizon, anthropogenic CH₄ and N₂O emissions in the 2000s
438 are equivalent to 4.2-4.8 (TD-BU) times land CO₂ sink in magnitude but opposite in sign, and
439 net balance of human-induced GHG in the terrestrial biosphere is 20.4 ± 6.8 Pg CO₂ eq/yr and
440 18.7 ± 5.8 Pg CO₂ eq/yr as estimated by BU and TD approaches, respectively. Among them,
441 anthropogenic CH₄ emissions are 7-10 times (BU-TD) as much as N₂O emissions in terms of
442 GWP20. At a 20-year time horizon, the cumulative radiative forcing of contemporary
443 anthropogenic CH₄ emission alone is 3.8-4.2 (TD-BU) times as much as that of land CO₂ sink
444 but opposite in sign, larger than its role at 100-year time horizon (1.3-1.4 times radiative forcing
445 of CO₂ sink). Therefore, to cut CH₄ emission could rapidly reduce GHG-induced radiative
446 forcing in a short time frame^{7,8,44}.

447

448 **Statistics**

449 We use mean \pm 1-sigma standard deviations (SD) to indicate the best estimates and their ranges.
450 Estimate ensembles are grouped for the TD and BU approaches, and the mean value of multiple

451 ensembles is calculated for each gas in a certain region and period. In the TD and BU groups, we
452 assume the individual estimates are independent from each other, and therefore, the SD for each
453 ensemble mean is calculated as the square root of the quadratic sum of standard deviations
454 reported in each estimate.

455

456 **Continental-level estimations and divergence of biogenic-GHG fluxes**

457 Using the TD and BU ensembles, we estimated the net human-induced biogenic GHG balance
458 during the 2000s for 7 continents or regions, which include North America, South America,
459 Europe, Northern Asia, Southern Asia, Africa and Oceania (Figure 1). Primarily owing to large
460 CH₄ and N₂O emissions, both approaches show that Southern Asia is a net human-induced
461 biogenic GHG source in the magnitude of 6.3 ± 3.7 and 4.4 ± 1.2 Pg CO₂ eq/yr as estimated by
462 TD and BU, respectively, with the GWP100 metric (Table S3). Southern Asia has about 90% of
463 the global rice fields and represents over 60% of the world's nitrogen fertilizer consumption.
464 China and India together consume half of global nitrogen fertilizer²¹. This leads to the highest
465 regional CH₄ and N₂O emissions as the two approaches consistently reveal. This finding is also
466 consistent with previous studies conducted in China and India⁴⁵⁻⁴⁷. South America was estimated
467 to be a CO₂ sink with a large uncertainty (Table S3). Although South America is a large CH₄ and
468 N₂O source, most of these emissions are present at pre-industrial times. Natural wetlands in
469 South America accounted for 31-40% of global wetland CH₄ emissions in the 2000s, and 26-30%
470 of the global natural soil N₂O emissions were derived from this region. Therefore, the
471 contribution of this continent to human-induced GHG balance is negligible or acts as a small
472 sink. Likewise, Africa is estimated to be a small CO₂ sink or CO₂-neutral region, but adding CH₄

473 and N₂O emissions makes this continent contribute a small positive radiative forcing, slightly
474 warming the planet.
475
476 North America and Northern Asia are found to be a neutral region to net human-induced
477 biogenic GHG sink, with 100-year cumulative radiative forcing of biogenic CH₄ and N₂O
478 emissions fully or partially offsetting that of land CO₂ sink in this continent (Table S3). The
479 largest CO₂ sink was found in North America, ranging from -0.37 ± 0.22 to -0.75 ± 1.87 Pg C/yr
480 as estimated by TD and BU, respectively, likely due to larger area of highly productive and
481 intensively managed ecosystems (e.g., forests, woodlands, and pasture) that were capable of
482 sequestering more CO₂. Our estimate falls within the newly-reported CO₂ sink of -0.28 to -0.89
483 Pg C/yr in North America by synthesizing inventory, atmospheric inversions, and terrestrial
484 modeling estimates⁴⁸. Considering three gases together, TD estimates showed that the North
485 America acts as a net GHG sink with a large standard deviation (human-induced biogenic GHG
486 of -2.35 ± 6.87 Pg CO₂ eq/yr, Figure 3 and Table S3). By contrast, BU estimates suggested that
487 North America was a small GHG sink, in the magnitude of -0.38 ± 0.93 Pg CO₂ eq/yr based on
488 GWP100. Our estimate is comparable to previous GHG budget syntheses for North America^{10,37}.
489 TD estimates indicated that Oceania and Europe act as a small negative net radiative forcing over
490 100 years (-0.98 ± 1.17 and -0.42 ± 3.86 Pg CO₂ eq/yr, respectively), while BU estimates
491 indicated a negligible contribution in Oceania, and a positive net radiative forcing (0.76 ± 0.57
492 Pg CO₂ eq/yr) in Europe. According to BU estimates, CO₂ emission from drained peatland in
493 Europe accounted for about one third of global total during the period 2000s³⁵, which partially
494 explains the warming effect of biogenic GHG in this region as revealed by BU.
495

496

497 It is important to note that only human-caused biogenic GHG fluxes are included in this study,
498 and the regional GHG balance will clearly move towards a net source if the emissions related to
499 fossil fuel combustion and usage are taken into account.

500

501 Our analyses indicate that the TD and BU estimates show a larger divergence at continental scale
502 than global scale. We notice that the high radiative forcing estimate of human-induced biogenic
503 GHG balance (6.30 ± 3.66 Pg CO₂ eq/yr) in the TD approach in Southern Asia is partially
504 because the land biosphere in this region is estimated to be a net CO₂ source of 0.36 Pg C/yr with
505 a large standard deviation of 0.99 Pg C/yr by TransCom Inversions^{31,49}. It includes CO₂ sources
506 and sinks from respiration, primary production, disturbances, rivers outgassing, and land use
507 change. In contrast, most BU estimations using land ecosystem models do not consider the full
508 set of factors responsible for CO₂ release^{32,33}. The discrepancy between TD and BU estimates for
509 Southern Asia may come from several reasons. First, the land use history data commonly used
510 for driving terrestrial biosphere models, e.g., HYDE⁵⁰ and GLM⁵¹, was reported to overestimate
511 cropland area and cropland expansion rate in China and to under-estimate it in India compared to
512 regional dataset^{52,53}, thus biasing BU estimates of land conversion-induced carbon fluxes. But
513 none of BU models included in this study conducted global simulation with such regional dataset
514 updated. Second, large uncertainties exist in estimating carbon release due to tropical
515 deforestation^{4,54-57}. Third, carbon emissions due to peat fires and peatland drainage were a large
516 but usually ignored carbon source in tropical Asia (EDGAR 4.2³⁹ and Joosten et al., 2010³⁵). In
517 the BU estimates we included, some models consider peat fire by using input driver of fire
518 regime from satellite images, while most of them don't consider drained peatland and accelerated

519 SOC decomposition. Therefore, BU models may underestimate the CO₂ emissions at intensively-
520 disturbed areas, resulting in a small CO₂ source of 0.03 ± 0.29 Pg C/yr. BU estimations show
521 that the net human-induced biogenic GHG balance in Southern Asia turned out to warm the
522 planet with the 100-year cumulative radiative forcing of 4.44 ± 1.17 Pg CO₂ eq/yr.

523

524 Net GHG balance in Africa was positive but with discrepancy between the TD and BU
525 approaches. TD estimates suggest that Africa was a weak source of CO₂ and a strong source of
526 CH₄ and N₂O, resulting in a positive net radiative forcing of 1.20 ± 3.05 Pg CO₂ eq/yr. However,
527 BU ensembles estimate that African terrestrial biosphere acted as a relatively smaller climate
528 warmer (0.34 ± 1.42 Pg CO₂ eq/yr) due to an anthropogenic land sink of CO₂ (-0.52 ± 1.38 Pg
529 CO₂ eq/yr) and a strong source of CH₄ and N₂O. The divergent estimates in Africa might have
530 several reasons. First, it was difficult to constrain emissions using TD in this region, due to the
531 lack of atmospheric data. No tropical continent is covered by enough atmospheric GHG
532 measurement stations, making the TD results uncertain in those regions, with almost no
533 uncertainty reduction from the prior knowledge assumed before inversion. Second, there were
534 also large uncertainties in BU estimates. Some of the BU models ignored fire disturbance that is
535 likely to result in a carbon source of 1.03 ± 0.22 Pg C/yr in Africa^{24,38} and this emission has been
536 partially offset by carbon uptake due to regrowth. Another reason might be the overestimated
537 CO₂ fertilization effect, which could be limited by nutrient availability. Only few BU models
538 addressed interactive nutrient cycles in their simulation experiments³².

539

540 **Uncertainty sources and future research needs**

541 A wide variety of methods, such as statistical extrapolations, and process-based and inverse
542 modeling, were applied to estimate CO₂, CH₄ and N₂O fluxes. TD methods are subject to large
543 uncertainties in their regional attribution of GHG fluxes to different type of sources⁵⁸. BU
544 approaches are however limited by our understanding of underlying mechanisms and the
545 availability and quality of input data. In addition, the TD approach is dependent on BU estimates
546 as prior knowledge, especially in the tropics where both uncertainties are very large.

547

548 For example, terrestrial CO₂ uptake estimates from process-based model ensembles in Africa,
549 South America, and Southern Asia are larger than those from TD approaches, while smaller than
550 TD estimates in North America, Europe, Oceania and Northern Asia (Figure 3, Table S3). The
551 larger BU CO₂ sink estimate might be related to biased land use history data, excluded fire
552 emission and CO₂ release due to extreme disturbances such as insect outbreaks and
553 windthrow^{24,32}. Another reason is the lack of fully-coupled carbon-nitrogen-phosphorous cycles
554 in most BU models that overestimate the CO₂ fertilization effect particularly in regions of large
555 biomass and large productivity⁵⁹⁻⁶¹. However, larger CO₂ sink observed from tropical regrowth
556 forests compared to intact forests⁵⁵ might be underestimated because few models are capable of
557 capturing CO₂ uptake related to tropical secondary forest management and age structure. The
558 post-disturbance and plantation-induced shift toward rapid carbon accumulation in young forests
559 that were poorly or not represented in terrestrial ecosystem models might be one of the factors
560 responsible for CO₂ sink underestimation as revealed by several studies conducted in mid- and
561 high-latitudes⁶²⁻⁶⁴. The modeled ecosystem responses to frequent occurrence of extreme climate
562 events in BU studies are another uncertainty in estimating variations of land CO₂ sink^{65,66}.

563

564 The estimates of terrestrial CH₄ fluxes remain largely uncertain. One major uncertainty in BU
565 wetland CH₄ emission estimate is wetland areal extent data⁶⁷. Global inundated area extent was
566 reported to decline by approximately 6% during 1993-2007 with the largest decrease in tropical
567 and subtropical South America and South Asia⁶⁸. However, the majority of BU models failed
568 either in capturing dynamic inundation area or in simulating inundation and saturated conditions.
569 Tropical emissions, the dominant contributor for global wetland emission, are particularly
570 difficult to quantify due to sparse observations for both TD (atmospheric mixing ratios) and BU
571 (flux measurements) approaches and large interannual, seasonal variability, and long-term
572 change in the inundation extent for the BU modeling approach^{5,36,68}. At high latitudes, current
573 dynamic inundation data could not well represent permanent wetlands⁶⁷, most of which are
574 occupied by peatland. Due to large soil carbon storage in peatlands, such area is an important
575 CH₄ source. In addition, a large divergence exists in the estimation of rice field CH₄ emissions
576 (Table S2). The estimated global CH₄ emissions from rice fields are sensitive to rice field area,
577 management practices (e.g., water regime, nutrient fertilizer), and local climate and soil
578 conditions that directly affect activities of methanotroph and methanogen^{20,69,70}. Models need
579 better representation of CH₄ production and consumption processes modified by agricultural
580 management, such as continuous flooding, irrigation with intermediate drainage, or rainfed⁷⁰.
581
582 Compared to CO₂ and CH₄, there were fewer studies for global N₂O emissions. The TD
583 approach is constrained by sparse or inconsistent measurements of atmospheric N₂O mixing
584 ratios^{19,71}. Decadal trends during 1981-2010 from BU approaches were primarily from two
585 process-based models^{18,72}, instead of IPCC methodology based on the N₂O emission factors. The
586 major uncertainty source, therefore, includes data characterizing spatiotemporal variation of

587 reactive nitrogen enrichment, modeling schemes representing multiple nitrogen forms,
588 transformation, and their interactions with other biogeochemical and hydrological cycles, as well
589 as key parameters determining the sensitivity of N₂O emission to temperature, soil moisture, and
590 availability of oxygen^{45,46,72-74}. A large divergence exists in the estimation of natural soil N₂O
591 emission by inventory, empirical and process-based models, implying that our understanding of
592 the processes and their controls remain uncertain^{18,72,75-77}. Tropical areas are the major
593 contributors to large divergence. N₂O sources from tropical undisturbed wetland and drained
594 wetland/peatland are likely to be underestimated⁷⁸.

595

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Extended Data Table 1 | Decadal estimates of global terrestrial CO₂, CH₄ and N₂O fluxes derived from Top-Down and Bottom-Up approaches

GHG	Sector	1980s		1990s		2000s	
		Top-down	Bottom-up	Top-down	Bottom-up	Top-down	Bottom-up
CO ₂ (Pg C/yr)	Net land CO₂ sink	-0.4±1.1	-0.3±1.1	-0.9±1.0	-0.6±1.1	-1.6±0.9	-1.5±1.2
	1) Natural wetland	125.3±43.5	168.8±31.1	112.5±6.0	154.5±36.0	131.3±24.8	162.8±40.1
	2) Soil sinks	-15.8±6.4	-19.7±14.3	-20.3±0.0	-21.5±14.3	-24.0±6.0	-22.6±14.3
	3) Termite, Wild animal & Others	27.0±0.4	19.5±3.8	24.0±5.3	19.5±3.8	32.3±10.5	19.5±3.8
	Natural*	136.5±44.0	168.6±34.5	116.3±8.0	152.5±38.9	138.8±27.6	159.6±42.8
	4) Biomass burning	34.5±2.3	16.3±5.7	28.5±3.6	19.1±7.9	17.3±7.9	14.8±5.4
	5) Rice cultivation		45.4±16.8	86.3±21.0	26.3±5.6	33.0±2.0	28.9±7.6
	6) Manure management		7.8±0.2		7.9±0.1		8.0±0.3
	7) Ruminant		64.8±2.2		66.0±0.9		70.0±3.3
	8) Landfill and Waste		33.6±2.3		39.5±2.0		44.7±3.3
CH ₄ (Tg C/yr)	Agriculture & Waste*	156.0±12.4	151.6±17.1	179.3±45.4	139.7±6.0	168.8±26.4	151.6±9.0
	Net CH₄ flux	327.0±45.7	336.5±38.7	324.0±46.6	311.3±39.5	324.8±38.6	325.9±43.3
	Pre-industrial CH₄ emission	125.4±14.4					
	Human-induced CH₄ flux	201.6±48.1	211.0±41.3	199.6±48.8	185.8±42.1	199.4±41.2	200.5±45.7
	1) Natural soil		7.9±1.3	6.6±0.5	8.2±1.3	7.5±0.4	8.4±0.9
	2) Biomass burning		0.7±0.1	0.7±0.1	0.7±0.1	0.6±0.1	0.6±0.2
	3) Agricultural soil		2.6±0.3		3.3±0.2		4.0±0.3
	4) Manure management		0.2±0.0		0.2±0.0		0.3±0.0
	5) Indirect emission		0.5±0.1		0.9±0.1		0.7±0.1
	6) Human Sewage		0.2±0.6		0.2±0.0		0.3±0.0
N ₂ O (Tg N/yr)	Agriculture & Waste *		4.7±4.2	4.1±0.6	4.6±0.2	4.4±0.6	5.5±0.7
	Net N₂O flux		14.0±4.3	11.3±0.8	14.3±0.9	12.6±0.7	15.2±1.0
	Pre-industrial N₂O emission	7.4±1.3					
	Human-induced N₂O flux		6.6±4.5	3.9±1.5	6.9±1.6	5.2±1.5	7.8±1.6

Note: * denotes that additional data are included in the calculation of greenhouse gas fluxes from this sub-total sector. Therefore, the sub-total GHG fluxes are not necessarily equal to the sum of individual sector values shown in this table. The complete set of data used for calculation could be found in supplementary Table S2.

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