Multi-gas and multi-source comparisons of six land use emission datasets and AFOLU estimates in the Fifth Assessment Report, for the tropics for 2000-2005.

Short title: AFOLU dataset comparisons

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34   Forestry, LULUCF, mitigation, Fifth Assessment Report, gross emissions flux.

36   **ABSTRACT**

37   The Agriculture, Forestry and Other Land Use (AFOLU) sector contributes with ca. 20-25%

38   of global anthropogenic emissions (2010), making it a key component of any climate change

39   mitigation strategy. AFOLU estimates remain, however, highly uncertain, jeopardizing the

40   mitigation effectiveness of this sector. Comparisons of global AFOLU emissions have shown

41   divergences of up to 25%, urging for improved understanding on the reasons behind these

42   differences. Here we compare a diversity of AFOLU emission datasets (i.e. FAOSTAT,

43   EDGAR, the newly developed AFOLU "Hotspots", "Houghton", "Baccini", and EPA) and

44   estimates given in the Fifth Assessment Report, for the tropics (2000-2005), to identify

45   plausible explanations for the differences in: i) aggregated gross AFOLU emissions, and ii)

46   disaggregated emissions by sources, and by gases (CO_2, CH_4, N_2O). We also aim to iii)

47   identify countries with low agreement among AFOLU datasets, to navigate research efforts.

48   Aggregated gross emissions were similar for all databases for the AFOLU: 8.2 (5.5-12.2), 8.4

49   and 8.0 Pg CO_2e.yr^{-1} (Hotspots, FAOSTAT and EDGAR respectively), Forests: 6.0 (3.8-10),

50   5.9, 5.9 and 5.4 PgCO_2e.yr^{-1} (Hotspots, FAOSTAT, EDGAR, and Houghton), and

51   Agricultural sectors: 1.9 (1.5-2.5), 2.5, 2.1, and 2.0 PgCO_2e.yr^{-1} (Hotspots, FAOSTAT,

52   EDGAR, and EPA). However, this agreement was lost when disaggregating by sources,

53   continents, and gases, particularly for the forest sector, with fire leading the differences.

54   Agricultural emissions were more homogeneous, especially livestock, while croplands were

55   the most diverse. CO_2 showed the largest differences among datasets. Cropland soils and

56   enteric fermentation led the smaller N_2O and CH_4 differences. Disagreements are explained

57   by differences in conceptual frameworks (i.e. carbon-only *vs* multi-gas assessments,

58   definitions, land use versus land cover, etc), in methods (Tiers, scales, compliance with

59   Intergovernmental Panel on Climate Change (IPCC) guidelines, legacies, etc) and in

60   assumptions (i.e. carbon neutrality of certain emissions, instantaneous emissions release, etc)

61   that call for more complete and transparent documentation for all the available datasets.

62   Enhanced dialogue between the carbon (CO_2) and the AFOLU (multi-gas) communities is

63   needed to reduce discrepancies of land use estimates.

64

1. INTRODUCTION

66   Modelling studies suggest that to keep the global mean temperature increase to less than 2°C

67   and to remain under 450 ppm of CO_2 by 2100, CO_2 emissions must be cut 41-72% below

68   2010 levels by 2050 (IPCC, 2014), and global emissions levels must be reduced to zero (a

69   balance between sources and sinks) before 2070 and below zero, through removal processes,

70   after that (Anderson, 2015; UNEP, 2015). To reach these ambitious goals, tremendously rapid

improvements in energy efficiency and nearly a quadrupling of the share of zero and low

carbon energy supply (i.e. renewables, nuclear energy, and carbon dioxide capture and storage

(CCS), including bioenergy (BECCS)) would be needed by 2050 (IPCC, 2014; Friedlingstein

et al., 2014; UNEP, 2015). Since there is no scientific evidence on the feasibility of CCS

technologies (Anderson, 2015), renewables and the land use sector are among the most

plausible options (Canadell and Schulze, 2014). Optimistic estimates suggest that the AFOLU

sector (here indistinctively also called land use sector) could contribute from 20 to 60% of the

total cumulative abatement to 2030 including bioenergy (Smith et al., 2014).

The Agriculture, Forestry, and other Land Use (AFOLU) sector roughly contributes with a

quarter (10-12 $PgCO_2e.yr^{-1}$) of the total anthropogenic greenhouse gas (GHG) emissions (50

$PgCO2e.yr^{-1}$) (Smith et al., 2014) through a few human activities: deforestation, forest

degradation, and agriculture including cropland soils, paddy rice, and livestock (Smith et al.,

2014). Despite the acknowledged importance of the emissions from the land use sector in

global mitigation strategies, assessing GHG emissions and removals from this sector remains

technically and conceptually challenging (Abad-Viñas et al., 2014; Ciais et al., 2014). This

challenge relates to an incomplete understanding of the processes that control the emissions

from the land use sector (Houghton et al., 2012), especially post-disturbance dynamics (Frank

et al., 2015; Poorter et al., 2016) and to various sources of error that range from inconsistent

definitions, methods, and technical capacities (Romijn et al., 2012, 2015; Abad-Viñas et al.,

2014), to special features of the land use sector such as legacy and reversibility/non-

permanence effects (Estrada et al., 2014), or to the difficulty to separate anthropogenic from

natural emissions (Estrada et al., 2014; Smith et al., 2014). As a result, the AFOLU emissions

are the most uncertain of the all the sectors in the global budget, reaching up to 50 percent of

the emissions mean (Houghton et al., 2012; Smith et al., 2014; Tubiello et al., 2015). This is

important since uncertainties jeopardize the effectiveness of the AFOLU sector to contribute

to climate change mitigation. Thus, country compliances to their mitigation targets are likely

to be controversial when the uncertainty is equal to or greater than the pledged emission

reductions (Grassi et al., 2008; Pelletier et al., 2015).

Currently, data on AFOLU emissions are available through national greenhouse gas

inventories, which are submitted to the United Nations Framework Convention on Climate

Change (UNFCCC), but these national estimates cannot be objectively compared due to

differences in definitions, methods, and data completeness (Houghton et al., 2012; Abad-

Viñas et al., 2014). More comparable AFOLU data are offered in global emission databases

such as EDGAR or FAOSTAT (Smith et al., 2014; Tubiello et al., 2015), or more sectorial

datasets such as the Houghton's Forestry and other Land Use (FOLU) data (Houghton et al.,

2012), and the US Environmental Protection Agency non-CO_2 emissions for agriculture -

including livestock (USEPA, 2013). While national inventories and global databases are

currently the best bottom up emissions data we count on, their utility to inform on what the

atmosphere receives has been contested. Late research shows disagreements between the

trends of reported emissions and atmospheric growth since 1990 for CO_2 (Francey et al.,

2010, 2013a, 2013b), for CH_4 (Montzka et al., 2011), and for N_2O (Francey et al., 2013b). In

the case of CO_2, Francey *et al.* conclude that the differences between atmospheric and

emission trends for CO_2 might be more related to under-reported emissions (~9 PgC = 33

$PgCO_2$ for the period 1994-2005), than to adjustments in the terrestrial sinks (i.e. increased

CO_2 removals in oceans and forests). On the other hand, global AFOLU databases suffer from

inconsistencies that lead to global CO_2e emissions differences of up to 25% (2000-2009)

(Tubiello et al., 2015): 12.7 vs 9.9 $PgCO_2e.yr^{-1}$ for EDGAR and FAOSTAT, respectively.

These datasets also disagreed in the contribution of the AFOLU sector to the total

anthropogenic budget in 2010 (i.e. 21% and 24% for FAOSTAT vs EDGAR) (Tubiello et al., 2015), and on the relative share of the emissions from agriculture versus FOLU since 2010 Tubiello et al., 2015). Thus, while EDGAR implies a relatively equal contribution (IPCC, 2014), FAOSTAT reports agricultural emissions being larger contributors to the total anthropogenic budget (11.2±0.4%) than forestry and other land uses (10±1.2%) (Tubiello et al., 2015), with a steady growth trend of 1% since 2010.

Understanding the inconsistencies among AFOLU datasets is an urgent task since they preclude our accurate understanding of land-atmosphere interactions, GHG effects on climate forcing and, consequently, the utility of modelling exercises and policies to mitigate climate change (Houghton et al., 2012; Grace et al., 2014; Smith et al., 2014; Sitch et al., 2015; Tian et al., 2016). The land use sector plays a prominent role in the Paris Agreement (Art.5), with many countries including it as mitigation targets in their Nationally Determined Contributions (NDCs) (Grassi and Dentener, 2015; Richards et al., 2015; Streck, 2015). It is then urgent to understand how much and why different AFOLU datasets differ in their emissions estimates, so that we can better navigate countries' land-based mitigation efforts, and help to validate their proposed claims under the UNFCCC.

Here we compare gross AFOLU emissions estimates for the tropics, for 2000-2005, from six datasets: FAOSTAT, EDGAR, "Houghton", "Baccini", the US Environmental Protection Agency data (EPA), and a recently produced, spatially explicit AFOLU dataset, that we will hereon call "Hotspots" (Roman-Cuesta et al,. 2016). We aim to identify differences and plausible explanations behind: i) aggregated AFOLU, FOLU and Agricultural gross emissions, ii) disaggregated contributions of the emission sources for the different datasets,

145 iii) disaggregated contribution of the different gases (CO_2, CH_4, N_2O), and iv) national scale

146 disagreements among datasets.

147

148 **2. METHODS**

149 *2.1 Study area*

150 Our study area covers the tropics and the subtropics, including the more temperate regions of

151 South America (33° N to 54° S, 161° E to 117° W). Land use change occurs nowhere more

152 rapidly than in the tropics (Poorter et al., 2016) so its study has global importance. Moreover,

153 the tropics suffer from the largest data and capacity gaps (Romijn et al., 2012; 2015) and their

154 need to access AFOLU data and understand their differences is more crucial. We selected the

155 period 2000-2005 for being the common temporal range for all the datasets. This period is not

156 for the recent past but that does not affect the comparative nature of this research. Our study

157 area focuses at the country level and includes eighty countries, following Harris et al., (2012).

158 We ran the comparisons on gross emissions. While gross and net emissions are equally

159 important, they offer different information (Richter and Houghton, 2011; Houghton et al.,

160 2012). Net land use emissions consider the emissions by the sources and the removals by the

161 sinks (i.e. forest growth, forest regrowth after disturbances, organic matter stored in soils) in a

162 final emission balance where the removals are discounted from the emissions. Gross

163 assessments can consider both the emissions produced by the sources (gross emissions) and

164 the removals absorbed by the sinks (gross removals), but they are not balanced out. Gross

165 emissions are useful to navigate mitigation implementation since they offer direct information

166 on the sources and sinks that need to be acted upon through policies and measures to enhance

167 and promote mitigation (see further information on net and gross alternatives in Roman-

168 Cuesta et al., 2016).

169

2.2 AFOLU datasets

Hotspots (Roman-Cuesta et al., 2016)*:* this is a multi-gas (CO_2, CH_4, N_2O) spatially explicit (0.5°) database on gross AFOLU emissions and associated uncertainties for the tropics and subtropics for the period 2000-2005, at Tier 2 and Tier 3 levels (see Supplement for the definition of Tiers). This database locates the hotspots of tropical AFOLU emissions, which should help to estimate mitigation potentials, and prioritize the areas and the land activities that require most urgent mitigation action. It combines available published GHG datasets for the key sources of emissions in the AFOLU sector as identified by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (AR5, Smith et al., 2014): deforestation, forest degradation (fire, wood harvesting), crop soils, paddy rice, and livestock (enteric fermentation and manure management). It also includes agricultural peatland decomposition using Tier 1 emission factors (see details in Roman-Cuesta et al., 2016). . Forest emissions focus on aboveground biomass, with the exception of peat fires. More detailed methodological information is available in Roman-Cuesta et al., (2016).

FAOSTAT: covers agriculture, forestry and other land uses and their associated emissions of CO_2, CH_4 and N_2O, following IPCC, 2006 Guidelines at Tier 1 (Tubiello et al., 2013, 2014). Emissions are estimated for nearly 200 countries, annually, for the reference period of 1961–2012 (agriculture) and 1990–2012 (FOLU), based on national activity data submitted by countries and further collated by FAO. Projected emission data are available for 2030 and 2050. FAOSTAT includes estimates of emissions from biomass fires, peatland drainage and fires, based on geo-spatial information, as well as on forest carbon stock changes (both emissions and removals) based on national-level FAO Forest Resources Assessment data (FRA 2010).

195 *EDGAR:* The Emissions Database for Global Atmospheric Research (EDGAR) provides

196 global GHG emissions from multiple gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF6) at 0.1°

197 and country levels. The EDGAR database covers all IPCC sectors (energy, industry, waste

198 management, and AFOLU), mostly applying IPCC 2006 guidelines for emission estimations

199 (EDGAR 2012). We downloaded the EDGAR's 4.2 Fast Track 2010 (FT 2010). FT 2010

200 emissions cover the period 2000-2010 in an annual basis, at the country level.

201

202 *"Houghton":* Houghton's bookkeeping model calculates the net and gross fluxes of carbon

203 (CO_2 only) between land and atmosphere that result from land management (Houghton, 1999,

204 2012; Houghton and Hackler, 2001; Houghton et al., 2012). The net estimate includes

205 emissions of CO_2 from deforestation, shifting cultivation, wood harvesting, wood debris

206 decay, biomass burning (for deforestation fires only, peatland fires were not included in our

207 version of their data), and soil organic matter from cultivated soils. It also includes sinks of

208 carbon in forests recovering from harvest and agricultural abandonment under shifting

209 cultivation.. The model does, however, not include forests that are not logged, cleared or

210 cultivated. Rates of growth and decomposition are ecosystem specific and do not vary in

211 response to changes in climate, CO_2 concentrations, or other elements of environmental

212 change. Therefore, forests grow (and wood decays) at the same rates in 1850 and 2015.

213 Unlike other databases all carbon in the ecosystem considered is accounted for: live

214 vegetation, soil, slash (woody debris produced during disturbance), and wood products. We

215 downloaded regional annual emissions from the TRENDS (1850-2005) dataset for the tropics:

216 Central and South (CS) America, tropical Africa and South and South East Asia. Only net

217 emissions were available. No spatially disaggregated data were offered (i.e. countries).

218 Houghton's data are, unlike all the other datasets, net aggregated FOLU estimates, for CO_2-

219 only.

220

"Baccini": These are gross FOLU tropical emissions published by Baccini et al., (2012). Data

are gross emissions for the period 2000-2010 disaggregated into: deforestation (4.18

$PgCO_2.yr^{-1}$), wood harvesting (1.69 $PgCO_2.yr^{-1}$), biomass burning (2.86 $PgCO_2.yr^{-1}$) and,

wood debris decay (3.04 $PgCO_2.yr^{-1}$). We excluded this last variable to make it more

comparable to the other datasets, where CWD is frequently excluded (Table 1). Baccini's

estimates referto a tropical area slightly smaller than our study region and they are offered as

an aggregated value (no continental or country data available)

228

The US Environmental Protection Agency (EPA): global non-CO_2 projected emissions for the

period 1990-2030 for the Agriculture, Energy, Industrial Processes and Waste sectors, for

more than twenty gases. EPA uses future net emissions projections of non-CO_2 GHGs as a

basis for understanding how future policy and short-term, cost-effective mitigation options

can affect these emissions. EPA follows the Global Emissions Report, which uses a

combination of country-prepared, publicly-available reports consistent with IPCC guidelines

and guidance (USEPA, 2013). When national emissions estimates were unavailable, EPA

produced its own non-CO_2 emissions using IPCC methodologies (i.e., international statistics

for activity data, and the default IPCC Tier 1 emission factors). Deviations to this

methodology are discussed in each of the source-specific methodology sections of USEPA

(2012). No FOLU estimates are included in this dataset. We downloaded agricultural

emissions offered as 5-year intervals at country level, disaggregated by gas (N_2O and CH_4),

and by emission sources.

242

IPCC AR5: The AR5 is a synthesis report, not a repository of global data. However, new

AFOLU data are produced by the merging of peer-reviewed data such as Figures 11.2, 11.4,

245 11.5 and 11.8 in chapter 11 of the AR5 (Smith et al., 2014). We will contrast our six datasets

246 against the data from these newly produced figures.

247

248 Table 1 shows a summary of key similarities and differences of the assessed AFOLU datasets

249 and the data from the AR5. The exact variables used for each database are described in Table

250 S1 in the Supplement.

251

252 *2.3 Estimating comparable gross AFOLU emissions for all datasets*

253 We focus on human-induced gross emissions only, excluding fluxes from unmanaged land

254 (i.e. natural wetlands). We focus on direct emissions excluding indirect emissions whenever

255 possible (i.e. nitrate leaching and surface runoff from croplands). Delayed fluxes (legacies)

256 are important (i.e. underestimations of up to 62% of the total emissions when recent legacy

257 fluxes are excluded) (Houghton et al., 2012) but are frequently omitted in GHG assessments

258 that derive from remote sensing, such as the deforestation emissions used in the Hotspots

259 database, which relies on Harris et al., 2012). Wood harvesting emissions also excluded

260 legacy fluxes. We assumed instantaneous emissions of all carbon that is lost from the land

261 after human action (Tier 1, IPCC 2006) (i.e. deforested and harvested wood), with no

262 transboundary considerations (i.e. the emissions are assigned wherever the disturbance takes

263 place, particularly important for Harvested Wood Products). Life-cycle substitution effects

264 were neither considered for harvested wood (Peters et al., 2012). Some exceptions were

265 allowed when data were already aggregated (i.e. for Houghton's and EPA's datasets we could

266 not exclude indirect emissions linked to forest decay and agriculture, respectively), or because

267 their legacy (past decay) estimates corresponded to an important source (i.e. EDGAR's post

268 burned decay and decomposition emissions represent deforestation) (Tubiello et al., 2015).

269 Databases include a diversity of emission sources and gases under AFOLU, not always

270   following IPCC requirements (some exclude peatland emissions, some include energy into the

271   AFOLU emissions, some exclude non CO_2 emissions, etc). However, to compare the AFOLU

272   emission estimates among databases we choose exactly the same sources: deforestation, wood

273   harvesting, fire, livestock (enteric fermentation + manure management), cropland soil

274   emissions, rice emissions, emissions from drained histosols), and the same gases CO_2, CH_4,

275   and N_2O, and documented what was included in each case (See Table S1 the Supplement).

276   For the case of fire, for all the databases, we excluded CO_2 emissions that came from biomass

277   burning in non-woody vegetation such as-savannas and agriculture, since they are assumed to

278   be in equilibrium with annual regrowth processes (for CO_2 gases only) (IPCC 2003, 2006).

279

280   *2.4 Correcting known differences among datasets estimates*

281   Tubiello *et al.* (2015) identified four main differences that resulted in larger estimates for the

282   EDGAR data than for FAOSTAT, under the AFOLU estimates of the AR5 (Smith et al.,

283   2014): 1. The inclusion of energy emissions under the agriculture budget, 2. Inclusion of

284   savannah burning, 3. Higher rice emissions due to the use of the IPCC 1996 guidelines instead

285   of the IPCC 2006 guidance, 4. FOLU's unresolved differences due to unclear metadata on

286   EDGAR's proxy for deforestation (post burned decay and decomposition). We have corrected

287   for the first two in our data comparison. No energy, and no CO_2 for savannah burning have

288   been included in the AFOLU estimates in any of our analyses.

289

290   *2.5 Country emissions*

291   To characterize countries emissions' variability we estimated the standard deviations for the

292   different emission sectors: i. forest (deforestation + fire + wood harvesting), ii. agriculture

293   (cropland soils + paddy rice), iii. livestock, and the aggregated AFOLU emissions, for the

294   three most complete datasets (Hotspots, FAOSTAT, EDGAR), per country. We grouped the

295 standard deviations into four percentiles to aggregate countries into levels of emission

296 variability: high agreement (=low variability, low standard deviations, $<25^{th}$ percentile),

297 moderate agreement (25th-50th percentiles), low agreement (25th-50th percentiles), and very

298 low agreement (= very high variability, very high standard deviations, $>75^{th}$ percentile). See

299 Supplement for a further discussion on issues regarding countries' emissions variability.

300

3. RESULTS AND DISCUSSION

301

3.1 Aggregated AFOLU, FOLU and Agricultural emissions

302

303 We found good agreement among datasets for the aggregated tropical scales with AFOLU

304 values of 8.0 (5.5-12.2) (5th-95th percentiles), 8.4 and 8.0 $PgCO_2e.yr^{-1}$ (for the Hotspots,

305 FAOSTAT and EDGAR, respectively). FOLU (deforestation and forest degradation)

306 contributed with 6.0 (3.8-10), 5.9, 5.9 and 5.4 $PgCO_2e.yr^{-1}$ for the Hotspots, FAOSTAT,

307 EDGAR, and Houghton datasets respectively. Agriculture (livestock, cropland soils and rice

308 emissions) reached 1.9 (1.5-2.5), 2.5, 2.1, and 2.0 $PgCO_2e.yr^{-1}$ for the Hotspots, FAOSTAT,

309 EDGAR, and EPA datasets respectively (Figure 1, Table 2). Forest emissions represented

310 ≥70% of the tropical AFOLU gross mean annual budget for 2000-2005 (the Hotspots database

311 and Houghton showing the highest and the lowest estimates), and agriculture represented the

312 remaining 25-30% AFOLU emissions (FAOSTAT and Hotspots showing the highest and the

313 lowest values). Houghton's FOLU value (5.4 $PgCO_2.yr^{-1}$) is a net estimate that includes

314 carbon dynamics associated to forest land use changes, and forest removals from areas under

315 logging and shifting cultivation and it is, as expected, lower than the forest gross emissions.

316 Its value for the tropics was, however, higher than the net FOLU value used in the IPCC AR5

317 (4.03 $PgCO_2e.yr^{-1}$ for 2000-2009) (Houghton *et al.* 2012). Since boreal and temperate forest

318 sinks are reported to be quasi-neutral (Houghton et al., 2012), these differences are unclear.

319 There is a variety of Houghton' net FOLU estimates in current bibliography (i.e. 4.03

320   PgCO$_2$e.yr^{-1} for 2000-2009 in Smith *et al.* (2012), 4.9 for 2000 and 4.2 for 2010 (Tubiello et

321   al., 2015) that likely correspond to different updates of the same dataset, but create confusion

322   and would call for verified official values that could be consistently used.

323

324   The IPCC AR5 offers a FOLU gross value for the tropics of ca. 8.4 PgCO$_2$.yr^{-1} (2000-2007)

325   (Fig 11.8 in AR5, Smith et al., 2014) (Fig S1, Supplement) which corresponds to Baccini's

326   estimates using Houghton's bookkeeping model. This value is in the upper range of the

327   Hotspots gross FOLU emissions: 6 (3.8-10) PgCO$_2$e.yr^{-1} (2000-2005), and higher than the

328   mean gross FOLU emissions from all the other datasets (approx. 6 PgCO$_2$e.yr^{-1}) (Table 2).

329   The time periods are not identical and we do not compare the same gases (i.e. the

330   bookkeeping model focuses on CO$_2$ only, while we run a multi-gas assessment). However, the

331   differences mainly relate to unreported choices behind the inclusion/exclusion of emission

332   sources and the description of their methods, in the AR5. Thus, the 8.4 PgCO$_2$.yr^{-1} gross

333   estimate does not include fire, and has larger contributions from shifting cultivation (2.35

334   PgCO$_2$.yr^{-1}) and wood-harvesting (2.49 PgCO$_2$.yr^{-1}), than the deforestation and wood-

335   harvesting emissions in the Hotspots selected datasets (Figure 2). Numbers used in Figure

336   11.8 also exclude other gross emissions offered in Baccini et al. (2012), which is the citation

337   used in Fig. 11.8. Explicit, complete, and transparent documentation is encouraged for the

338   next AFOLU figures in the IPCC Assessment Reports. Another consideration of AFOLU

339   estimates in the Assessment Reports relates to the use of the bookkeeping model to estimate

340   land use, land use change and forest (LULUCF) emissions. As useful as this model is, its

341   framework does not follow the IPCC AFOLU guidelines (IPCC, 2006), particularly regarding

342   the concept of managed land. Thus, forests that are on managed land but are not suffering

343   from direct human activities are considered carbon neutral (Houghton *pers. comm.*). Partly

344   because of that, the net emission estimates of LULUCF from Houghton et al. (2012) used in

345 the AR5 (4.03 $PgCO_2.yr^{-1}$ 2000-2009) differ from LULUCF country reports for the same

346 period, which are close to zero (Grassi and Dentener, 2015; Federici et al., 2016). The use of

347 IPCC compliant models for the IPCC Assessment Reports, or/and some documentation that

348 warned about these inconsistencies, would be useful in future assessments.

349

350 Emissions in the agricultural sector are mostly net, since sink effects in the soils are small and

351 frequently temporal (USEPA, 2013; Smith et al., 2014). Comparisons against global

352 agricultural emissions show that for the year 2000, global estimates more than doubled the

353 Hotspots values (i.e. 5 and 5.5 $PgCO_2e.yr^{-1}$ *vs* ca. 2 $PgCO_2e.yr^{-1}$ in all datasets) (Tubiello et

354 al., 2015) (Table 2), suggesting larger contributions of agricultural emissions from non-

355 tropical countries. Unexplained methodological differences such as the inclusion or not of

356 indirect emissions and the lack of an exhaustive list of the variables included in the

357 agricultural emissions, difficult further comparisons.

358

359 *3.2 Disaggregated gross emissions: contributions of the emission sources*

360 While the gross aggregated estimates suggested a good level of agreement among datasets

361 (Figure 1), differences occur when comparing the emissions sources leading the AFOLU

362 budgets (Figure 2). The FOLU sector showed the largest differences, mainly due to the

363 estimates of forest degradation, and particularly fire (FAOSTAT and EDGAR showed the

364 lowest and highest values). The forest sector is the most uncertain term in the AFOLU

365 emissions due to both uncertainties in areas affected by land use changes and other

366 disturbances, and by uncertain forest carbon densities (Houghton et al., 2012; Grace et al.,

367 2014; Smith et al., 2014). Agricultural sources were more homogeneous (ca. 2 $PgCO_2e.yr^{-1}$

368 for all datasets) (Figure 1), with livestock and cropland soil emissions as the most and least

369 similar (Figure 2). The homogeneity in livestock emissions was expected since most datasets

370 use common statistics (FAO) to derive herd numbers per country.

371

3.2.1 Deforestation

373 Deforestation emissions were 2.9 (1.0-10.1), 3.7, and 2.5 and 4.2 $PgCO_2.yr^{-1}$ (Hotspots,

374 FAOSTAT, EDGAR, and Baccini, respectively), with Baccini and EDGAR showing the

375 highest and the lowest values. Their values represent, however, very different scenarios: gross

376 deforestation for the Hotspots and Baccini datasets (forest losses only), net deforestation for

377 FAOSTAT (forest losses minus forest gains), and forest fire and post-burn decay for EDGAR

378 (Table 3). The Hotspots (Harris et al., 2012) and Baccini et al., (2012) datasets offer gross

379 deforestation estimates that rely on Hansen et al., (2010)'s forest cover loss areas. However,

380 they report different tropical emissions (0.81 and 1.14 $PgC.yr^{-1}$) because they use different

381 carbon density maps: Harris *et al.* (2012) rely on Saatchi *et al.*(2011) and Baccini rely on

382 Baccini *et al.*(2010). EDGAR does not provide a category for deforestation, and their Forest

383 Fire and Decay category (5F) (Table 3, and Table S1 in the Supplement) is used as a proxy for

384 deforestation (Tubiello et al., 2015). Such an approximation leads to underestimations since

385 not all carbon losses from deforestation are necessarily associated with the use of fire

386 (Tubiello et al., 2015). In spite of being net emissions, the deforestation estimates for

387 FAOSTAT were higher than the gross estimates of Hotspots and Baccini. This is partly due to

388 FAOSTAT's inclusion of fire emissions from humid tropical forests (see section 3.2.3), which

389 the other datasets did not. Baccini's larger estimates of gross deforestation included more

390 carbon pools than the other datasets (i.e. soil, Coarse Woody Debris (CWD), litter). Baccini *et*

391 *al.* (2012) reported that their estimated gross and net emissions from tropical deforestation

392 were the same value (4.2 Pg $CO_2.yr^{-1}$). The difference with Houghton's net emissions (5.4

393 $PgCO_2.yr^{-1}$) (Figure 2) corresponds, then, to non-offset carbon emissions from other land uses

394 and activities included in the bookeeping model: degradation by logging and shifting

395 cultivation, decomposition and decay, and cultivated soils. Houghton's tropical net emissions

396 for 2000-2005 are high, but lower than Houghton's reported net estimates in the 80's (7

397 $PgCO_2.yr^{-1}$) (Houghton, 1999).

398

399 *3.2.2 Forest degradation: wood harvesting and fire emissions*

400 Forest degradation can be defined in many ways (Simula, 2009), but no single operational

401 definition has been agreed upon by the international community (Herold et al., 2011a). It

402 typically refers to a sustained human-induced loss of carbon stocks within forest land that

403 remains forest land. In this study, similarly to Federici et al., (2015), we consider degradation

404 any annual removal of carbon stocks that does not account for deforestation, without temporal

405 scale considerations (i.e. time needed for disturbance recovery, or time to guarantee a

406 sustained reduction of the biomass). We assessed two major degradation sources: wood

407 harvesting and fire. Soil degradation is poorly captured in many datasets, and mainly focuses

408 on fire in equatorial Asian peatland forests and drained peatlands (Hooijer et al., 2010).

409 Better understanding of the processes and emissions behind forest degradation would be key

410 for climate mitigation efforts not only because forest degradation is a wide spread

411 phenomenon (i.e. affects much larger areas than deforestation (Herold et al., 2011b)) but also

412 because the lack of knowledge of net carbon effects frequently results in assumptions of

413 carbon neutrality of the affected standing forests, particularly for fire (Houghton et al., 2012;

414 Le Quéré et al., 2014), which is likely leading to an underestimation of forest and AFOLU

415 emissions (Brando et al., 2014; Turetsky et al., 2015; Roman-Cuesta et al., 2016).

416

417 Gross emissions from forest degradation were larger than deforestation for the Hotspots,

418 EDGAR and Baccini's datasets, with degradation-to-deforestation ratios of 108%, 120%, and

419 128%, respectively. FAOSTAT had degradation emissions of 60% of the deforestation, partly

420   due to its anomalously low fire contribution (see next section). Houghton et al., (2012)

421   pointed out that global FOLU net fluxes were led by deforestation with a smaller fraction

422   attributable to forest degradation, while the opposite was true for gross emissions (degradation

423   being 267% of deforestation emissions). This large ratio relates to their inclusion of shifting

424   cultivation under degradation. This is a definition issue, which would not fit the definition of

425   degradation chosen in this study, where a complete forest cover loss would represent

426   deforestation and not degradation.

427

428   *3.2.2.1 Fire*

429   Fire led the gross forest degradation emissions in the tropics in 2000-2005 (Figure 2): 2 (1.1-

430   2.7), 0.2, 3.4, 2.9 $PgCO_2e.yr^{-1}$ for the Hotspots, FAOSTAT, EDGAR, and Baccini datasets,

431   respectively) (Figure 2). The Hotspots estimates are conservative compared to Van der Werf

432   et al., (2010)'s global emissions of 7.7 $PgCO_2e.yr^{-1}$ for 2002-2007, due to the removal of CO_2

433   from deforestation fires (to avoid double counting with deforestation emissions), to the

434   exclusion of fires in grasslands and agricultural residues, and to the Hotspots' smaller study

435   area. FAOSTAT and EDGAR had the lowest and the highest fire values. FAOSTAT lowest

436   values relate to omissions that are currently in the process of being corrected (Rossi *pers.*

437   *comm.*): 1. the complete exclusion of CO_2 from fire in humid tropical forests and other forests

438   (Table 3, Table S1), which FAOSTAT relocated as net forest conversion emissions, partly

439   explains their larger deforestation values (FAOSTAT kept, however, CH_4 and N_2O for fire in

440   humid tropical forests and other forests), and 2. The use of default parameters for fuel in peats

441   from the IPCC 2006 Guidelines instead of the new IPCC Wetland supplement which offer

442   considerable higher values (Rossi et al., 2016). Moreover, FAOSTAT uses GFED3.0-burned

443   area (Giglio et al., 2010) in their estimates while the other datasets use GFED3.0-emissions

444   (Van der Werf et al., 2010). EDGAR fire emissions were the largest most likely because they

included decay. Their dataset considers some undefined "forest fires" (5A) and "wetland/peatland fires and decay" (5D) (Table 3; Table S1 in the Supplement). Peatland decay probably explains EDGAR's larger emissions in Asia, while we assume that EDGAR's highest fire emissions for CS America might respond to deforestation fires which were not included in the Hotspots to avoid double counting with deforestation, and relocated in FAOSTAT to deforestation emissions (Figure 3, Table 3). The Hotspots dataset showed higher gross fire emissions for Africa due to the inclusion of woodland fire, which EDGAR and FAOSTAT probably excluded. Baccini et al., (2012)'s fire emissions: 2.9 $PgCO_2e.yr^{-1}$ (2000-2010) derive from Houghton's bookkeeping but it is unclear how these emissions were estimated.

In spite of the importance of fire as a degradation source, this variable is frequently incompletely included, either through unaccounted gases (i.e. CH_4 and N_2O are excluded in the carbon community but their omission represent 17-34% of the gross CO_2 fire emissions) (Valentini et al., 2014; Roman-Cuesta et al., 2016), or to unaccounted components (i.e fires in tropical temperate forests such as conifers or dry forests such as woodlands, are frequently excluded) (Houghton et al., 2012). Unaccounted fire emissions also derive from methodological choices (i.e. only inter-annual fire anomalies being considered) (Le Quéré et al., 2014), from poor satellite observations such as understory fires in humid closed canopy forests) (Alencar et al., 2006; 2012, Morton et al., 2013), or satellite fire omissions in certain regions (i.e. high Andean fires) (Bradley and Millington, 2006; Oliveras et al., 2014). Other omissions relate to the current exclusion of non-Asian peatland fires (i.e American tropical montane cloud forest peatland fires) (Asbjornsen et al., 2005; Roman-Cuesta et al., 2011; Oliveras et al., 2013; Turetsky et al., 2015).

469   Fire suffers, moreover, from a series of assumptions that do not apply so easily to other types

470   of degradation: 1. Assuming a non-human nature of the fires (deforestation fire *vs* wildfires),

471   which in tropical areas contrasts with multiple citations referring to the 90% human causality

472   of fires (Cochrane et al., 1999; Roman-Cuesta et al., 2003; Alencar et al., 2006; Van der Werf

473   et al., 2010). 2. Assuming *force-majeure* conditions that lead to non-controllable fires due to

474   extreme climate conditions, which frequently results in incomplete assessment and reporting

475   of emissions. This assumption contrasts with research on how human activities have seriously

476   increased fire risk and spread in the tropics (Uhl and Kauffman, 1990; Laurance and

477   Williamson, 2001; Roman-Cuesta et al., 2003; Hooijer et al., 2010), and clearly expose how

478   most of the fires in the humid tropics would not occur in the absence of human influences

479   over the landscape (Roman-Cuesta et al., 2003). 3. Assuming carbon neutrality and full

480   biomass recovery after fire in standing forests. This is a generous assumption that contrasts

481   with numerous studies on tropical forest die-back following fire events in non-fire adapted

482   humid tropical forests (Cochrane et al., 1999; Barlow et al., 2008; Roman-Cuesta et al., 2011;

483   Brando et al., 2012; Oliveras et al., 2013; Balch et al., 2015). All these phenomena casts

484   doubts on the robustness of these assumptions and call for a much more comprehensive

485   inclusion of fire emissions into forest degradation budgets.

486

487   *3.2.2.2 Wood harvesting*

488   There is not a unique way to estimate wood harvesting emissions as exposed in the guidelines

489   for harvested wood products of the IPCC (IPCC 2006). Assumptions regarding the final use

490   of the wood products, decay times, substitution effects, international destination of the

491   products and time needed for forests to recover their lost wood, can fully change the emission

492   budgets. In out study, wood harvesting emissions were 1.2 (0.7-1.6), 2.0, 1.7 $PgCO_2.yr^{-1}$ for

493   the Hotspots, FAOSTAT and Baccini data, respectively (Tables 3, Table S1 in the

494 Supplement). Harvested wood products derive from FAO's country reports (i.e. FAOSTAT

495 forest products). All datasets included fuel wood and industrial roundwood (Tables 3, Table

496 S1). EDGAR excluded fuelwood from the AFOLU budget and placed it instead into the

497 energy budget (EDGAR, 2012), which explains its absence in Figure 2. Wood harvesting

498 emissions were larger in FAOSTAT than in the Hotspot data (Figure 2) partly due to the

499 inclusion of some extra categories of fuels (i.e. charcoal and residues) that were not included

500 in the Hotspot database (Table 3, Table S1 in the Supplement). Charcoal represents 26% of

501 the total wood-harvesting emissions in FAOSTAT. Differences on wood harvesting affected

502 more Asia and CS America (where the Hotspot data were half of FAOSTAT's), whilst Africa

503 presented almost identical values (Figure 3), reasons for these continental differences are

504 unclear. Baccini's high emissions on wood harvesting could partly relate to their inclusion of

505 extra biomass due to felling damages (i.e. 20-67% of the AGB is damaged, and 20% is left

506 dead in BGB) (Houghton, 1999).

507

508 *3.2.3 Livestock*

509 Livestock emissions were the most homogeneous among the emissions sources (Figure 2)

510 with estimates of 1.2 (0.8-1.5), 1.1, 1.2, 1.1 $PgCO_2e.yr^{-1}$ for the Hotspots, FAOSTAT,

511 EDGAR and EPA respectively, in range with the estimates in the AR5 (Fig 11.5 in Smith et

512 al., 2014). Values were similar in spite of deriving from different Tiers (i.e. Tier 3 for Herrero

513 et al., (2013), Tier 1 for FAOSTAT and EDGAR. EPA used Tier 3 but for incomplete data

514 series, otherwise Tier 1 was applied (USEPA, 2013)). All datasets included enteric

515 fermentation (CH_4) and manure management (N_2O, CH_4). All of them relied on FAO data for

516 livestock heads, although they used different years (i.e. 2000 for Herrero et al., (2013) data in

517 the Hotspots, and 2007-2010 for EDGAR). From a continental perspective, FAOSTAT and

518 EDGAR estimates were the closest while the Hotspots and EPA's were less similar. The

519   Hotspots showed higher emissions for Africa and Asia and lower for CS America, than the

520   other three datasets. Divergences likely relate to different Tiers. CS America and Asia showed

521   the highest values, with Africa following closely (Figure 3), similar to what is reported in the

522   AR5 (Smith et al., 2014). Globally, livestock is the largest source of CH_4 emissions, with

523   three-fourth of the emissions coming from developing countries, particularly Asia (USEPA,

524   2013, Tubiello et al., 2014). Three out of the top-5 emitting countries are in the tropics:

525   Pakistan, India and Brazil (USEPA, 2013) and while Asia hosts the largest livestock

526   emissions, the fastest growing trends in 2011 correspond to Africa (Tubiello et al., 2014).

527

528   *3.2.4 Cropland emissions*

529   The estimates of cropland emissions reached values of 0.18 (0.16-0.19), 0.56, 0.6 and 0.64

530    $PgCO_2e.yr^{-1}$ for the Hotspots, FAO, EDGAR and EPA datasets respectively, for N_2O and CO_2

531   from changes in soil organic carbon content. Cropland soil emissions (N_2O and soil organic

532   carbon stocks (CO_2)) heavily depend on land management practices (i.e. tillage, fertilization

533   and irrigation practices) and climate (Crowther et al., 2015). We chose exactly the same land

534   practices in all datasets to allow comparisons (Table 3, S1 in the Supplement). For this reason,

535   we excluded N_2O emissions from grassland soils, drainage of organic soils, and restoration of

536   degraded lands (Table 3). This restrictions resulted in lower emissions than those estimated

537   for cropland soils in the AR5 (Fig. 11.5 in Smith et al., 2014). The Hotspots and EPA showed

538   the lowest and the highest estimates (Figures 2, 3). With the exception of the Hotspots, the

539   other datasets agreed well at the tropical scale, with FAOSTAT and EDGAR being almost

540   identical, also at continental scales. EPA disagreed more than the other datasets at the

541   continental scales, with underestimations for Asia, probably related to the parameterization of

542   their emission model. All three datasets used FAO's activity data, and for EDGAR and

543   FAOSTAT the same emission factors must have been used. The Hotspot showed anomalously

low emissions partly because it only included six major crop types (maize, soya, sorghum, wheat, barley, millet) for which the emission model (DAYCENT) counted on reliable parametrization (*Ogle pers. comm*). Emissions from other important crops in the tropics (i.e. sugar cane, tobacco, tea, etc) were excluded, as well as emissions from croplands in organic soils, due to model constraints.

3.2.5 Peatland drainage for agriculture

Estimates of drained peatands (mainly for agricultural purposes) suggest large omissions in the Hotspots database with emissions one order of magnitude lower (28 $TgCO_2e.yr^{-1}$) than FAOSTAT (ca. 500 $TgCO_2e.yr^{-1}$) and one order of magnitude lower than the values reported for peatland drainage in Asia alone (Hooijer et al. 2010) (355-855 $TgCO_2e.yr^{-1}$). The lower values in the Hotspots dataset relate to much smaller agricultural areas with histosols (0.4 mill ha) than those reported by FAOSTAT for the same countries (7mill ha). This area difference is partly due to the methodological approach used by Ogle et al. (2013) where only six major crop covers are considered: maize, wheat, sorghum, soya beans, millet and barley, and partly to the unmatching spatial scales of histosols and croplands (i.e. 1km for histosols and 50km for croplands) which result in underestimations of the final area.

3.2.6 Paddy rice

When paddy fields are flooded, decomposition of organic material gradually depletes the oxygen present in the soil and floodwater, causing anaerobic conditions in the soil that favour methanogenic bacteria that produce CH_4. Some of this CH_4 is dissolved in the floodwater, but the remainder is released to the atmosphere, primarily through the rice plants themselves. Net emission estimates for paddy rice were 0.55 (0.4-0.833), 0.33, 0.37, 0.30 $PgCO_2e.yr^{-1}$ for the Hotspots, FAOSTAT, EDGAR and EPA datasets, respectively. The Hotspots showed the

569 highest emissions (Figure 2), but only in Asia (Figures 3). Part of the reason behind these

570 differences refers to the final gases estimated in Li et al., (2013)'s which included CH_4, N_2O

571 and decomposition of Soil Organic Carbon (SOC) (CO_2) (Table 3, S1), while the others only

572 focused on CH_4. In Li et al., (2013)'s estimates, N_2O were 48% of the CH_4 emissions,

573 explaining the doubled emissions in the Hotspots database. SOC was a sink, with -0.076

574 $PgCO_2.yr^{-1}$.

575

576 Based on the explanations above, Table 4 points out the likely least reliable emission sources

577 for each dataset considering disagreements among emission estimates due to

578 biased/divergent/incomplete definitions and methods. Houghton's sinks are suggested as least

579 reliable since they suffer from compatibility issued with IPCC guidance and exclude sinks

580 from non-disturbed areas and sinks from forests undergoing disturbances other than wood

581 harvesting or recovery from shifting cultivation (Grassi and Dentener 2015; Federici et al.,

582 2016).

583

584 *3.3 Differences in the relative contribution of greenhouse gases (CO_2, CH_4, N_2O)*

585 GHG emissions (CO_2, CH_4, N_2O) showed good agreement at the sectoral level (FOLU and

586 agriculture) (Figure 5), that disappeared at the disaggregated level (Figure 6). CO_2 showed the

587 largest disagreements among datasets and gases, led by forests emissions and particularly fire.

588 SOC accumulation was reported in the Hotspots data (Li et al., 2013) but it is uncertain if it is

589 included in the other datasets.

590

591 Non-CO_2 emissions showed lower variability than CO_2 (Figure 6). Livestock led CH_4

592 emissions and showed the largest differences among datasets, with the Hotspot data (Herrero

593 et al., (2013) having the lowest CH_4 emissions, which were compensated with larger N_2O than

594   the other datasets (Figure 6 b,c). At a global level, wetlands dominates natural CH_4 emissions,

595   while agriculture and fossil fuels represent 2/3 of all human emissions, with smaller

596   contributions coming from biomass burning, the oceans, and termites (Montzka et al., 2011).

597   Fire non-CO_2 emissions were quite similar among datasets, confirming that FAOSTAT

598   omissions were CO_2 related (see section 3.2.3). Thus, as exposed in FAOSTAT's metadata,

599   only N_2O and CH_4 are considered in forest fires, excluding CO_2 from aboveground biomass.

600   As expected, N_2O emissions in crops showed large differences, with the Hotspots having the

601   lowest values (3 times lower). Rice N_2O emissions were omitted in all datasets except the

602   Hotspots (Li et al., 2013), which also included SOC.

603

604   The importance of multigas assessments relates to their role in climate change mitigation due

605   to their radiative forcing (RF), understood as a measure of the warming strength of different

606   agents (gases and not gases) in causing global warming ($W.m^{-2}$). CO_2 is the most (400ppm in

607   2015) and longest living gas which makes it the leading force of global warming (Anderson

608   2012). Non-CO_2 GHG are less abundant in the atmosphere (1,774 ppb and 319 ppb for CH_4

609   and N_2O in 2005 respectively) but have larger warming potentials (x 28 for CH_4) and (x 265

610   for N_2O) (AR4) but shorter lifetimes than CO_2 (~9 and ~120 years, respectively). In spite of

611   their shorter lifespans they offer an additional opportunity to mitigate climate change

612   (Montzka et al., 2011) partly because they play a role in atmospheric chemistry that

613   contributes to short-term warming (Montzka et al., 2011) and partly because their presence

614   counteracts CO_2 terrestrial sinks (Tian et al., 2016),

615

616   *3.4 Country level emissions*

617   Country comparisons showed poor agreement among datasets for all the emission sectors,

618   particularly for the largest emitters (i.e. Brazil, Argentina, India, Indonesia) (Figures 7, 8).

Forests led the AFOLU disagreements (as observed by the similarity of Figure 7 a,b). From a continental perspective, Central and South America showed more countries with high levels of disagreement, suggesting the need for further data research.

3.5 Some reflections on the datasets

3.5.1 Original goals

Different datasets were developed for different purposes that have influenced the methods and approaches chosen to estimate their land use GHGs. Thus, EDGAR was created with an air pollution focus making its land emissions weaker. Contrastingly, FAOSTAT carries FAO's focus on land particularly agriculture (data available since the 60s), with forest data added later through the FRA assessments (1990, 2005, 2010, 2015). The 'Hotspot' database was created to identify the areas with the largest land use emissions in the tropics (emissions hotspots), while Houghton's accent is on historical LULUCF emission trends (since 1850). EPA concentrates on industrial, energy, and agricultural emissions -forests are excluded- with an interest on human health and mitigation. Moreover, due to its long existence, several datasets rely on FAOSTAT's long-term agricultural data, which is probably the reason behind the higher homogeneity of agricultural emission estimates (i.e. crops, rice, and livestock) among datasets). FAOSTAT's forest emissions use FRA data, which get updated every 5 years. Different FRA versions strongly influence forest emission estimates which makes it important to acknowledge the FRA version used when contrasting FAOSTAT emissions. when comparing estimates (i.e. differences up to 22% between the forest sink estimates using FRA2015 and FRA2010 have been reported by Federici et al., 2015). Similarly, official updates of Houghton's bookkeeping TRENDS data, as well as researchers' self-tuned versions of his model, result in emission differences that are difficult to track.

4.2 IPCC guidelines and guidance: Under the UNFCCC, countries are requested to use the latest IPCC AFOLU guidelines to estimate their GHG emissions (i.e. IPCC 2006 and 2003 for developed and developing countries, respectively). The use of different guidelines, Tiers, and approaches influences the final emission estimates. Compliance with IPCC has two main consequences: 1. the total area selected to report emissions, and 2. the choice of *land use* over *land cover*. In the first case, under IPCC guidance, the total area selected to report emissions would include all the land under human influence (the *managed land* concept, which includes areas under active and non-active management). Houghton's bookkeeping model (and the carbon modelling community in general) do not comply well with the *managed land* concept, resulting in different net emissions from forest land uses and land use changes (LULUCF) than IPCC compliant country emissions (Grassi and Dentener, 2015; Federici et al., 2016). In the second case, the selection of *land uses* instead of *land covers* has partly been behind the recent controversy between FAO and the Global Forest Watch's reported estimates on deforestation trends (Holmgren 2015). Estimates of deforestation that rely on *land cover* are higher than those using *land use*, since forest losses under forest land uses -that remain forest land use- are not considered deforestation (i.e. logged areas will regrow). In our analysis, FAO and Houghton relies on *land use* for deforestation, while the 'Hotspots' and EDGAR rely on *land cover*. FAOSTAT and the 'Hotspots' rely on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). FAOSTAT uses Tier 1 and standard emission factors, while the 'Hotspots' use a combination of Tiers (Tier 3 for all emissions except wood harvesting and cropland emissions over histosols that rely on Tier 1). EDGAR reports the use of 2006 IPCC Guidelines for the selection of the emission factors but some of their methodological approaches are not always consistent with IPCC guidelines (i.e. deforestation expressed as the decay of burned forests, wood-harvesting is part of the energy sector, agricultural energy balances are included in the AFOLU budget). EPA methods are

669   reported to be consistent with IPCC guidelines and guidance, with Tier 1 methodologies used

670   to fill in missing or unavailable data (USEPA, 2013).

671

672   **4. CONCLUSIONS**

673   The Paris Agreement (COP21) counts on the Nationally Determined Contributions (NDCs) as

674   the core of its negotiations to fight climate change. As March 2016, 188 countries had

675   submitted their NDCs under the UNFCC (FAO, 2016) with agriculture (crops, livestock,

676   fishery and aquaculture) and forests as prominent features in meeting the countries' mitigation

677   and adaptation goals (86% percent of the countries include AFOLU measures in their NDCs,

678   placing it second after the energy sector) (FAO, 2016). However, there exists large variability

679   in the way countries present their mitigation goals, and quantified sector-specific targets are

680   rare (FAO, 2016). Variability relates not only to the lack of a standardized way to report

681   mitigation commitments under the NDCs, but also to uncertainties and gaps in the AFOLU

682   data. The Paris Agreement relies on a 5-year cycle stock-taking process to enhance mitigation

683   ambition, and to keep close to the 2°C target. To be effective and efficient, stock-taking needs

684   robust, transparent and certain numbers (at least with known uncertainties). This is true both

685   for national emission reports and NDCs, but also for the global datasets that can be used to

686   review the feasibility of countries' mitigation claims, and the real space for further mitigation

687   commitments. We have here compared the gross AFOLU emissions of six datasets to search

688   for disagreements, gaps, and uncertainties, focusing on the tropical region. Conclusions

689   depend on the spatial scale. For the tropical scale:

690   • Data aggregation offers more homogeneous emission estimates than disaggregated

691   data (i.e.continental level, gas level, emission source level).

692   • Forest emissions are the most uncertain of the AFOLU sector, with deforestation

693   having the highest uncertainties.

- Agricultural emissions, particularly livestock, are the most homogeneous of the AFOLU emissions.

- Forest degradation, both fire and wood harvesting, show the largest variabilities among databases.

- CO_2 is the gas with longer-term influence in climate change trends, but it remains the most uncertain among the AFOLU gases and the most variable, in absolute value, among datasets (Figure 5) Fire leads this variability (Figure 6).

- Among the non-CO_2 gases, N_2O showed the most variable emission estimates, in absolute value, in all the emission sources and for all the datasets (Figure 6).

- Emissions from histosols/peatlands remain incomplete or fully omitted in most datasets.

For the country and continental scales:

- Large emitters show the highest levels of data disagreement in the tropics, enhancing the need for data improvement to guarantee effective mitigation action.

- Forest lead the emission disagreement in the total AFOLU emissions.

- Central and South America showed the largest continental disagreements on emission data for all the land sectors.

4.1 Next steps

4.1.1 Enhancing dialogue between the carbon and the AFOLU research communities

Research ran by the carbon community is pivotal for AFOLU assessments and while these two research communities overlap, they do not focus on exactly the same topics. The carbon community works with CO_2 emissions-only, fully excluding non-CO_2 gases, particularly N_2O. It moreover rather focuses on forests and associated land use changes, excluding emissions from agriculture. The AFOLU community has, contrarily, a multi-gas approach (CO_2, CH_4,

719   N_2O) and includes emissions from both forests and agriculture. For these reasons, estimates of

720   the carbon community cannot be considered as AFOLU estimates, and certain confusion

721   appears in the IPCC's AR5 with an incorrect AFOLU labelling (Table 11.1, Fig S2 in the

722   Supplement). There is great space for these two communities to cooperate but further

723   dialogue is needed to promote closer and more coordinated action. Future steps might include

724   the adoption of the *managed land* concept by the carbon community; and ways to include

725   legacy emissions by the AFOLU community.

726

727   *4.2.2   Improving data quality*

728   The quality of the reported AFOLU emissions can be assessed through the UNFCCC

729   principles: completeness, comparability, consistency, accuracy and transparency, which can

730   help navigate the improvements of national monitoring systems. From these principles, the

731   reviewed datasets performed well in *consistency* (they applied similar methods and

732   assumptions over time, with the exception of 'Hotspots' that did not include temporal data).

733   *Transparency* was excellent for FAOSTAT with well elaborated and publicly available

734   metadata linked to their offered data, while EDGAR performed poorly due to insufficient

735   metadata. Improving transparency is an urgent call for future action. *Accuracy and*

736   *uncertainty* are also urgent calls. Thus, in spite of their importance to fully understand the

737   emission trends and dynamics, only Houghton and the 'Hotspots' provided uncertainties.

738   FAO offered uncertainties as a percent value for each emission source. *Completeness and*

739   *omissions* are also urgent tasks because all datasets are incomplete (Table 1) (i.e. missing

740   pools, missing gases) and omissions affect all datasets. Complete emission reporting should

741   consider the importance of:

742   • Forest soil CO_2 and N_2O emissions (Werner et al., 2007) (i.e. N_2O tropical forest soil

743   emissions of 0.7 $PgCO_2e.yr^{-1}$).

744   •   Emissions from CH_4 and N_2O from drained peatland soils, and from wetlands over

745   managed land (i.e. conservation).

746   •   All forest fire types (i.e. temperate conifers and woodlands; understory fires over

747   humid closed canopy forests (Alencar et al., 2006; Morton et al., 2013) (i.e. 85,500

748   km^2, 1999-2010 in southern Brazilian Amazon); fire emissions over peatland soils and

749   peatland forests out of Asia (Román-Cuesta et al., 2011; Oliveras et al., 2014) (i.e. 4-8

750        $TgCO_2e$, 1982-1999, for the tropical high Andes from Venezuela to Bolivia)

751   • CO_2 emissions from other components of wood harvesting other than fuel and

752   industrial roundwood (i.e. charcoal, residues).

753   • CO_2 emissions from tree biomass loss due to fragmentation (Numata et al., 2010; Pütz

754   et al., 2014) (i.e $0.2\,Pg\,C\,y^{-1}$)

755   • CO_2 due to decomposition and decay of forests under extreme events: hurricanes

756   (Read and Lawrence, 2003; Negron-Juarez et al., 2010) (i.e the 2005 convective

757   storm, the Amazon basin suffered from an estimated tree mortality of 542 ± 121 million

758   trees); intense droughts (Phillips et al., 2009, 2010; Brienen et al., 2015) (i.e. the 2005

759   Amazonian drought resulted in 1.2-1.6 PgC emissions and the atmosphere has yet to

760   see 13.9 $PgCO_2$ (3.8 PgC) of the Amazon necromass carbon produced since 1983);

761

762 Further suggestions on improving data gaps and knowledge for the AFOLU sector have been

763 reported by Smith *et al.* (2014); Houghton *et al.* (2012); USEPA (2013) and Sist *et al.* (2015),

764 with a focus on soil data and crop production systems, as well as an improved understanding

765 of the mitigation potentials, costs and consequences of land use mitigation options.

766

767 **5. REFERENCES**

768 Abad-Viñas, R., Blujdea, V., Federici, S., Hiederer, R., Pilli, R., Grassi, G.: Analysis and

proposals for enhancing Monitoring, Reporting, and Verification of greenhouse gases from Land Use, Land Use Change and Forestry in the EU. Technical Report 071201/2011/211111/CLIMA.A2. Joint Research Centre, Ispra, Italy, 2015. Available at: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC91414/lb-na-26813-en-n.pdf

Achard, F., Beuchle, R., Mayaux, P., Stibig, H. J., Bodart, C., Brink, A., Carboni, S., Desclée, B., Donnay, F., Eva, H. D., Lupi, A., Raši, R., Seliger, R. and Simonetti, D.: Determination of tropical deforestation rates and related carbon losses from 1990 to 2010. Global Change Biology, 20, 2540-2554, 2014.

Alencar, A., Nepstad, D., Vera-Diaz, MC.: Forest Understory Fire in the Brazilian Amazon in ENS and non-ENSO years: Area Burned and Committed Carbon Emissions. Earth Interactions, 10, 1-17, 2006.

Anderson, K.: The inconvenient truth of carbon offsets. Nature News, 484, 7, 2012.

Anderson, K.: Duality in climate science. Nature Geoscience, 8, 898–900, 2015.

Asbjornsen, H., Gallardo-Hernández, C., Velázquez-Rosas, N., García-Soriano, R.: Deep ground fires cause massive above- and below-ground biomass losses in tropical montane cloud forests in Oaxaca, Mexico. Journal of Tropical Ecology, 21, 427-434, 2005.

Baccini, A., Goetz, SJ., Walker, WS., Laporte, N. T., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P. S. A., Dubayah, R., Friedl, M. A., Samanta, S., Houghton, RA.: Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. Nature Climate Change, 2, 182-185, 2012.

Balch, J., Brando, P., Nepstad, D. Coe, M., Silverio, D., Massad, T., Davidson, E., Lefebvre, P., Oliveira-Santos, C., Rocha, W., Cury, R., Parsons, A., Carvalho, K.: The susceptibility of Southeastern Amazon Forests to Fire: Insights from a Large Scale Burn Experiment. BioScience, 65, 893-905, 2015.

793   Barlow, J., Peres, C.: Fire-mediated dieback and compositional cascade in an Amazonian

794   forest. Philosophical Transactions of the Royal Society, 363, 1787-1794, 2008.

795   Bellassen, V., Luyssaert, S.: Managing forests in uncertain times. Nature, 506, 153-156, 2014.

796   Brando, PM., Nepstad, DC., Balch, JK., Bolker, B., Christman, MC., Coe, M., Putz, F.: Fire-

797   induced tree mortality in a neotropical forest: the roles of bark traits, tree size, wood density,

798   and fire behaviour. Global Change Biology, 18, 630-641, 2012.

799   Brando, PM., Balch, JK., Nepstad, DC., Morton, D., Putz, F., Coe, M., Silverio, D., Macedo,

800   M., Davidson, E., Nobrega, C., Alencar, A., Soares-Filho, B.: Abrupt increases in

801   Amazonian tree mortality due to drought-fire interactions. Proceedings of the National

802   Academy of Sciences, 11, 6347-6352, 2014.

803   Brienen, R., Phillips, O., Feldspausch, T., Gloor, E., Lloyd, J., Lopez-Gonzalez, G.,

804   Morteagudo-Mendoza, A., Malhi, Y., Lewis, S., Vasquez Martinez, R., Alexiades, M.,

805   Alvarez, E., Alvarez-Loayzada, P., Zagt, R.: Long term decline of the Amazon carbon sink.

806   Nature, 519, 344-361, 2015.

807   Canadell, J., Schulze. D. Global potential of biospheric carbon management for climate

808   mitigation. Nature Communications, 5, 5282-5293, 2014.

809   Ciais, P., Dolman, J., Bombelli, A., Duren, A., Peregon, A., Rayner, P., Miller, C., Gobron,

810   N., et al.: Current systematic carbon-cycle observations and the need for implementing a

811   policy-relevant carbon observing system. Biogeosciences, 11, 3547-3602, 2014.

812   Cochrane, M., Alencar, A., Schulze, M., Souza, C., Nepstad, D., Lefebvre, P., Davidson, E.:

813   Positive feedbacks in the fire dynamics of closed canopy tropical forests. Science, 284,

814   1832-1835, 1999.

815   Crowther, T., Thomas, S., Maynard, D., Baldrian, P., Covey, K., Frey, S., van Diepen, L.,

816   Bradford, M.: Biotic interactions mediate soil microbial feedbacks to climate change.

817   Proceedings of the National Academy of Science, 112, 7033-7038, 2015.

818   EDGAR. The Emissions Database for Global Atmospheric Research (2012) Part III:

819   Greenhouse gas emissions. http://edgar.jrc.ec.europa.eu/docs/IEA_PARTIII.pdf

820   Estrada, M., Lee, D., Murray, B., O'Sullivan, R., Penman, J., Streck, C.: Land Use in a Future

821   Climate Agreement. # S-LMAQM-13-CA-1128 U.S. Department of State, 2014. Available

822   at: http://merid.org/land-use-in-ADP/

823   FAO. The Agriculture sectors in the intended nationally determined contributions. Analysis.

824   Environmental and natural resource management working paper 61. Rome, Italy. 2016.

825   Available at: http://www.fao.org/3/a-i5687e.pdf

826   Federici, S., Tubiello, F., Salvatore, M., Jacobs, H., Schmidhuber, J.: New estimates of CO2

827   forest emissions and removals: 1990-2015. Forest Ecol.Manag., 3, 89-98, 2015.

828   Federici, S., Grassi, G., Harris, N., Lee, D., Neeff, T., Penman, J., Sanz-Sanchez, M., Wolosin

829   M.: GHG fluxes from forests: an assessment of national reporting and independent science

830   in the context of the Paris Agreement. Working Paper. UCLA, San Francisco, 2016.

831   Available   at: http://www.climateandlandusealliance.org/wp-content/uploads/2016/06/

832   GHG_Fluxes_From_Forests_Working_Paper.pdf

833   Friedlingstein, P., Andrew, R., Rogelj, J., Peters G., Canadell J., Knutti, R., Luderer, G.,

834   Raupach, M., Schaeffer, M., van Vuuren, D., Le Quéré, C.: Persistent growth of CO_2

835   emissions and implications for reaching climate targets. Nature geoscience, 7, 709-715,

836   2014.

837   Forest Resources Assessment (FRA) (2005) http://www.fao.org/forestry/fra/fra2005/en/

838   Forest Resources Assessment (FRA) (2010). http://www.fao.org/forestry/fra/fra2010/en/

839   Frank, D., Reichstein, M., Bahn, M., Thonicke, K., Frank. D., Mahecha, M., Smith, P., van

840   der Velde, M. et al. Effects of climate extremes on the terrestrial carbon cycle: concepts,

841   processes and potential future impacts. Global Change Biology, 21, 2861-2880, 2015.

Francey, R., Trudinger, C., Van der Schoot, M., Krummel, P., Steele, L., Langenfelds, L.: Differences between trends in atmospheric CO2 and the reported trends in anthropogenic CO_2 emissions. Tellus, 62B, 316-328, 2010.

Francey, R., Trudinger, C., Van der Schoot, M., Law, M., Krummel, P., Langenfelds, R., Steele, P., Allison, C., Stavert, A., Andres, R., Rödenbeck, C.: Atmospheric verification of anthropogenic CO_2 emission trends. Nature Climate Change, 3, 520-525, 2013a.

Francey, R., Trudinger, C., Van der Schoot, M., Law, M., Krummel, P., Langenfelds, R., Steele, P., Allison, C., Stavert, A., Andres, R., Rödenbeck, C.: Reply to Anthropogenic CO_2 emissions. Nature Climate Change, 3, 603-604, 2013b.

Giglio, L., Randerson, J., van der Werf, G., Kasibhatla, P., Collatz, G., Morton D., DeFries, R.: Assessing variability and long-term trends in burned area by merging multiple satellite fire products. Biogeosciences, 7, 1171–1186, 2010.

Grace, J., Mitchard, E., Gloor, E.: Perturbations in the carbon budget of the tropics. Global Change Biology, 20, 3238-3255, 2014.

Grassi, G., Dentener, F.: Quantifying the contribution of the Land Use Sector to the Paris Climate Agreement. The LULUCF sector within the Intended Nationally Determined Contributions. EUR 27561.JRC Science for Policy Report. Ispra, Italy, 2015. Available at: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC98451/jrc%20lulucf-indc%20report.pdf

Grassi, G., Monni, S., Federici, S., Achard, F., Mollicone, D.: Applying the conservativeness principle to REDD to deal with uncertainties of the estimates. Environmental Research Letters, 3, 035005, 2008.

Hansen, M., Stehman, S., Potapov, P.: Quantification of global gross forest cover loss. Proceedings of the National Academy of Sciences, 107, 8650-8655, 2010.

866 Harris, N., Brown, S., Hagen, S., Saatchi, S., Petrova, S., Salas, W., Hansen, M., Potapov, P.,

867 Lotsch, A.: Baseline Map of Carbon Emissions from Deforestation in Tropical Regions.

868 Science, 336, 1576-1578, 2012.

869 Herrero, M., Havlik, P., Valin, H., Notenbaert, A., Rufino, M., Thornton, P., Blümmel, M.,

870 Weiss, F., Grace, D., Obesteiner, M.: Biomass use, production, feed efficiencies, and

871 greenhouse gas emissions from global livestock systems. Proc. Natl. Acad. Sci., 110, 20888-

872 20893, 2013.

873 Herold, M., Roman-Cuesta, RM., Heymell, V., Hirata, Y., Van Laake, P., Asner, G., Souza,

874 C., Avitabile, V., MacDicken, K.: A review of methods to measure and monitor historical

875 carbon emissions from forest degradation. FAO. Unasylva, 238, 16-24, 2011a. Available at:

876 http://www.fao.org/docrep/015/i2560e/i2560e04.pdf

877 Herold, M., Roman-Cuesta, RM., Mollicone, D., Hirata, Y., Van Laake, P., Asner, G., Souza,

878 C., Skutch, M., Avitabile, V., MacDicken, K.: Options for monitoring and estimating hisoric

879 carbon emissions from forest degradation in the context of REDD+. Carbon Balance and

880 Management, 6, 13-20, 2011b.

881 Holmgren, P. Can we trust country-level data from global forest assessments? Available at:

882 http://blog.cifor.org/34669/can-we-trust-country-level-data-from-global-forest-

883 assessments?fnl=en Last view September 2016.

884 Hooijer, A., Page, S., Canadell, J., Silvius, M., Kwadijk, J., Wosten, H., Jauhiainen, J.:

885 Current and future CO_2 emissions from drained peatlands in Southeast Asia.

886 Biogeosciences, 7, 1505-1514, 2010.

887 Houghton, RA.: The annual net flux of carbon to the atmosphere from changes in land use

888 1850-1990. Tellus B, 51, 298-313, 1999.

889 Houghton, RA.: How well do we know the flux of CO_2 from land-use change? Tellus B, 62,

890 337-351, 2010.

891   Houghton, RA.: Carbon emissions and the drivers of deforestation and forest degradation in

892   the tropics. Current Opinion in Environmental Sustainability, 4, 597-603, 2012.

893   Houghton, RA., Hackler, JL.: Carbon Flux to the Atmosphere from Land-Use Changes: 1850

894   to 1990. ORNL/CDIAC-131, NDP-050/R1. Carbon Dioxide Information Analysis Center,

895   U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A,

896   2001.

897   Houghton, RA., House, JI., Pongratz, J., van der Werf, G., DeFries, R., Hansen, M., Le

898   Quere, C., Ramankutty, R.: Carbon emissions from land use and land-cover change.

899   Biogeosciences, 9, 5125-5142, 2012.

900   IPCC. Intergovernmental Panel on Climate Change.: Good Practice Guidance for Land Use,

901   Land Use and Forestry.. IPCC National Greenhouse Gas Inventory Programme. (ed. Penman

902   J, Gytarsky M, Hiraishi T, Krug T, Kruger D, Ppatti R, Buendia L, Miwa K, Ngara T,

903   Tanabe K, Wagner F) IGES. Kanagawa, Japan, 2003 http://www.ipcc-

904   nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/GPG_LULUCF_ FULL.pdf

905   IPCC. Intergovernmental Panel on Climate Change.: AFOLU Guidelines for National

906   Greenhouse gas Inventories. Vol. 4: Agriculture, Forestry and Other Land Use (eds

907   Eggleston S, Buendia L, Miwa K, Ngara T, Tanabe K). IGES, Kanagawa, Japan. 2006.

908   http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.htm

909   IPCC. Intergovernmental Panel on Climate Change.: Summary for Policymakers. In: Climate

910   Change 2014: Mitigation of Climate Change.Contribution of Working Group III to the Fifth

911   Assessment Report of the Intergovernmental Panel on Climate Change (eds Edenhofer O,

912   Pichs-Madruga R, Sokona Y, E, Farahani E, Kadner S, Seyboth K, Adler A, Baum I,

913   Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlomer S, von Stechow C, Zwickel

914   T, Minx JC). Cambridge University Press, Cambridge, United Kingdom and New York,

915   NY, USA, 2014.

916 Laurance, W., Williamson, G.: Positive feedbacks among forest fragmentation, drought and

917   climate change in the Amazon. Conservation Biology, **15**, 1529–1535, 2001.

918 Le Quéré, C., Peters, G.P., Andres, R. J., Andrew, R. M., Boden, T. A., Ciais, P.,

919   Friedlingstein, P., Houghton, R.A., Marland, G., Moriarty, R., Sitch, S., Tans, P., Arneth,

920   A., Arvanitis, A., Bakker, D. C.E., Bopp, L., Canadell, J. G., Chini, L. P., Doney, S. C.,

921   Harper, A., Harris, I., House, J.I., Jain, A. K., Jones, S. D., Kato, E., Keeling, R. F., Klein

922   Goldewijk, K., Körtzinger, A.,Koven, C., Lefèvre, N., Maignan, F., Omar, A., Ono, T.,

923   Park, G.-H., Pfeil, B., Poulter, B., Raupach, M. R., Regnier, P., Rödenbeck, C., Saito, S.,

924   Schwinger, J., Segschneider,J., Stocker, B. D., Takahashi, T., Tilbrook, B., van Heuven, S.,

925   Viovy, N., Wanninkhof,R., Wiltshire, A., and Zaehle, S. Global carbon budget 2013, Earth

926   System Science Data, 6, 235-263, 2014.

927 Li, C., Salas, W., DeAngelo, B., Rose, S.: DNDC9.5 in EPA (2013) Global Mitigation of non-

928   CO2 Greenhouse Gases: 2010-2030. EPA Technical Report-430-R-13-011, US, 2013.

929   Country data available at: http://www.epa.gov/climatechange/EPAactivities/economics/

930   nonco2 projections.html

931 Montzka, SA., Dlugokencky, EJ., Butler, JH.: Non-CO2 greenhouse gases and climate

932   change. Nature, 476, 43-51, 2011.

933 Morton, DC., Le Page, Y., DeFries, R., Collatz, GJ., Hurtt, GC.: Understory fire frequency

934   and the fate of burned forests in southern Amazonia. Philosophical Transactions of the

935   Royal Society B, 368, 20120163, 2013.

936 Negron-Juarez, RI., Chambers, J., Guimaraes, G., Zeng, H., Raupp, C., Marra, D., Ribeiro,

937   G., Saatchi, S., Nelson, B., Higuchi, N.: Widespread Amazon forest tree mortality from a

938   single cross-basin squall line event. Gephysical Research Letters, 37, L16701, 2010.

939 Numata, I., Cochrane, M., Roberts, D., Soares, J., Souza, C., Sales, M.: Biomass collapse and

940   carbon emissions from forest fragmentation in the Brazilian Amazon. Journal of

941   Geophysical Research, 115, G03027, 2010.

942 Ogle, S. et al. in EPA (2013) Global Mitigation of non-CO2 Greenhouse Gases: 2010-2030.

943   EPA Technical Report-430-R-13-011, 2013.(data available upon request) Country data

944   available at:http://www.epa.gov/climatechange/EPAactivities/economics/nonco2projections.

945   html

946 Oliveras, I., Malhi, Y., Salinas, N., Huaman, V., Urquiaga-Flores, E., Kala-Mamani, J.,

947   Quintano-Loaiza, JA., Cuba-Torres, I., Lizarraga-Morales, N., Roman-Cuesta, RM.:

948   Changes in forest structure and composition after fire in tropical montane cloud forests near

949   the Andean treeline. Plant Ecology and Diversity,7, 329-340, 2013.

950 Oliveras, I. Anderson, D., Malhi, Y.: Application of remote sensing to understanding fire

951   regimes and biomass burning emissions of the tropical Andes. Global Biogeochemical Cy

952   cles, 28, 480-496, 2014.

953 Pelletier, J., Busch, J., Potvin, C.: Addressing uncertainty upstream or downstream of

954   accounting for emissions reductions from deforestation and forest degradation. Climatic

955   Change, 130, 635-648, 2015.

956 Peters, G., Davis, J., Andrew, R.: A synthesis of carbon in international trade. Biogeosciences,

957   9, 3247-3276, 2012.

958 Phillips, O., Aragao, L., Lewis, S., et al.: Drought Sensitivity of the Amazon Rainforest.

959   Science, 323, 1344-1347, 2009.

960 Phillips, O., van der Heijden, G., Lewis, S., et al.: Drought-mortality relationships for tropical

961   forests. New Phitologist, 187, 631-646, 2010.

962 Phillips, O., Lewis, S.:Evaluating the tropical forest carbon sink. Global Change Biology, 20,

963   2039-2041, 2014.

964 Poorter, L., Bongers, F., Aide et al.: Biomass resilience of Neotropical secondary forests.

965   Nature, 530, 211-214, 2016.

966 Pütz, S., Groeneveld, J., Henle, K., Knogge, C., Martensen, A., Metz, M.: Long-term carbon

967   loss in fragmented Neotropical forests. Nature communications, 5, 5037-5045, 2014.

968 Read, L., Lawrence, D.: Recovery of biomass following shifting cultivation in dry tropical

969   forests of the Yucatan. Ecological Applications, 13, 85–97, 2003.

970 Richards, M., Bruun, T., Campbell, BM., Gregersen, L., Huyer, S., Kuntze, V., Madsen, T.,

971   Oldvig, M., Vasileiou, I.: How countries plan to address agricultural adaptation and

972   mitigation: An analysis of Intended Nationally Determined Contributions. CGIAR Research

973   Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, 2015.

974 Richter, D., Houghton, RA.: Gross CO_2 fluxes from land-use change: implications for

975   reducing global emissions and increasing sinks. Carbon management, 2, 41-47, 2011.

976 Roman-Cuesta, RM., Gracia, M., Retana, J.: Environmental and human factors influencing

977   fire trends in Enso and non-Enso years in tropical Mexico. Ecological Applications, 13,

978   1177–1192, 2003.

979 Roman-Cuesta, RM., Salinas, N., Asbjornsen, H. et al.: Implications of fires on carbon

980   budgets in Andean cloud montane forest: The importance of peat soils and tree resprouting.

981   Forest Ecology and Management, 261, 1987–1997, 2011

982 Roman-Cuesta, RM., Rufino, M., Herold, M., Butterbach-Bahl, K., Rosenstock, T., Ogle, S.,

983   Li, S., Herrero, M., Poulter, B., Verchot, L., Martius, C., Stuiver, J., De Bruin, S.: Hotspots

984   of tropical land use emissions: patterns, uncertainties, and leading emission sources for the

985   period 2000-2005. Biogeosciences, 13, 4253–4269, 2016.

986 Romijn, E., Herold, M., Koistra, L., Murdiyarso, D., Verchot, L.: Assessing capacities of non-

987   Annex I countries for national forest monitoring in the context of REDD+. Environmental

988   Science Policy, 19–20, 33–48, 2012.

Romijn, E., Lantican, C., Herold, M., Lindquist, E., Ochieng, R., Wijaya, A., Murdiyarso, D., Verchot, L.: Assessing change in national forest monitoring capacities of 99 tropical countries. Forest Ecology and Management, 352, 109–123, 2015.

Saatchi, S., Harris, N., Brown, S., et al.: Benchmark map of forest carbon stocks in tropical regions across three continents. Proceedings of the National Academy of Sciences, 108, 9899-9904, 2012.

Simula, M.: Towards defining forest degradation: comparative analysis of existing definitions. Forest Resources Assessment. Working Paper 154. FAO. Rome, Italy, 2009. Aavailable at: ftp://ftp.fao.org/docrep/fao/012/k6217e/k6217e00.pdf

Sist, P., Rutishauser, E., Peña-Claros, M., et al.: The Tropical Managed Forests Observatory: a research network addressing the future of logged forests. Applied Vegetation Science, 18, 171-174, 2015.

Smith, P., Martino, D., Cai, Z., et al.: Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences, 363, 789‑813, 2008.

Smith, P., Bustamante, M., Ahammad, H., et al.: Agriculture, Forestry and Other Land Use (AFOLU). In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds Edenhofer O, Pichs-Madruga R, Sokona Y, E, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlomer S, von Stechow C, Zwickel T, Minx JC). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

Streck, C.: Forests and Land Use in the Paris Agreement. Climate Focus. 2015. Available at: http://www.climatefocus.com/sites/default/files/20151223%20Land%20Use%20and%20the%20Paris%20Agreement%20FIN.pdf

1013   Tian, H., Lu, C., Ciais, P., Michalak, A., Canadell, J., Saikawa, E., Huntzinger, D., Gurney,

1014   K., Sitch, S., Zhang, B., Yang, J., Bousquet, P., Bruhwiler, L., Chen, G., Dlugokencky, E.,

1015   Wofsy, S.: The terrestrial biosphere as a net source of greenhouse gases to the atmosphere,

1016   Nature, 531, 225–228, 2016.

1017   Tubiello, F., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N., Smith, P.: The FAOSTAT

1018   database of greenhouse gas emissions from agriculture. Environmental Research Letters, 8,

1019   015009-19, 2013.

1020   Tubiello, F., Salvatore, M., Cóndor Golec, R., Ferrara, A., Rossi, S., Biancalani, R., Federici,

1021   S., Jacobs, H., Flammini, A.: Agriculture, Forestry and Other Land Use Emissions by

1022   Sources and Removals by Sinks 1990 – 2011 Analysis. Working Paper Series ESS/14-

1023   02.FAO   Statistical   Division.   Rome,   Italy,   2014.   Available   at:

1024   http://www.fao.org/docrep/019/ i3671e/i3671e.pdf

1025   Tubiello, F., Salvatore, M., Ferrara, A., House, J., Federici, S., Rossi, S., Biancalani, R.,

1026   Condor Golec, R., Jacobs, H., Flammini, A., Prosperi, P., Cardenas-Galindo, P.,

1027   Schmidhuber, J., Sanz Sanchez, MJ., Srivastava, N., Smith, P. The contribution of

1028   Agriculture, Forestry and other Land Use Activities to Global Warming, 1990-2012. Global

1029   Change Biol., 21, 2655–2660, 2015.

1030   Turetsky, M., Benscoter, B., Page, S., Rein, G., Van der Werf, G., Watts, A.: Global

1031   vulnerability of peatlands to fire and carbon loss. Nature Geosciences, 8, 11-14, 2015.

1032   Uhl, C., Kauffman, J.: Deforestation effects on fire susceptibility and the potential response of

1033   the tree species to fire in the rainforest of the eastern Amazon. Ecology, 71, 437–449, 1990.

1034   USEPA. United States Environmental Protection Agency. Global Anthropogenic Non-CO_2

1035   Greenhouse Gas Emissions: 1990-2030. EPA 430-R-12-006. Washington, DC. 2012.

1036   Available at: http://www.epa.gov/climatechange/economics/international.html

1037 USEPA. United States Environmental Protection Agency. Global Mitigation of non-CO2

1038   Greenhouse Gases: 2010-2030. Technical Report-430-R-13-011, 2013. Available at:

1039   http://www.epa.gov/climate change/Downloads/EPAactivities/MAC_Report_2013.pdf

1040 Valentini, R., Arneth, A., Bombelli, A. et al.: A full greenhouse gases budget of Africa:

1041   synthesis, uncertainties and vulnerabilities. Biogeosciences, 11, 381-407, 2014.

1042 Van der Werf, G., Randerson, J., Giglio, L., Collatz, G., Mu, M., Kasibhatla, P., Morton, D.,

1043   DeFries, R., Jin, Y., van Leeuwen, T.: Global fire emissions and the contribution of

1044   deforestation, savannah, forest, agricultural, and peat fires (1997–2009). Atmospheric

1045   Chemistry and Physics, 10, 11707–11735, 2010.

1046 Werner, C., Butterbach-Bahl, K., Haas, E., Hickler, T., Kiese, R.: A global inventory of N_2O

1047   emissions from tropical rainforest soils using a detailed biogeochemical model. Global

1048   biogeochemical Cycles, 21, GB3010, 2007.

1049

6. CONTRIBUTIONS

1050

1051 RMRC, MR, MH designed the study. SO, BP provided data and ran quality controls of the

1052 data. RMRC, MR, MH, KBB, TR, LV, CM, SR, RH, SO, BP,SdB discussed the results and

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1054

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1055

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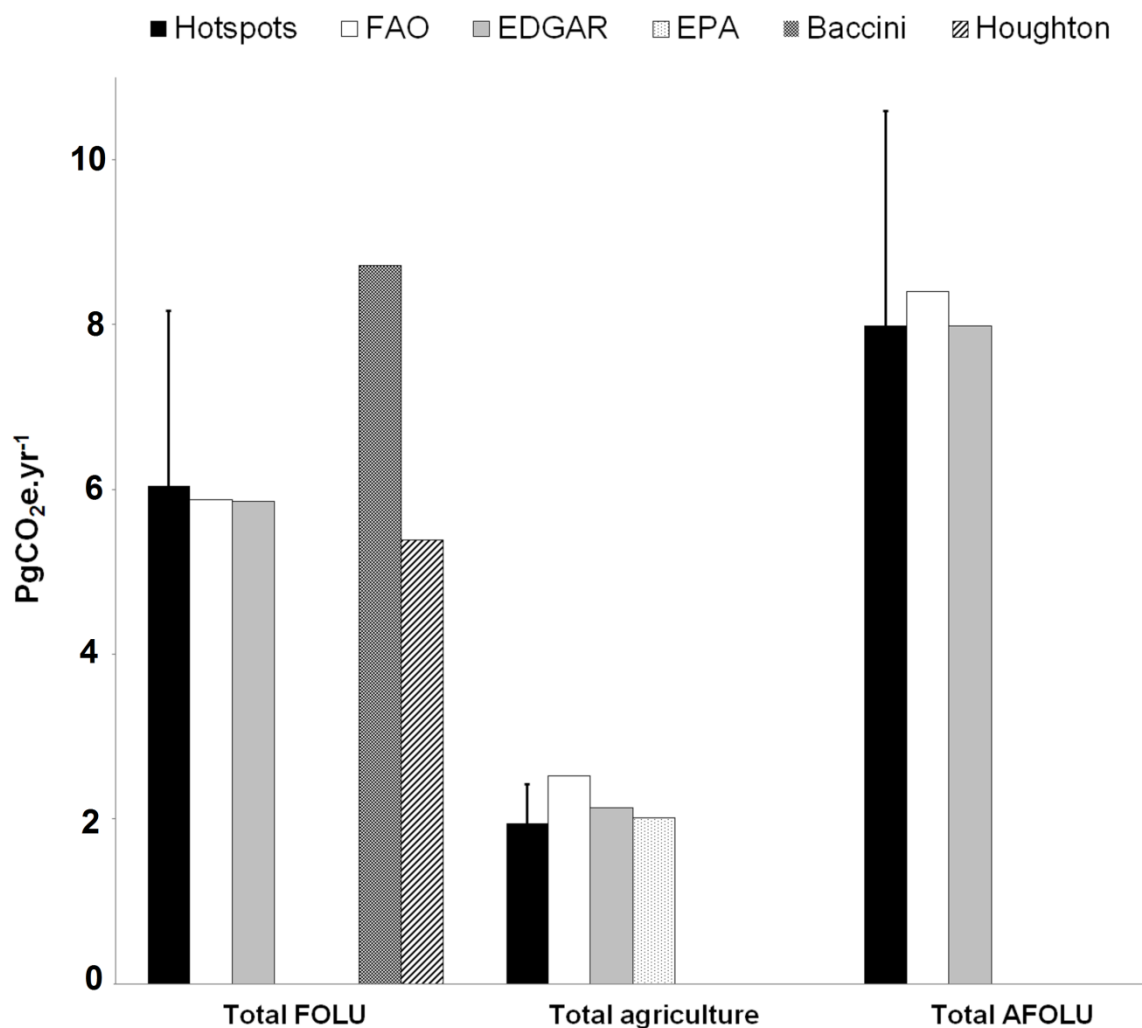
 Figures

Figure 1: AFOLU (Agriculture, Forestry and Other Land Use) emissions estimates ($PgCO_2e.yr^{-1}$) for the period 2000-2005 for the tropics, for six datasets (Hotspots, FAO (FAOSTAT), EDGAR, EPA, Baccini and Houghton), disaggregated into FOLU (Forestry and Other Land Use) and Agricultural emissions. Uncertainties are only provided in the Hotspot dataset. EPA data do not include a FOLU sector. Houghton and Baccini's are FOLU, CO_2-only, datasets and do not include agricultural emissions. Houghton offers net emissions while Baccini's data are gross emissions for deforestation + fire + wood harvesting (Baccini et al., 2012).

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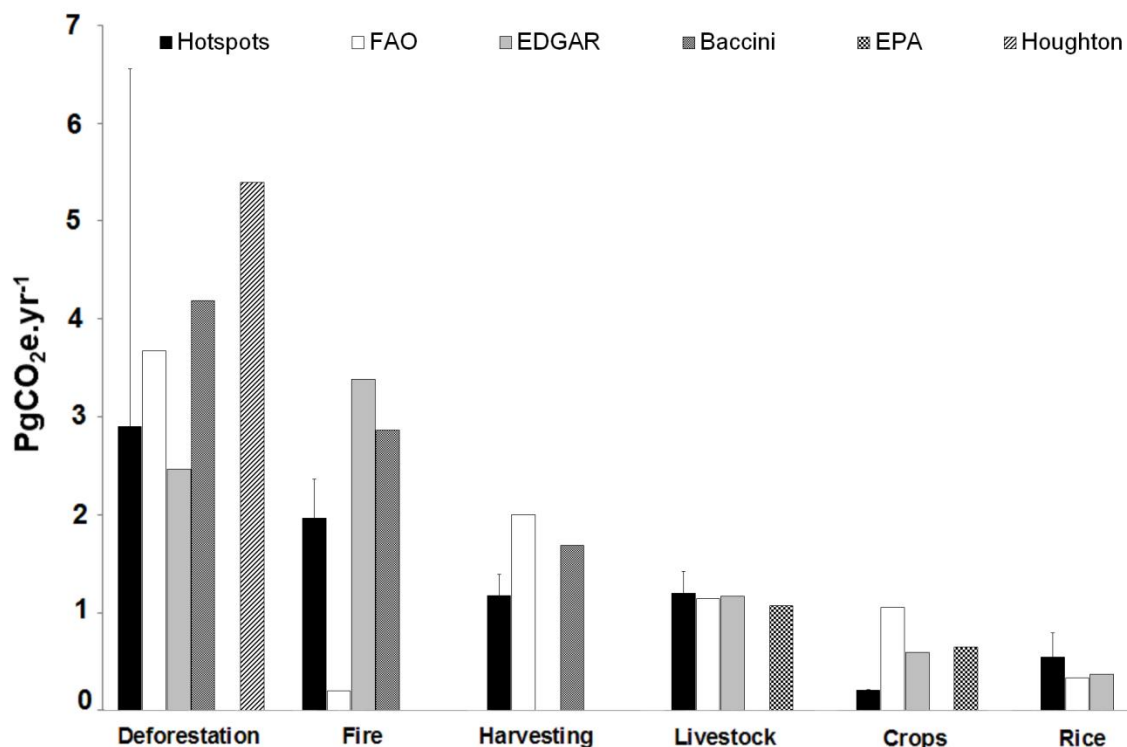

1075

1076 **Figure 2:** Tropical gross annual emissions (2000-2005) comparisons, for the leading emission

1077 sources in the AFOLU sector, for the Hotspots, FAOSTAT, EDGAR, Baccini, EPA and

1078 Houghton datasets). Bars indicate uncertainty estimates (1σ from mean). No uncertainty

1079 estimates are available for the other datasets.Houghton's data are net land use emissions

1080 rather than deforestation and are offered for visual comparisons against Baccini's gross

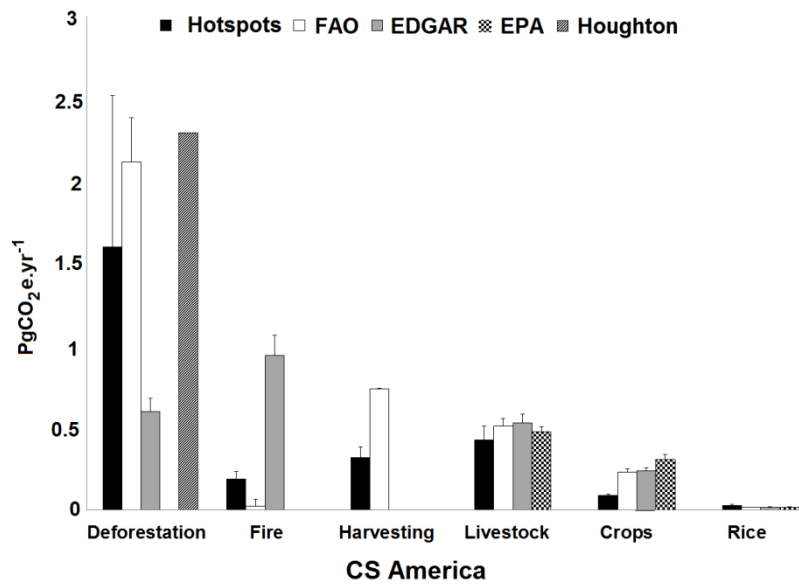
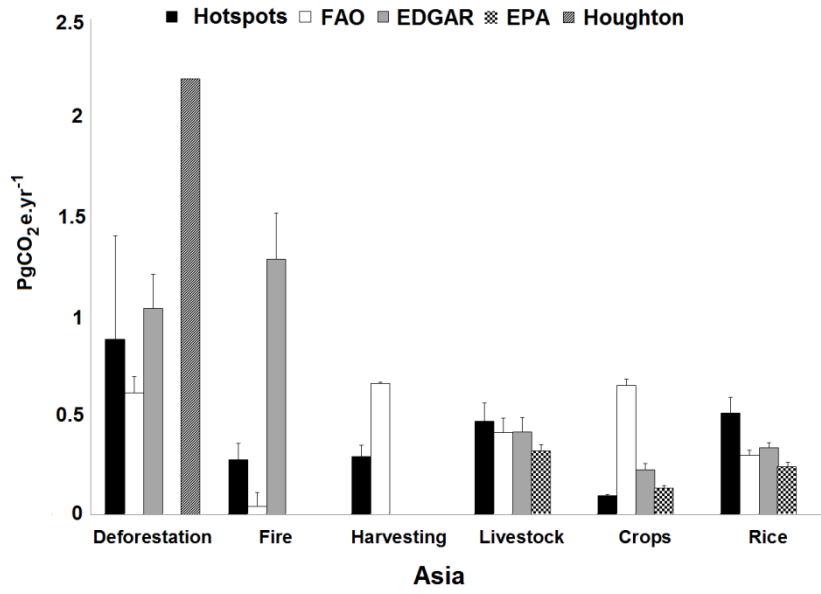
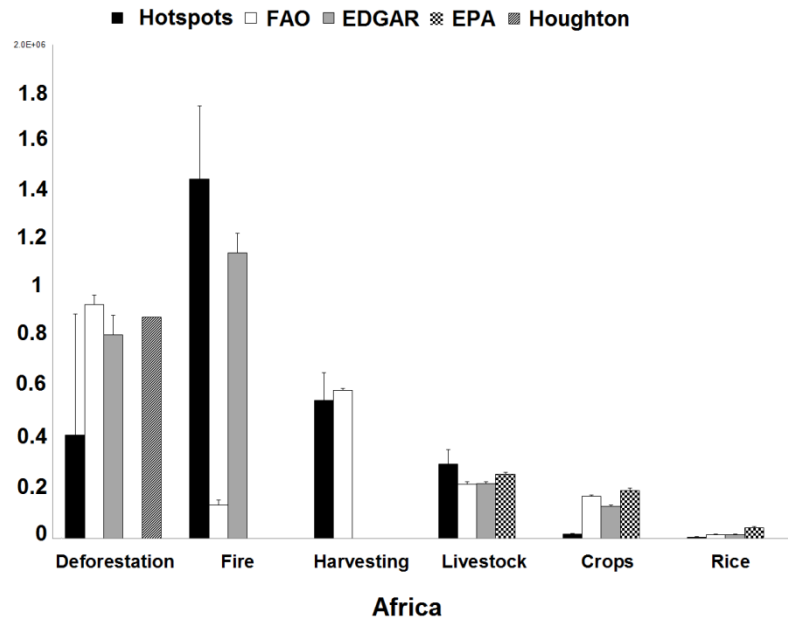
1081 deforestation estimate which includes gross deforestation + fire + wood harvesting.

1082 Uncertainties are only provided in the Hotspot dataset. EPA data do not include a FOLU

1083 sector. Forest degradation would be the sum of fire and harvesting emissions.

Africa

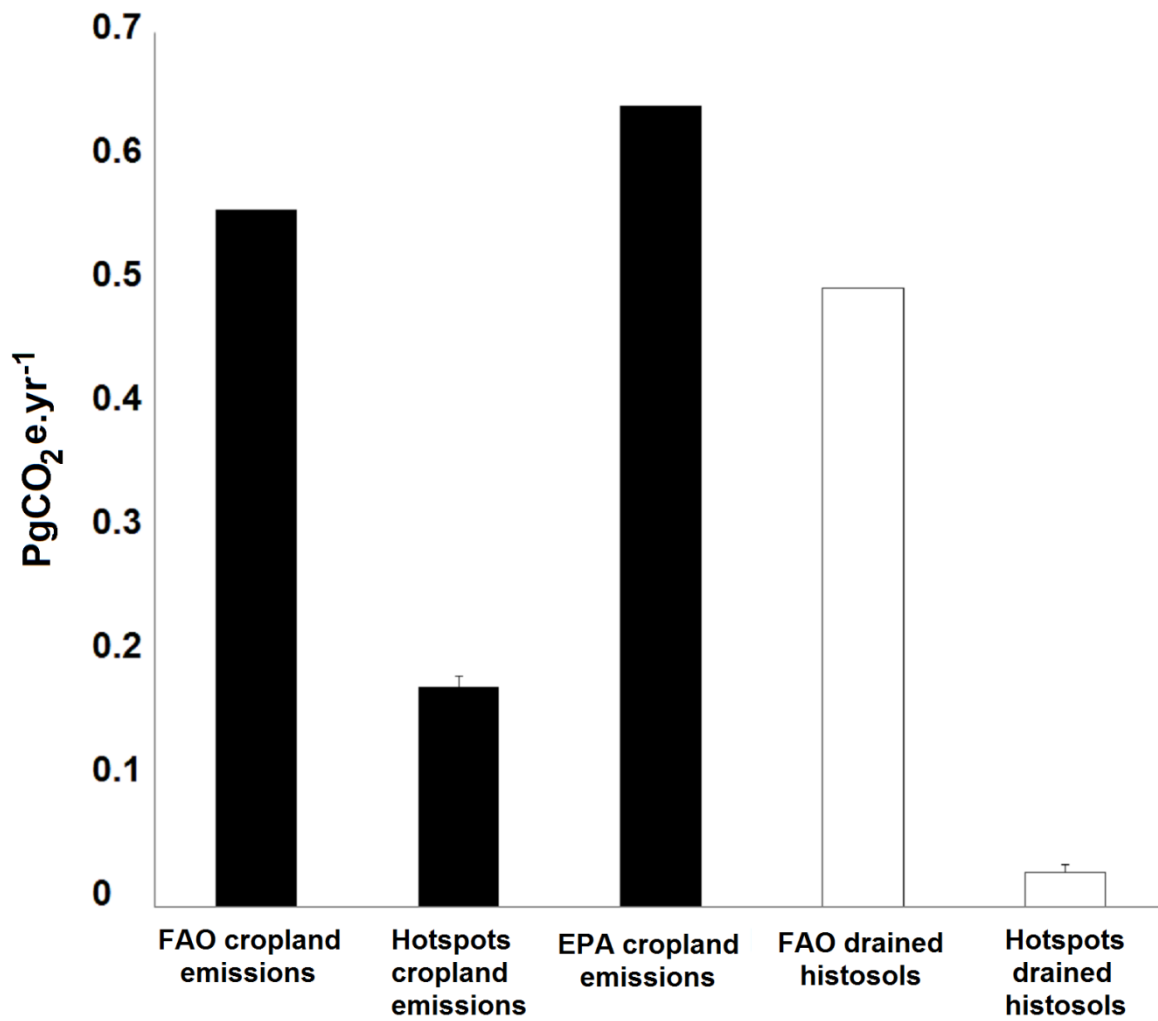
Asia

CS America

1085   **Figure 3**: Continental disaggregated emissions for the individual emission sources

1086   ($PgCO_2e.yr^{-1}$). Bars indicate uncertainty estimates (1σ from mean). No uncertainty estimates

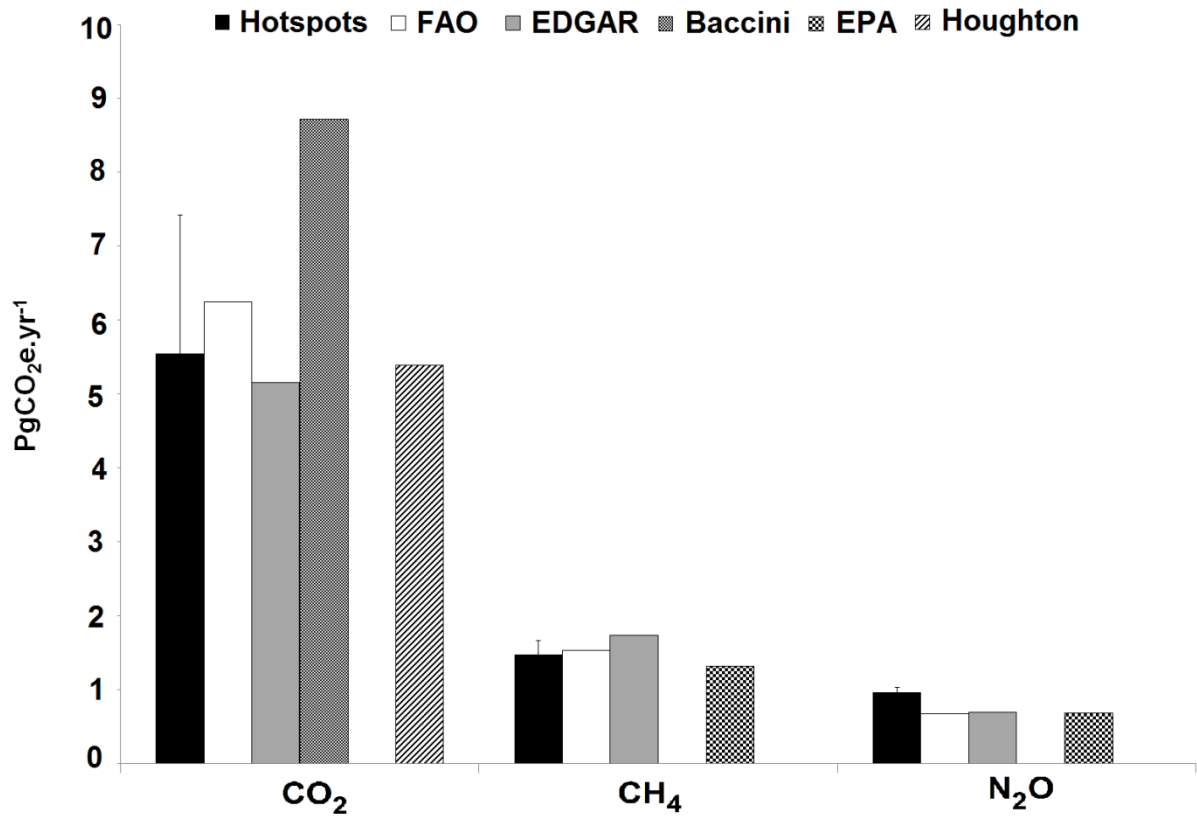
1087   are available for the other datasets.

1088

1089

1090

1091 **Figure 4**: Disaggregation of cropland soil emissions from drained peatlands for datasets with

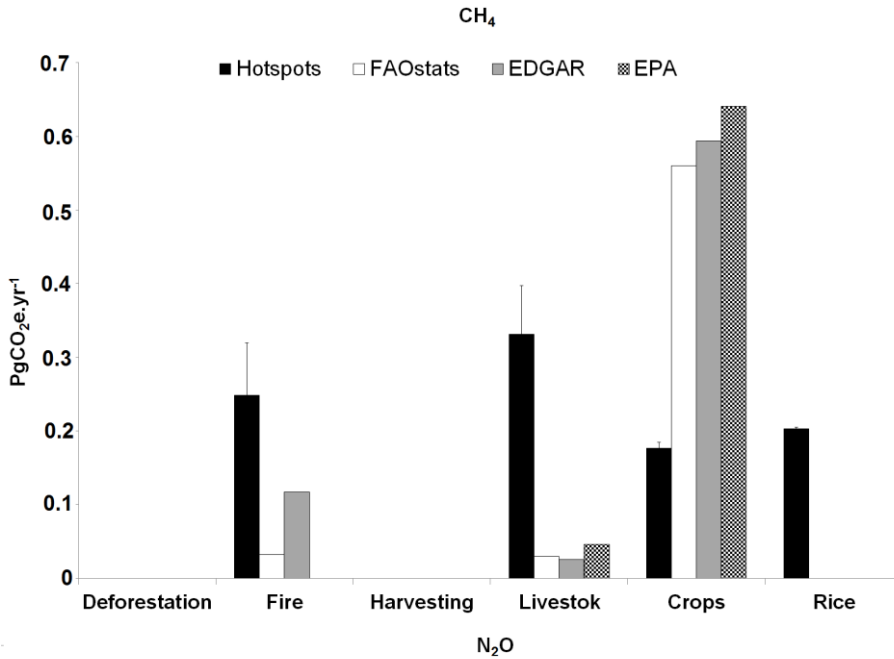
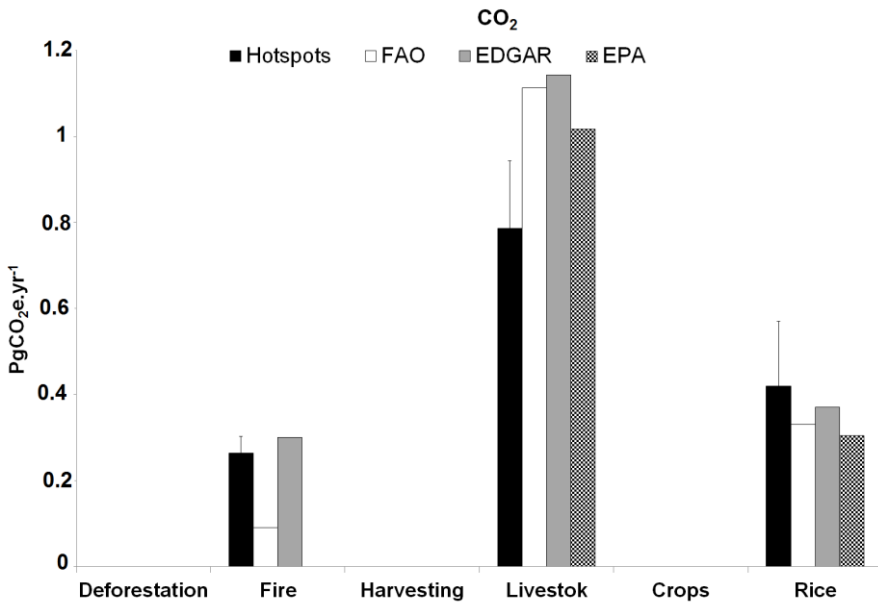
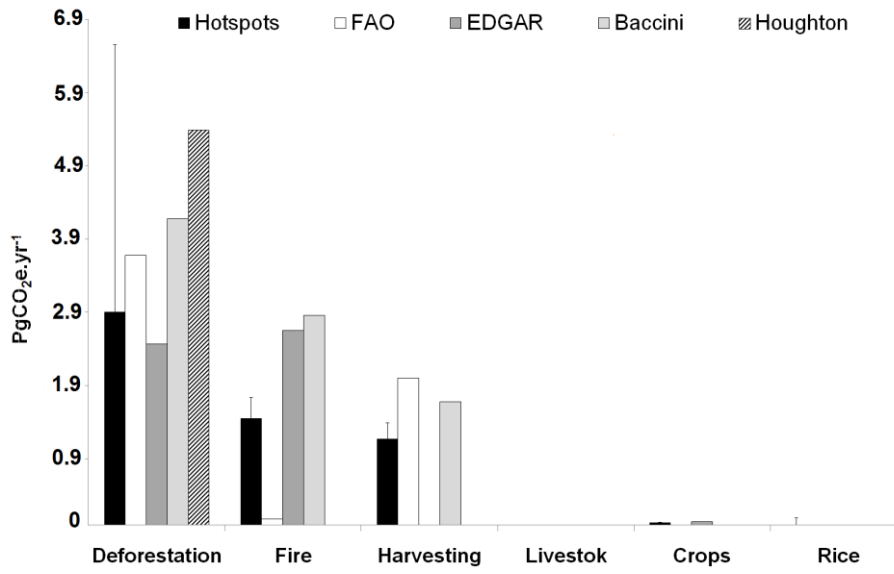
1092 available data: FAOSTAT and Hotspots. Organic soils are excluded in EPA's cropland

1093 emissions.

1094

1095 **Figure 5:** Contribution of the different AFOLU GHGs (CO2, CH4 and N2O) for the different

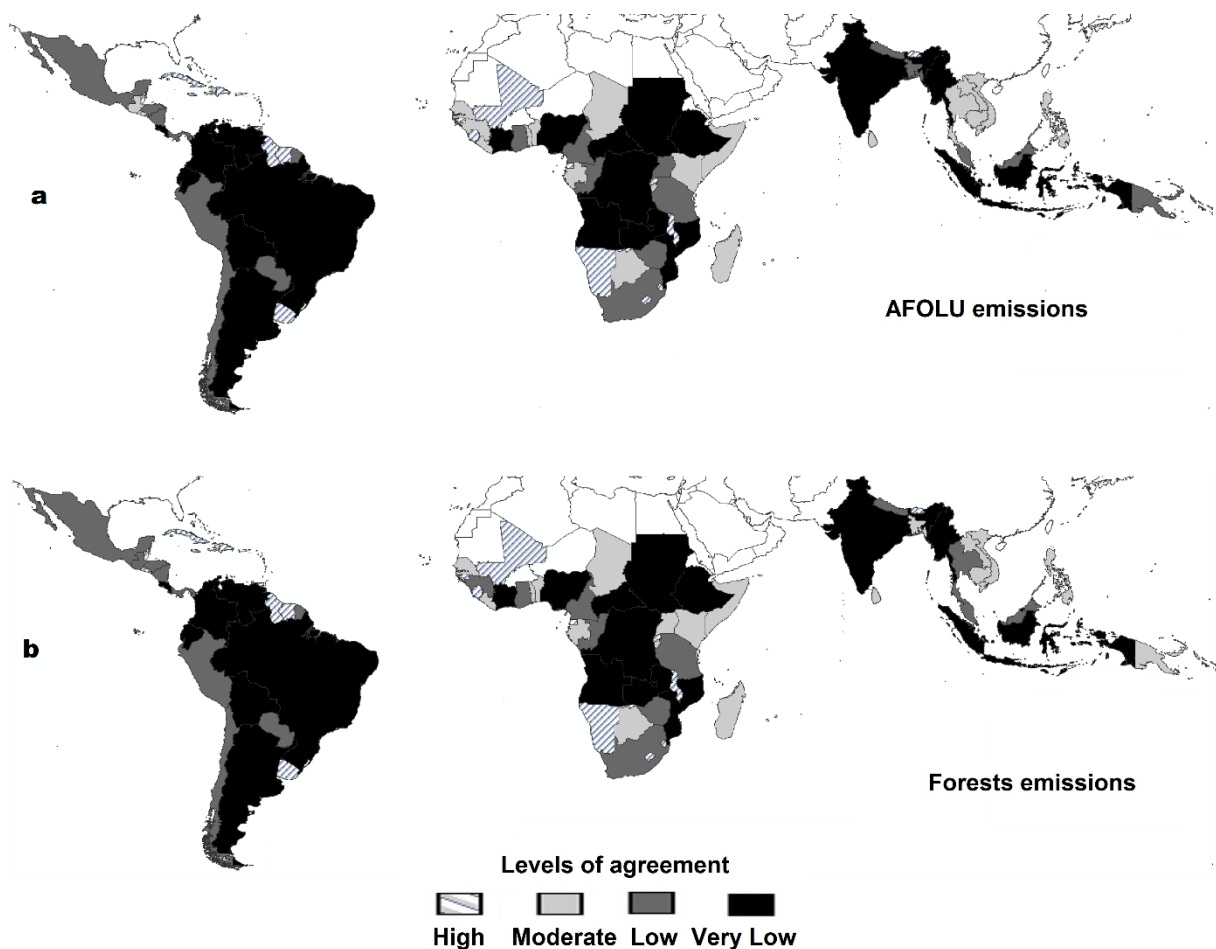
1096 datasets. Bars indicate uncertainty estimates (1σ from mean). No uncertainty estimates are

1097 available for the other datasets.

1098

1099 **Figure 6**: GHG emission contribution (CO_2, CH_4 and N_2O) of the leading AFOLU emission

1100 sources. Bars indicate uncertainty estimates (1σ from mean). No uncertainty estimates are

1101 available for the other datasets.

1102

1103

1104   **Figure 7**: Country level agreement for (a) AFOLU and (b) forest emissions for the

1105   FAOSTAT, EDGAR and 'Hotspots' databases. The categories of agreement are percentiles of

1106   the standard deviations and represent data dispersion = data variability (i.e. High agreement =

1107   low data variability = low data dispersion $\leq 25^{th}$ percentile, Moderate agreement: 25th-50th

1108   percentiles, Low agreement: 50th-75th percentiles, and Very Low agreement = high data

1109   variability $\geq 75^{th}$ percentile)

1110

Figure 8: Country level agreement for (a) Cropland and (b) livestock emissions for the

FAOSTAT, EDGAR and 'Hotspots' databases. The categories of agreement are percentiles of

the standard deviations and represent data dispersion = data variability (i.e. High agreement =

low data variability = low data dispersion $\leq 25^{th}$ percentile, Moderate agreement: 25th-50th

percentiles, Low agreement: 50th-75th percentiles, and Very Low agreement = high data

variability $\geq 75^{th}$ percentile)

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1119 **Tables**

	Hotspots	**FAOSTAT**	**EDGAR**	**Houghton**	**Baccini**	**EPA**	**AR5**
Gross/Net emissions	Gross	Gross	Gross	Net	Gross	Gross	Net
Uncertainty[a]	√	No	No	No	No	No	√
Transparency	High	High	Low[b]	Low	Low	Intermediate	Low
IPCC compliant	√	√	√	Not fully[c]	Not fully[d]	√	Not fully[e]
Forest carbon Pools	AGB + BGB	AGB + BGB	AGB	AGB+BGB+Soil +CWD+Litter	AGB+BGB+Soil +CWD+Litter	Soil	AGB+BGB+Soil +CWD+Litter
Gases	CO_2,CH_4, N_2O	CO_2,CH_4, N_2O	CO_2,CH_4, N_2O	CO_2	CO_2	CO_2,CH_4, N_2O	CO_2 for forests. CO_2,CH_4, N_2O for agriculture and peatlands.
Tier 1	√	√	√			√	-
Tier 2, 3	√			√	√	√	-
Spatial Disaggregation[f]	Pixel (0.5°)	Country	Country[g]	Region	Region	Country	Region
Peatlands	√	√	√	No	No	No	√

1120 **Table 1:** differences and similarities of the assessed AFOLU datasets.

1121 a Uncertainty at the level of disaggregation at which data are available to download.

1122 b Low means there is no metadata available, or metadata does not properly document the

1123 processes followed to estimate the emissions.

1124 c EDGAR data on deforestation emissions does not follow IPCC guidelines.

1125 d The bookkeeping approach does not follow the concept of managed land, and does not

1126 include the sink of forests remaining forests in managed land other than logged forests and

1127 those regrowing after shifting cultivation.

1128 e Based on Houghton et al. (2012).

1129 f Available disaggregated data.

1130   g We selected data at the country scale to favour comparability with other datasets (i.e.

1131   FAOSTAT) even though data are available at pixel level (0.1°).

1132

(a)	Gross Tropical ($PgCO_2e.yr^{-1}$)						
	2000-2005					2000-2007	
	Hotspots	FAOSTAT	EDGAR-JRC	Houghton	EPA	Baccini	AR5
Agriculture	1.9 (1.5-2.5)	2.5	2.1	-	2.0	-	
FOLU	6 (3.8-10)	5.9	5.9	5.4*	-	12.3**	8.2***
AFOLU	8 (5.5-12.2)	8.4	8	-	-	-	

(b)	Net Global $PgCO_2e.yr^{-1}$						
	2000			2010			2000/09
	FAOSTAT	EDGAR-JRC	Houghton	FAOSTAT	EDGAR-JRC	Houghton	AR5
Agriculture	5	5.5	-	5.2	5.8	-	5
FOLU	4.9	6.5	4.9	4.9	5.5	4.2	5
AFOLU	9.9	12	-	10.1	11.3	-	10

1133

1134 **Table 2:** Summary of (a) tropical gross emissions estimates for agriculture, FOLU (Forestry and Other Land Use) and AFOLU (Agriculture,

1135 Forestry and Other Land Use) for all the datasets (Hotspots, FAOSTAT, EDGAR, EPA, Houghton) (2000-2005) and published data (Baccini et

1136 al. (2012), AR5 (Smith et al., 2014)) (2000-2007), and of (b) net global estimates as reported by Tubiello et al., (2015). Houghton and EPA offer

1137 FOLU and agricultural data only, respectively, and therefore estimates for AFOLU are not complete.

1138 *Data exposed in Figure 11.2 in Chapter 11 Smith et al. (2014), it corresponds to a net FOLU estimate without agriculture.

1139 ** Baccini et al., (2012) reported gross estimates for the FOLU components.

1140 *** Baccini et al., (2012) estimates selected for the AR5 FOLU values in Figure 11.8, Chapter 11, WG-III.

1141

	Deforestation	Wood Harvesting	Fire	Enteric Fermentation	Manure management	Agricultural soils	Cropland over histosols	Rice	Others
CO_2	Hotspots[1] FAOSTAT[2] Houghton[3] Baccini[1]	Hotspots[4] FAOSTAT[5] Houghton[4] Baccini[4]	Hotspots[6] FAOSTAT[7] EDGAR[8] Houghton[9] Baccini[9]				Hotspots[10] FAOSTAT[11]		EDGAR[12]
CH_4			Hotspots[13] FAOSTAT[14] EDGAR[15]	Hotspots FAOSTAT EDGAR EPA	Hotspots FAOSTAT EDGAR EPA			Hotspots FAOSTAT EDGAR EPA	
N_2O			Hotspots[13] FAOSTAT[14] EDGAR[15]		Hotspots FAOSTAT EDGAR EPA	Hotspots[16,17] FAOSTAT[16,18] EDGAR[16,17,19] EPA[16,19]	Hotspots FAOSTAT	Hotspots	
dSOC						Hotspots		Hotspots	

Table 3: Characteristics of the emission sources used in this comparative assessment disaggregated by greenhouse gases for the period 2000-2005, for the Hotspots, FAOSTAT, EDGAR, EPA, Houghton, and Baccini's datasets (based in gross emissions from Baccini et al. (2012). Superindices specify differences among datasets and/or indicate the exact data included in our database comparisons. EPA offers only non-CO_2 emissions for agriculture. Houghton offers only CO_2 FOLU emissions. Baccini's gross emissions include deforestation, fire and wood harvesting only. dSOC refers to changes in Soil Carbon stocks. Wood harvesting and fire are considered as forest degradation.

1147   [1] Gross deforestation.

1148   [2] Net deforestation. Forest fire emissions included in deforestation

1149   [3] Houghton net CO_2-only estimates are not deforestation emissions, but land use and land use change fluxes including deforestation, forest

1150   degradation, and cropland, abandoned land, and agricultural soil organic carbon (SOC).

1151   [4] Nationally reported fuel wood and industrial roundwood.

1152   [5] Nationally reported fuel wood, charcoal, fuel residues and industrial roundwood.

1153   [6] Long-term CO_2 emissions only (i.e savannas/agricultural fires excluded). Peat, forests and woodland fires are included (as defined by Van der

1154   Werf et al., 2010). Deforestation fires excluded

1155   [7] CO_2 from the combustion of organic soils. Forest fire emissions excluded.

1156   [8] CO_2 Forest fires + wetland/peatland fires and decay (5A, and 5D classes).

1157   [9] Humid forest deforestation fires, and peatland fires + decay.

1158   [10] CO_2 emissions from organic soils. Tier 1 approach. EF=20 $tC.ha^{-1}.yr^{-1}$ (IPCC 2006). Only for the six crop types reported by the agricultural

1159   soils (maize, soya, sorghum, wheat, barley, millet). N_2O emissions not included.

1160   [11] CO_2 emissions from organic soils. Tier 1 approach. EF=20 tC.ha^{-1}.yr^{-1} (IPCC 2006). N_2O emissions not included.

1161   [12] CO_2 for fuelwood is part of the energy balance.

1162   [13] CH4 and N2O emissions for peat, forests and woodland, savannahs and agriculture fires.

1163   [14] CH4, N2O emissions from fire in humid tropical forests and other forests, as well as CH4, N2O from the combustion of organic soils.

1164   [15] CH4, N2O for forest fires + wetland/peatland fires and decay (5A, and 5D classes).

1165   [16] Direct agricultural emissions only

1166   [17] Fertilizers, manure, crop residues

1167   [18] Synthetic fertilizers + Manure applied to soils + Crop residues + Manure applied to pastures.

1168   [19] Indirect emissions

1169

	Hotspots	FAOSTAT	EDGAR	Houghton*	Baccini	EPA	AR5*
Deforestation			▓		▓		
Fire		▓			▓		▓
Wood-harvesting			▓				
Livestock							
Cropland	▓					▓	
Paddy Rice							
Peatland	▓					▓	
Forest sinks				▓			▓

Table 4: Identification of the least reliable emission sources for each dataset considering disagreements among emission estimates due to biased/divergent/incomplete definitions and methods.