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Biofuel burning and human respiration bias on satellite estimates of fossil fuel CO_2 emissions

P Ciais[1,6], Y Wang[1,2], R Andrew[3], F M Bréon[1], F Chevallier[1], G Broquet[1], G J Nabuurs[4], G Peters[3], M McGrath[1], W Meng[5], B Zheng[1] and S Tao[5]

[1] Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ-UPSACLAY, Gif sur Yvette, France
[2] The Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, People's Republic of China
[3] CICERO Center for International Climate Research, Oslo, Norway
[4] Wageningen University and Research, Wageningen, The Netherlands
[5] Laboratory for Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing 100871, People's Republic of China
[6] Author to whom any correspondence should be addressed.

E-mail: philippe.ciais@lsce.ipsl.fr

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Abstract

The satellites that have been designed to support the monitoring of fossil fuel CO_2 emissions aim to systematically measure atmospheric CO_2 plumes generated by intense emissions from large cities, power plants and industrial sites. These data can be assimilated into atmospheric transport models in order to estimate the corresponding emissions. However, plumes emitted by cities and powerplants contain not only fossil fuel CO_2 but also significant amounts of CO_2 released by human respiration and by the burning of biofuels. We show that these amounts represent a significant proportion of the fossil fuel CO_2 emissions, up to 40% for instance in cities of Nordic countries, and will thus leave some ambiguity in the retrieval of fossil fuel CO_2 emissions from satellite concentration observations. Auxiliary information such as biofuel use statistics and radiocarbon measurement could help reduce the ambiguity and improve the framework of monitoring fossil fuel CO_2 emissions from space.

The Paris Agreement (PA) sets in place a framework through which all signatory countries will report every two years their greenhouse gas emissions, emissions and sinks in managed lands and progress towards achieving their Nationally Determined Contributions. In the national inventory reports, emissions are estimated by multiplying activity statistics by emission factors for different sectors and gases. The Modalities, Procedures and Guidelines for countries to report their emissions are defined by the Katowice Rulebook (UNFCCC 2019) and the IPCC Guidelines (IPCC 2006, 2019). During the inventory process, inventory compilers are required to verify their results against independent science-based estimations.

Among the different greenhouse gases emitted by human activities, CO_2 released by the burning of fossil fuels and the production of cement is the most important driving cause of increased radiative forcing and climate change. It is thus particularly important to dispose of accurate and frequently updated estimates of fossil CO_2 emissions, supported by independent estimations.

To address this need, space agencies, together with the research community, are developing global satellite capabilities to monitor fossil fuel CO_2 emissions using satellites (Crisp *et al* 2018). The main principle of emission monitoring from space is to measure the atmospheric CO_2 concentration signal produced by emission sources concentrated into *hotspots areas* such as cities and power plants. The sampling of those atmospheric CO_2 plumes is greatly improved by spaceborne imagers, like the OCO-3 instrument launched to the International Space Station on 4 May 2019, the future GEOCARB instrument onboard a geostationary satellite, and future constellations of Low Earth Orbiting satellites like CO_2M in Europe (Ciais *et al* 2015) and TANSAT-2 in China. Those satellites collect or are designed to collect kilometric-resolution images of CO_2 concentration averaged over the air column to characterize atmospheric CO_2 plumes under clear sky conditions when satellites fly over a hotspot area. Those images will have an individual measurement precision at pixel scale no better than 0.5 ppm, which implies a threshold for emission detection in practice (Wang *et al* 2019; see Methods). Images of plumes can be processed using atmospheric inversion systems to infer corresponding CO_2 emission fluxes. The CO_2 concentration image of a plume is related by these systems to the emissions that occurred during the few hours before the satellite overpass.

For supporting the PA Enhanced Transparency Framework, satellite-based monitoring of fossil CO_2 emissions should help both to establish emission baselines and to monitor emission trends over time with a very high accuracy. Nationally Determined Contributions translate into annual emission reduction rates that typically do not exceed a few percent per year. The most ambitious decarbonization scenarios consistent with low warming targets imply an annual decrease of global fossil CO_2 emissions on the order of 5%–7% per year. At city scale, many local governments have committed to voluntary efforts to reduce their emissions at a rate of few percent per year. In this context, satellite-based monitoring systems of fossil CO_2 emissions should reach an accuracy of few percent to evaluate the current emission baselines from inventories, and an accuracy better than ≈1%–2% per year for monitoring the emission trends to evaluate the effectiveness of mitigation efforts.

Meeting such high accuracy targets for monitoring fossil CO_2 emissions using satellite-based atmospheric inversions of total CO_2 emissions is very challenging for a number of technical reasons, and because plumes emitted by hotspot areas contain a mixture of CO_2 produced by fossil fuel burning, biofuel burning and human and livestock respiration. Those bio-emissions and their trends will need to be quantified with independent data and removed from the total CO_2 emissions seen by satellites to allow the monitoring of fossil fuel CO_2 emissions alone.

In order to illustrate this point, we calculated biofuel emissions collocated with fossil fuel emissions over hotspot areas that could be detected by satellites, using spatially explicit inventories of both types of emissions (see methods). The data in figure 1 show the average biofuel emissions and fossil fuel emissions of hotspot areas that will be detected by satellite imagers with an accuracy of 0.5 ppm, grouped into classes of increasing emissions defined as small cities, cities, and megacities for different regions of the world. The average share of biofuel and fossil fuel CO_2 emissions in powerplants in each region is also shown in that figure. In developed regions such as Europe (EU) and the US, biofuel emissions occur in biomass-based and co-fired power plants and in cities from the mix of biofuel used with oil in vehicles and from households that use wood for heating. In developing regions such as Africa, biomass is widely used for cooking and heating, resulting into a larger average share of biofuels relative to fossil fuels CO_2 emissions. In China (CN), the share of biofuels emitted in cities is smaller than in Europe (EU) and India (IN) (figure 1).

Figure 2 shows a map of the ratio of biofuel to fossil fuel CO_2 emissions for cities and powerplants in Europe. This ratio can be as large as 50% over Nordic cities that use more biomass for heating in winter, and is on the order of 10% in western and Southern European cities. The information brought by CO_2 retrievals from satellites does not separate biofuels from fossil fuels over those hotspot areas, implying that atmospheric inversions results will confound fossil fuel with biofuels emissions.

In the accounting framework of the PA, the reporting of biofuels and fossil fuels emissions must be strictly dissociated. On the one hand, fossil fuel carbon emissions cause a net increase of CO_2 concentrations and climate warming. Therefore, countries target reductions of their fossil fuel (and cement) emissions. On the other hand, the use of biofuels is considered to be CO_2 -and climate- neutral by the PA accounting rules under the assumption that CO_2 emissions from biofuel burning are balanced by CO_2 uptake from the vegetation. Further, for biofuel biomass grown in a country, the emission is already reported under harvested products under the LULUCF sector by this country, and the uptake of CO2 by former growth of biomass is included in the change of forest carbon stocks. In the real world, biofuels may not be carbon neutral because their production requires energy and because the net carbon balance of growing biomass in the land use sector, processing it and using it in the energy sector is not zero in some cases (Fargione *et al* 2008). Although in cases of sustainable forest management, it was shown to be close to zero (Nabuurs *et al* 2017), supporting the assumption of the PA accounting.

We also calculated the emissions of CO_2 respired by humans which are collocated with fossil fuel emissions in hot-spot areas by using spatially explicit inventories of fossil fuel emissions, and data on crop harvest and consumption in populated areas from Wolf *et al* 2015 (see Methods). The data in figure 1 show that over the cities that produce plumes of CO_2 detectable from space, human respiration represents a source to the atmosphere of 0.32 Gt CO_2 per year, compared to 10 Gt CO_2 per year of fossil fuel CO_2 emissions. Livestock fed with crop products also emit CO_2 to the atmosphere, but those emissions are more diffuse and a small fraction occurs in the vicinity of hotspot areas detectable from space (0.18 Gt CO_2 per year). Like for biofuels, human and livestock CO_2 respiration is globally neutral for climate change because it is matched by crop plant CO_2 uptake.

Overall, at global scale, the sum of respiration and biofuels emissions shown in figure 3(a) amounts to about 8.1 $GtCO_2$ per year, which is 22% of fossil fuel emissions from coal, gas, and oil use in the period 2005–2010. In China, the sum of respiration and biofuel CO_2 emissions was even larger than emissions from oil burning for the period 2005–2010 (figure 3(b)). In India, biofuel

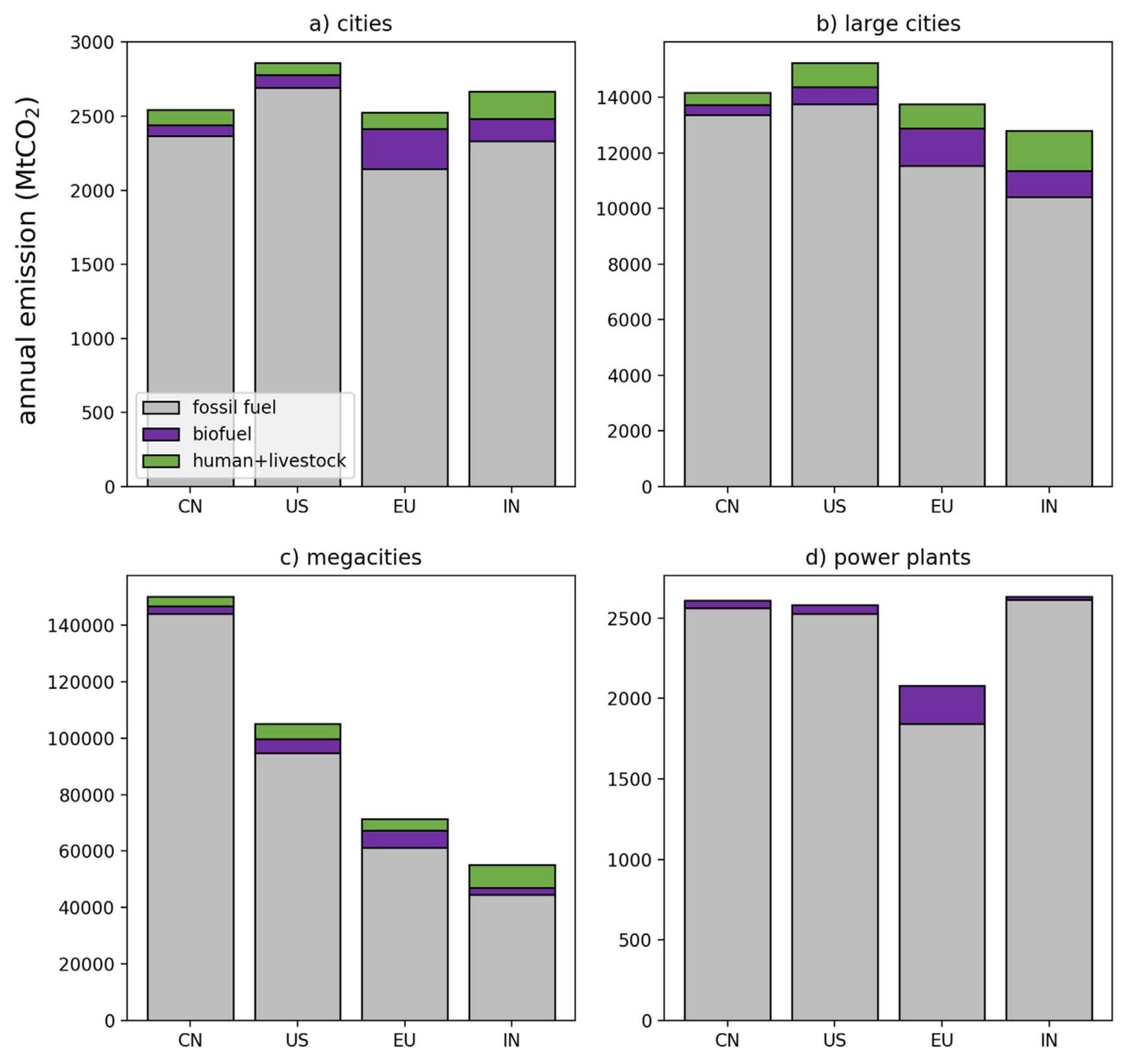

Figure 1. Emissions of CO_2 from urban areas hotspots that form plumes of atmospheric CO_2 observable by satellites, with separate contributions from fossil fuels burning (gray), biofuel burning (green) and human plus livestock respiration (yellow). 'Cities' denote all urban hotspots emitting less than 5 $MtCO_2$ per year, 'large cities' all hotspots emitting between 5 and 50 $MtCO_2$ per year, and 'megacities' emitting more than 50 $MtCO_2$ per year. Different regions for which all observable hotspots emissions are aggregated are China (CN), USA, European Union (EU28) and India (IN). The totals from all megacities within a region is shown, not the average for each megacity. Power plants emissions are from those powerplants emitting more than 1 $MtCO_2$ per year, some being fueled by fossil fuels and others by biofuels.

emissions were larger than all emissions from fossil fuels until 1991, and from 2005 to 2010, the sum of respiration and biofuel CO_2 emissions was equivalent in magnitude to 60% fossil fuel emissions. In the European Union, biofuel emissions have increased from 4% of fossil fuel emissions in 1990 to 17% in 2016. In the USA, this fraction remained stable in the range of 5%–7% since 1990.

The superposition of CO_2 emitted from biofuel burning, human and livestock respiration with CO_2 from fossil fuel burning in the plumes from hotspot areas also confound the monitoring of fossil fuel emission trends from space. Estimates of trends of fossil fuel, biofuel and respiration emissions can be compared in figure 3. In the European Union (EU28) for instance, biofuel CO_2 emissions increased by 18.6 $MtCO_2$ per year between 2005 and 2016 while fossil CO_2 emissions decreased by 66.3 $MtCO_2$ per year (figure 3(b)). Supposing comprehensive and perfectly accurate satellite monitoring, spaceborne data would diagnose during that period a decreasing trend of emissions of -47.8 $MtCO_2$ which is only 72% of the decreasing trend of fossil fuel emissions.

Last, ecosystem biogenic sources and sinks from peri-urban ecosystems and urban green area also have a significant confounding effect on CO_2 plumes generated from cities and power plants. However, this effect is highly variable among different cities and has not been systematically assessed for all cities over the globe. Few studies have shown that for the Paris area in summer, biogenic uptake offsets 20% of fossil CO_2 emissions (Lian *et al* 2019), that in the Los Angeles area, green areas also affect significantly CO_2 gradients measured between upwind and downwind locations ($\leqslant$20%, Newman *et al* 2013, 2016), and that in Boston,

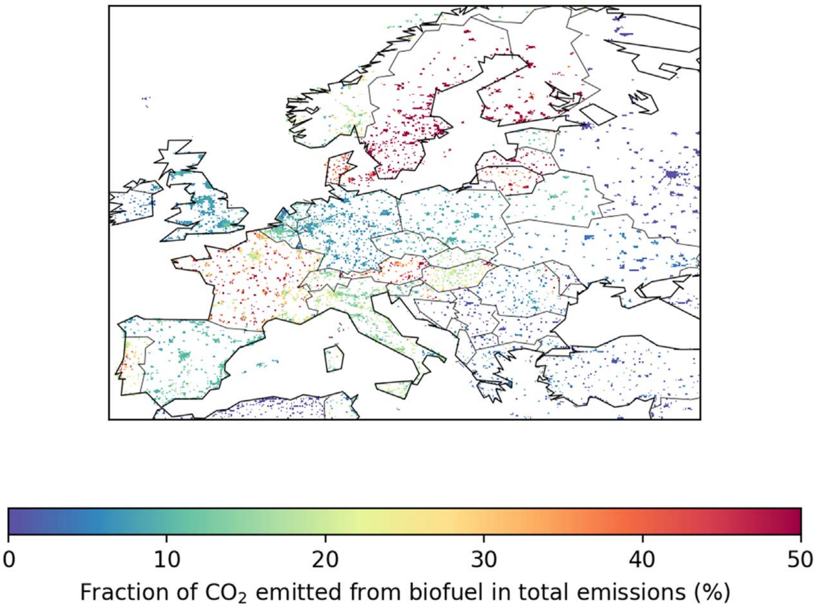

Figure 2. Fraction of CO_2 emitted by biofuels combustion in hotspot areas (cities and powerplants whose emissions can be detected by satellites—see methods) to total biofuel plus fossil fuel CO_2 emissions.

the urban biosphere took up 20% (late October) to 100% (July) of the daytime CO_2 enhancement generated by fossil fuel emissions (Sargent *et al* 2018).

Methods

In figure 1, we derived the emissions created by so called *hotspot areas* that have CO_2 emissions above a minimum emission threshold to generate total-column CO_2 plumes detectable by satellite imagers. The minimum emission detection threshold was calculated to be 1.32 gCO_2 per m^2 per hour. Such an emission threshold generates a 0.5 ppm excess of atmospheric XCO_2 during the 6 h before a satellite overpass without wind (Wang *et al* 2019). The 0.5 ppm excess correspond to the best XCO_2 accuracy of current space-borne instruments for satellite imagers described in Ciais *et al* 2015.

Hotspot areas were determined as follows. First, we used two global gridded maps at 10 km spatial resolution of fossil fuel CO_2 emissions and of biofuel CO_2 emissions, respectively. These maps are from the spatialized inventory developed by the Department of Environmental Science of Peking University (PKU) and accessible at http://inventory.pku.edu.cn and known as PKU-CO_2, described in Wang *et al* 2013. For each country, the biofuel CO_2 emissions from PKU-CO_2 is multiplied by a scaling factor such that the national total matches the IEA's Extended Energy Balances (IEA 2018). Second, we used a global gridded map of CO_2 bio-emissions from livestock and human respiration from Wolf *et al* (2015). Fossil fuels and biofuels combustion *hotspot areas* correspond to cities and power plants with emissions above a satellite detection threshold. Gridded livestock and human emissions *hotspot areas* correspond to cities for humans and to regions with high animal densities for livestock with emissions above a satellite detection threshold.

We then combined those maps of fossil fuel, biofuel and human/livestock bio-emissions with a map of urban extent from the Global Rural-Urban Mapping Project (GRUMPv1, revision 01) (Balk *et al* 2006, CIESIN 2017). Firstly, small urban areas, which are defined in GRUMPv1 as 'urban extent' but with no settlement identified within or less than 3 m from the urban extent are removed in GRUMPv1. Then each urban area was checked whether it contains in the gridded CO_2 emission maps described above at least one grid box where the total CO_2 emission rate from fossil fuels, biofuels and respiration is higher than the threshold of 1.32 $gCO_2/m^2/hr$. Only the urban areas with at least one such grid box are retained. Details of this method to group emitting grid cells from a global emission map into a set of *hotspot areas* are given in Wang *et al* 2019.

This leads us to define for different regions of the globe four different categories of *hotspot areas*: 'cities' emitting less than 5 $MtCO_2$ per year, 'large cities' emitting between 5 and 50 $MtCO_2$ per year, and 'mega-cities' emitting more than 50 $MtCO_2$ per year, and 'power plants' those power plants emitting more than 1 $MtCO_2$ per year, some being fueled by fossil fuels and others by biofuels. The totals from all hotspot areas in each category within a region is shown, not the average for hotspot area.

Emissions from bioenergy in Extended Data (figure 3) for each region are calculated from IEA's Extended Energy Balances (IEA 2018) using the

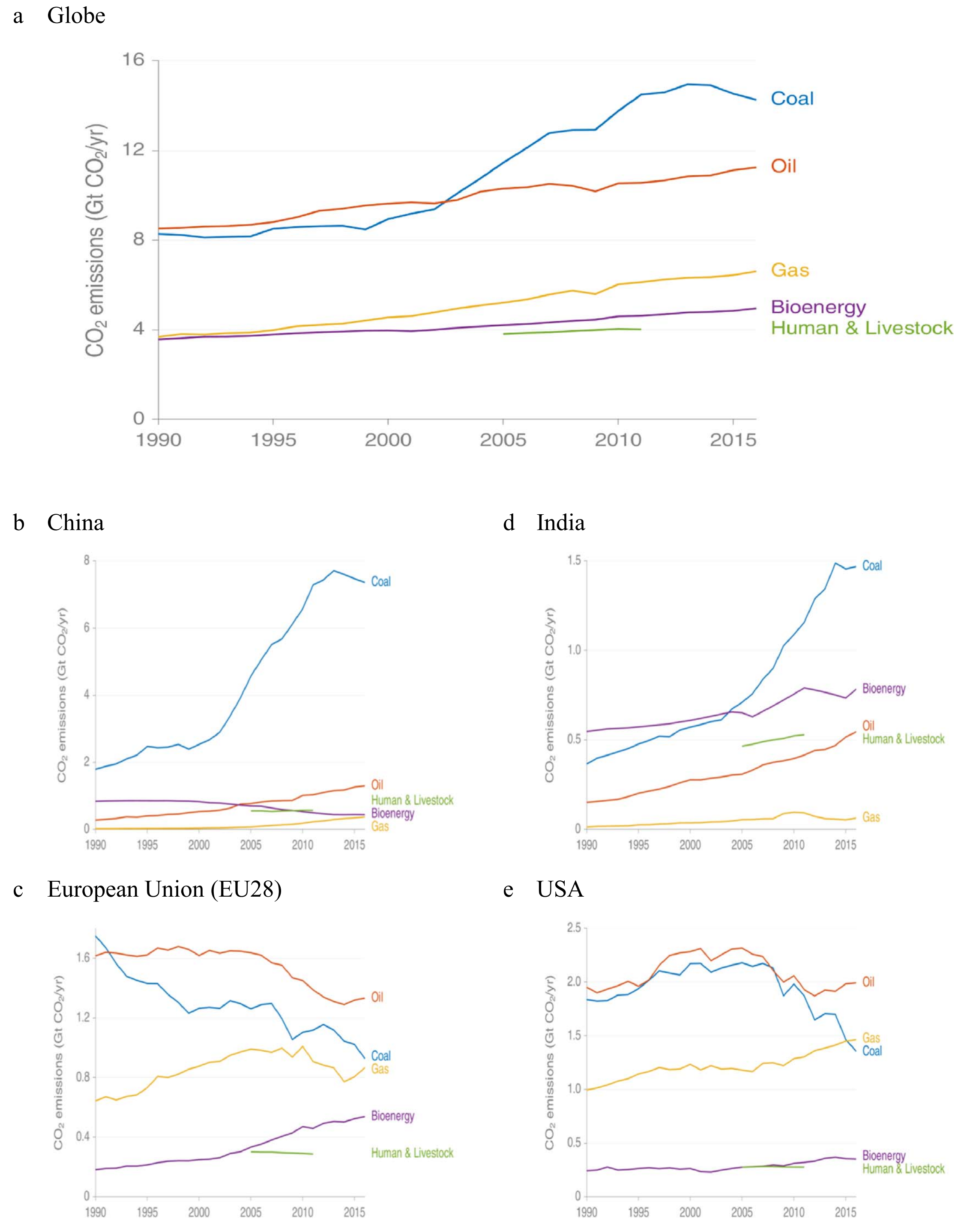

Figure 3. Trends in emissions from fossil fuel (for different fuel types), biofuels burning for energy and bio-emissions from respiration of humans and livestock. (a) World, (b) China, (c) European Union (EU28), (d) India, and (e) USA.

default emissions factors from the revised IPCC guidelines for National Greenhouse Gas inventories (IPCC 2006).

In summary, satellites passing over cities and powerplants will measure plumes of CO_2 dominated by fossil fuel emissions but containing a significant fraction of CO_2 from bio-emissions related to respiration and biofuels (figure 2), not speaking of the confounding effect from ecosystem sources and sinks within and around urban areas. It is a laudable attempt to harness space observations of atmospheric CO_2 to support the goals of the PA on climate change, but the presence of CO_2 release from biofuel combustion, respiration and CO_2 seasonal fluxes from urban ecosystem exchange within the CO_2 plumes may leave a strong ambiguity in the attribution to fossil fuel CO_2 emissions.

To help separate the fossil, biogenic, and human fluxes, we recommend that for power plants, precise information on the use of biofuel in each power plant should be collected. Information on trade flows of biomass should also make it possible to close the net carbon balance of the loop of the carbon cycle where crop and forest growth cause CO_2 sinks which are balanced by the harvest of biomass and subsequent biofuel burning and respiration CO_2 emissions. For cities, additional ground-based measurement networks of tracers that can isolate the contribution of fossil carbon from bio-emissions, like radiocarbon, could be integrated with the satellite-based observations of CO_2 plumes to allow a proper separation of bio-emissions from fossil fuel emissions, at least for some test cities. The need for such additional data to separate fossil fuels from bio-emissions suggests that satellite CO_2 retrievals cannot be a panacea for the Enhanced Transparency Framework of the Paris Agreement, but satellite CO_2 imagery still represents an important asset to stimulate the development of improved national inventories of anthropogenic CO_2 emissions.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID iDs

P Ciais https://orcid.org/0000-0001-8560-4943
Y Wang https://orcid.org/0000-0001-7176-2692
F Chevallier https://orcid.org/0000-0002-4327-3813
G J Nabuurs https://orcid.org/0000-0002-9761-074X
B Zheng https://orcid.org/0000-0001-8344-3445

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