nature portfolio

Peer Review File

The global carbon sink potential of terrestrial vegetation can be increased substantially by optimal land management

12th Jul 21

Dear Professor Xie,

Your manuscript titled "Assessing global terrestrial carbon sink potential from vegetation with optimal land management" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms (that is, either to incorporate the suggestions or provide a compelling argument why the point made by the reviewer is not valid) and in particular the methodological concerns addressed by REV#1, and meet our editorial thresholds as outlined below, hen we would be happy to look at a substantially revised manuscript.
In the following, we list our main editorial concerns.
*Editorial threshold 1:clarify the modeling assumptions and in particular on Eq (3) measuring a corrected version of the net primary productivity
**Editorial threshold 2:explain and define the role that Wetlands can play in your analysis

However, please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees’ comments (which should be in a separate document to any cover letter) and any completed checklist:

[link redacted]

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

Please do not hesitate to contact me if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

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Communications Earth & Environment
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EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

Editorial Policy Policy requirements

For your information, you can find some guidance regarding format requirements summarized on the following checklist:(https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Increasing terrestrial carbon sink by adopting OLMPs is a strategy proposed by many previous studies to offset anthropogenic carbon emissions. Because of the difficulty in collecting global-scale land management data, these studies are all regional scale. Instead, Sha et al. propose a method that relies on remote sensing and geographical data to assess global-scale terrestrial carbon sink potential from vegetation with OLMPs. In my view, if the method is validated, this can become a masterpiece in the scientific literature. However, my foremost concern is also the validity of the method.

The authors suggested that by subtracting RC from NPP (Eq. 3), they can obtain a new variable NPP_CR whose internal variation across all the location in the LVS zone can be fully attributed to human factors. Or in other words, NPP_CR should be constant within each LVS zone if there is no differed human impact. From what has been presented, I am not sure whether this statement is true, even though it should be very easy to verify. For example, the authors can examine whether the correlation between NPP_CR and climate drivers (such as temperature and precipitation) is close to zero.

The key result of this study (Figure 1) may further support my suspicion. Figure 1 shows that in most of cases, regions with high carbon gap density are those with high elevation gradient (such as Andes and Himalayas). Studies have shown that large biodiversity exists in these regions due to the variation of climate with altitude. The meteorological and soil data used by the authors are very likely not able to resolve this spatial variability. As a result, the large internal variation of NPP_CR in these regions is incorrectly attribute to human impact. But in reality, it is not.

The only evidence the authors provided to prove that the calculated carbon cap is caused by LMPs is the strong positive correlation between carbon gap and population density. But in my view, this strong positive correlation can also have other explanations irrelevant to OLMPs in Table S1. For example, high population density can increase the spatial heterogeneity of land surface, which eventually increases the internal variation of NPP_CR. Here, I have an example. Region A uses a single crop system that needs fewer people to care about and has lower internal variation of NPP_CR. Region B of the same area has different crops that needs more people to care about and has higher internal variation of NPP_CR. As illustrated, the lower carbon gap in A is not the result of OLMPs rather the result of the spatial homogeneity. To validate the method, I suggest the authors to do more detailed comparison using their method between regions where the data of LMPs exist.

Specific comments
1. References cited in the supplementary are missing.
2. There are many grammar errors in the manuscript. It may be helpful to ask native speakers to proofread it.

3. L344: Is “sasses” a typo?

Reviewer #2 (Remarks to the Author):

I would like to congratulate the authors for choosing a topic of high importance in the current climate context because: 1) shows that it is possible to reconcile adequate land use practices with climate goals without 2) expanding production areas (which would also affect biodiversity and sustainable development goals) or compromising food production. The text is clear, the established methods are well detailed (with good assumptions and justifications for the choice of parameters) and allow others to reproduce the study. However, I understand that there are some structural inconsistencies in results item (for example, between lines 99 and 118) and the authors should provide a deppen discussion (such as the implications of the results for the fulfillment of the Nationally Determined Contributions of the Paris Agreement - more details in the attached document). For these reasons, I suggest the authors to revise the manuscript to address specific concerns before a final decision is reached.

Reviewer #3 (Remarks to the Author):

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Assessing global terrestrial carbon sink potential from vegetation with optimal land management

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Assessing global terrestrial carbon sink potential from vegetation with optimal land management

Abstract: Excessive emissions of greenhouse gases (GHGs) — of which carbon dioxide (CO_2) is the most significant component, are regarded as the primary reason for increased atmospheric CO_2 concentration and global warming. Terrestrial vegetation sequesters 112–169 PgC each year, which plays a vital role in global carbon recycling. Vegetation carbon sequestration varies under different environmental conditions and land management practices (LMPs). Compared to traditional LMPs, optimal LMPs (OLMPs) help vegetation sequester additional CO2, termed as a carbon gap. Here we propose an integrated method to assess the carbon gap and identify the location-specific OLMPs by combining remotely sensed time-series of net primary productivity (NPP) dataset, segmented landscape-vegetation-soil (LVS) zones, and distance-constrained zonal analysis. The carbon gap from global land vegetation totals 13.74 PgC per year with OLMPs and half of the carbon gap clusters in ~15% of vegetated area. The study suggests implementing OLMPs is a promising way to mitigate climate changes.

Introduction

Keeping the global temperature increase below 1.5 °C in accord with the Paris Agreement would require prompt and substantial reductions in greenhouse gases (GHGs) emissions on the global scale[1]. Despite considerable effort internationally, many countries are likely to miss the emission control targets proposed in the Paris Agreement, and the world is on track for more than 3°C of warming by the end of the century[2,3]. To cut down GHGs emissions, numerous policies have long been proposed, including resorting to renewable energy, popularizing electric vehicles, optimizing land-use policies, as well as other GHGs cutting policies or programs[1,4]. Unfortunately, those policy options seem not being effectively deployed, given the continuous increase of the emissions of GHGs[5,6]. The atmospheric CO_2 has risen beyond 400 ppm in recent years, which is attributed to carbon emissions from fossil fuel combustion and explains the 1.5°C increase in air temperature since the 1880s[7,8].

Though cutting fossil fuel consumption provides a direct option to reduce carbon emissions, it shows limited effect in mitigating atmospheric CO_2 because the economy in many countries is still powered by fossil energy[4,9]. Vegetation dominates most terrestrial ecosystems (e.g., forests, grasslands, croplands, shrublands, and savannas) and absorbs 112–169 PgC each year from the atmosphere through a biochemical process called photosynthesis[8,10]. Improving vegetation carbon sequestration provides an alternative measure to counteract the excessive carbon emissions[10,11]. The net amount of carbon captured by plants through photosynthesis over a given period is called net primary production (NPP)[12,13]. NPP is positively correlated to carbon sink which is equivalent to NPP minus the component of soil heterotrophic respiration[14]; thus, NPP serves a good proxy for evaluating carbon sink. As a key component of energy and mass transformation in terrestrial ecosystems, NPP depends on a variety of factors, such as the supply of nutrients, water availability, soil profile characteristics, and landscape attributes (e.g., terrain and drainage)[15,16]. Those factors can be broadly categorized as the following three groups[17]: 1) climate impact (e.g., precipitation and temperature); 2) non-climatic natural factors such as soil property, landforms and biomes; and 3) human-related (HUMAN) land management practices.

First, vegetation will not attain the saturation of carbon sequestration capacity without appropriate climatic conditions[11]. Lack of rainfall caused physiological stress and limit vegetation photosynthesis in most arid regions[15]. The dependence of vegetation carbon sequestration on climatic factors is reflected by most NPP models[12]. For example, the climate-driven Miami model, which has been widely applied to map large-scale NPP[11,18,19], highlights the climatic factors' importance as vital drivers to carbon sequestration. Second, vegetation cannot maximize carbon sequestration without favorable natural conditions such as landforms[16], soil properties[20], and biome groups[11]. Lastly, carbon sequestration can be updated by land management practices (LMPs)[10], i.e., one LMP may result in higher or lower carbon sequestration than the other, under the same environmental contexts (the climatic and non-climatic conditions).

Previous studies confirm that land use and management strategies have massive effect on carbon sequestration from vegetation[19,21,22]. An optimal land management practice (OLMP) refers to an LMP that helps sequester higher, if not the highest, potential carbon from the managed vegetation given the current climatic, non-climatic and HUMAN conditions. Once LMPs are replaced with OLMPs, the vegetation will sequester more carbon. It is valuable to model the difference in carbon sequestration between with- and without- OLMPs, called carbon gap hereafter, for making smart land management policies and mitigating global climate changes. In a broad sense, OLMPs include the removal of negative human-related disturbances in naturally vegetated areas[21], and the application of human-intervened programs/practices that prove to be useful for improving vegetation productivity or restoring previously degraded vegetation[23,24]. The United Nations Convention to Combat Desertification (UNCCD) program introduces over 1,000 Sustainable Land Management (SLMs) practices based on the type of activities targeting to promote agricultural production while simultaneously supporting the environmental functions[25]. OLMPs include but are not limited to the SLMs, considering that all existing LMPs could be potentially selected as OLMPs if they help enhance vegetation productivity. For example, appropriate tillage practices on cropland may increase agricultural production (which in most cases also improves NPP); similarly, protection measures for trees close to road networks are necessary to improve forestry NPP[26]. Some cases of OLMPs are illustrated in *SI* Table S1. The effect of OLMPs on vegetation productivity pertains to local environmental and socio-economical contexts. The carbon gap of specific OLMPs can be evaluated by comparing NPP of field experiments with and without the OLMPs implemented. Considering manifest spatial variations of the natural and socio-economic contexts across the globe, there exist no universally applicable OLMPs. There is also a need for mapping carbon gaps through a globally and locally compatible approach so that both global comparison and local policy enactment are supported[27]. Herein, this work addresses the following questions: how much more carbon (i.e., carbon gap) could be further sequestered from global terrestrial vegetation with OLMPs implemented? How can the location-dependent OLMPs be decided from the local contexts at each location? Where do the most sensitive areas showing carbon sequestration improvement locate?

Results

Global carbon gap modeling and mapping

~~Remote sensing technique facilitates large-scale NPP mapping[18]. The Moderate Resolution Imaging Spectroradiometer (MODIS) enables high-temporal and long-term Earth observations; the MODIS MOD17A3 NPP is one of the most highly used products for quantifying vegetation carbon sequestration[28,29]. The carbon gap is assessed by combining time-series MOD17A3 NPP dataset, partitioned landscape-vegetation-soil (LVS) zones and distance-constrained zonal analysis. To derive NPP for global and regional comparisons, homogeneous zones are first partitioned from landform (L),~~

vegetation (V), and soil (S) perspectives so that any LVS zone presents no internal NPP variation from the LVS factors (see Methods). To differentiate the impacts of land management practices (or LMPs) on vegetation carbon sequestration and to quantify the carbon gap, a distance-constrained (DC) zonal analysis is devised to compute climate-rectified NPP (NPP_{CR}) and to derive the 90^{th} percentile statistic (NPP_{CR}^{90th}) from the NPP_{CR} inputs within a distance-constrained circular window with a radius ~20km (*SI Fig. S1*; see Methods). Lastly, the carbon gap and the OLMPs are decided for each location:

- if the NPP_{CR} at a location *i* is less than the NPP_{CR}^{90th}, the carbon gap at *i* will be equivalent to NPP_{CR}^{90th} minus NPP_{CR}^{i}; otherwise, the land management practice (LMP) at the location has already made the carbon sequestration level high enough and no extra carbon sequestration is available (i.e. carbon gap=0, if $NPP_{CR}^{i} \geq NPP_{CR}^{90th}$). Here the NPP_{CR}^{90th} is taken as a target carbon sequestration level for the current location.
- the candidate of OLMPs for a location are decided by referring to the LMPs at locations, within the distance-constrained local window, that boast identical environmental contexts but exhibit a higher level of carbon sequestration (i.e., where $NPP_{CR} \geq NPP_{CR}^{90th}$).

The temporally averaged total carbon gap (during 2001–2018) for vegetated land area is estimated to be 13.74 PgC yr^{-1}, with a spatially averaged carbon gap flux density of 124.3 gC m^{-2} yr^{-1} (*SI Table S2*). Considering that the terrestrial NPP totaled 67.90 PgC yr^{-1}, ~1/5 more carbon can be added to the existing vegetation carbon sequestration if OLMPs are implemented. With consideration of soil heterotrophic respiration (R_H) and the ratio of R_H to NPP about 0.71~0.74 (see Methods), the total carbon gap or an increase of NPP 13.74 PgC yr^{-1} could compensate more than 1/3 of the global fossil fuel emissions, which was reported to be 10.1 ± 0.6 PgC in 2019[4].

The terrestrial carbon gap flux showed significant spatial variations (Fig. 1). Locations with higher carbon gap density indicate that their current LMPs are highly recommended to be replaced with the

OLMPs identified from the neighborhood, aiming to improve NPP and thus narrow down the carbon gap. OLMPs could take different forms depending on the local environmental and social conditions (with typical examples illustrated in *SI Table S1*). ~~For instance, in the farm-dominated regions, LMPs such as cropping rotation, farm irrigation, or compost amendments were effective in improving agriculture productivity[10]. A previous study showed that multiple cropping, fertilizer application, and irrigation in China and India's agricultural lands had contributed significantly to the "greening Earth"[30]~~. The above mentioned LMPs, if proved to effective in improving vegetation productivity historically, can promote vegetation carbon sequestration once transferred/copied to neighboring locations with identical local conditions and lower NPP_{CR}. Conversely, in grassland ecosystems where degraded vegetation showed decreased productivity due to over-grazing[31], a destocking rate, or rotational grazing in a neighborhood could increase vegetation productivity[10,32]; thus the practices of destocking and rotational grazing can be taken as OLMPs.

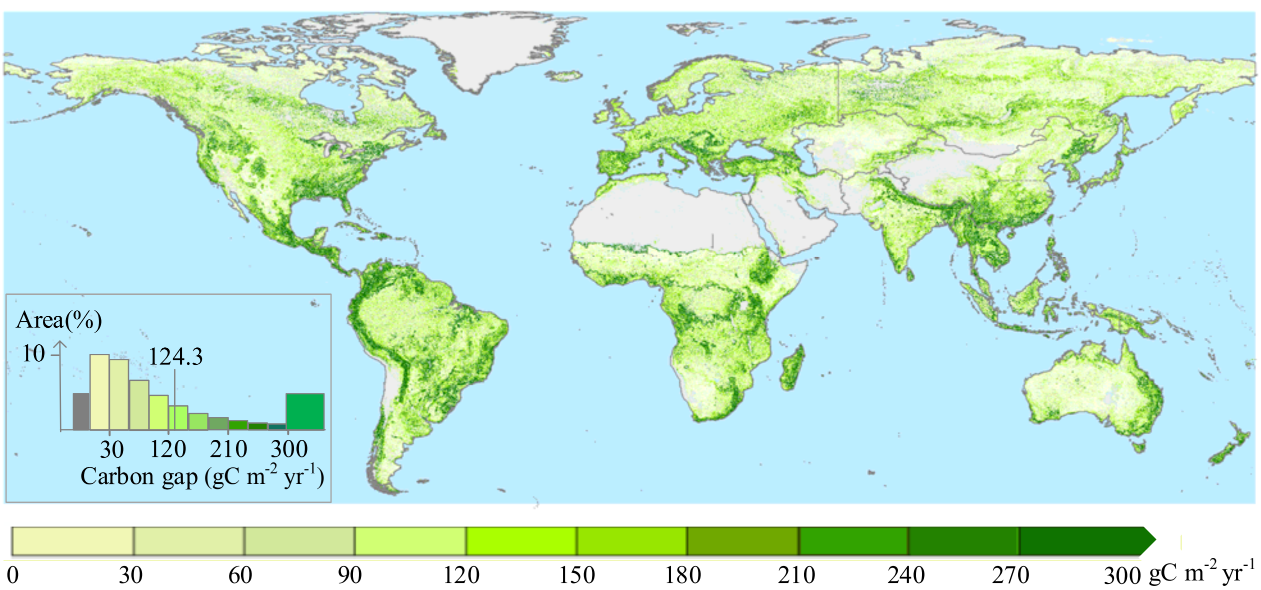
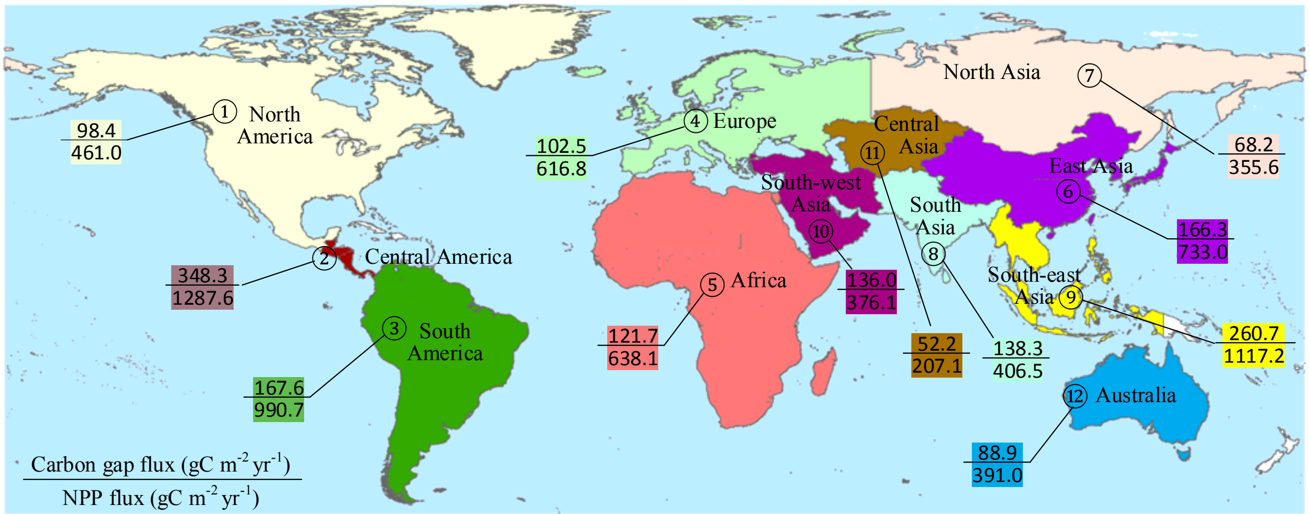


Fig. 1 | Distribution of global carbon gap density (flux). The density is expressed through pixel values at 500 m × 500 m spatial resolution. The inset figure shows the histogram of area percentage in each of the bins of the carbon gap density, where the most left grey bar indicates the area (=4.8% out of all vegetated area which is 110.5 × 10^6 km^2) having carbon gap=0 (where $NPP_{CR} \geq NPP_{CR}^{90th}$, indicating LMPs already being OLMPs) and the most right green bar, which also happens to cluster in also 4.8% of the total vegetated area, represents the portion having the most highest carbon gap density (>300 gC m^{-2} yr^{-1}); the vertical line in the inset histogram shows the location of the averaged carbon gap density (i.e., 124.3 gC m^{-2} yr^{-1}) for the whole area of the 12 continents/regions (North America, Central America, South America, Europe, Africa, Australia, East Asia, North Asia, South Asia, South-east Asia, South-west Asia, and Central Asia). Totally more 13.74 PgC yr^{-1} is expected to be sequestered from vegetation if OLMPs are implemented at the global scale.

The carbon gap differs among continents and biomes

Considerable differences in the flux density and in the totals of the carbon gap and NPP were observed among the 12 continents/regions (Fig. 2 vs. *SI Fig. S2*). Central America and South-east Asia present the highest carbon gap flux, reaching 348.3 and 260.7 gC m^{-2} yr^{-1}, respectively; they can capture an extra portion of 0.17 and 1.11 PgC every year, respectively. Africa and North America have the largest vegetated area and they can capture extra 2.37 and 1.86 PgC yr^{-1}, respectively. South America ranks the third-largest in the vegetated area (16.58 million km^2); because of its relatively high carbon gap flux (167.6 gC m^{-2} yr^{-1}), the carbon gap totals 2.78 PgC yr^{-1}, leading all the continents/regions. The total carbon gap is strongly correlated to the total NPP at the continental/regional level (r=0.98). However, the carbon gap flux (density) is found to be inconsistent with the NPP density at the pixel-scale and within each continent/region. At the pixel level, the carbon gap flux and NPP flux are compared by the ratio, i.e., the carbon gap flux divided by the NPP flux at pixel basis, which clearly shows the high spatial variations (*SI Fig. S3*). Furthermore, within each continent/region, the carbon gap density (Fig. 1) and NPP density (*SI Fig. S2*) do not correlate well either, which is confirmed by the scatter plots between the carbon gap density vs. NPP density (*SI Fig. S4*) and notably illustrated by two typical rainforests, i.e., the Amazon rainforest located within South America and the African rainforests (*SI Fig. S5*). Both the rainforests show highly dense NPP flux (1,273.3 and 1,062.7 gC m^{-2} yr^{-1} for Amazon and African rainforests, respectively) which nearly doubles the globally averaged NPP flux (which is 614.2

gC m^{-2} yr^{-1}); however, their carbon gap flux averages 117.5 and 121.1 gC m^{-2} yr^{-1} respectively, at a comparable level to that of the continentally averaged level, i.e., 124.3 gC m^{-2} yr^{-1}.



Continent#	1	2	3	4	5	6	7	8	9	10	11	12	Total
Veg. area (10^6×km^2)	18.89	0.50	16.58	9.24	19.51	11.66	13.28	4.03	4.26	1.93	3.18	7.49	110.54
Carbon gap (PgC yr^{-1})	1.86	0.17	2.78	0.95	2.37	1.94	0.91	0.56	1.11	0.26	0.17	0.67	13.74
± std.	0.17	0.01	0.21	0.05	0.13	0.10	0.06	0.02	0.07	0.02	0.01	0.05	/
NPP (PgC yr^{-1})	8.71	0.64	16.43	5.70	12.45	8.54	4.72	1.64	4.76	0.73	0.66	2.93	67.90
± std.	0.82	0.04	1.31	0.39	0.83	0.42	0.29	0.09	0.25	0.06	0.09	0.33	/

Fig. 2 | Carbon gap and NPP statistics aggregated at continent (region) level, with continent# labeled. The numerator and denominator of each fraction for the continents/regions show carbon gap flux/density (gC m^{-2} yr^{-1}) and NPP flux (gC m^{-2} yr^{-1}), respectively. In the table, the summed carbon gap and summed NPP are both presented with averaged value ± standard deviation (std.) for each continent (region) over the years during 2001–2018 (n=19). The summed carbon gap and summed NPP for each continent/region are significantly correlated (at the continental/regional scale, Pearson correlation coefficient *r*=0.98).

The carbon gap varies among different biomes (see definition in *SI Table S3* and *SI* Fig. S6). Forests show NPP flux of 1,106.2 gC m^{-2} yr^{-1}, much higher than the other biomes (Fig. 3 and *SI Fig. S7*). ~~Transforming land cover from one type to another, e.g., afforestation from croplands, may help to sequester more carbon[23]. However, while afforestation has been suggested for degraded croplands[23,24], concerns arise from decreased food supply due to a reduction in croplands as a result from afforestatio~~ ~~Hence, improving carbon sequestration through land conversions are not widely acceptable. Instead, the~~

~~carbon gap could be achieved by tailoring land management practices (i.e., by adopting OLMPs) without changing land use or land cover types, which has ecological and social benefits considering that implementing OLMPs improves NPP while keeping cropland areas stable.~~

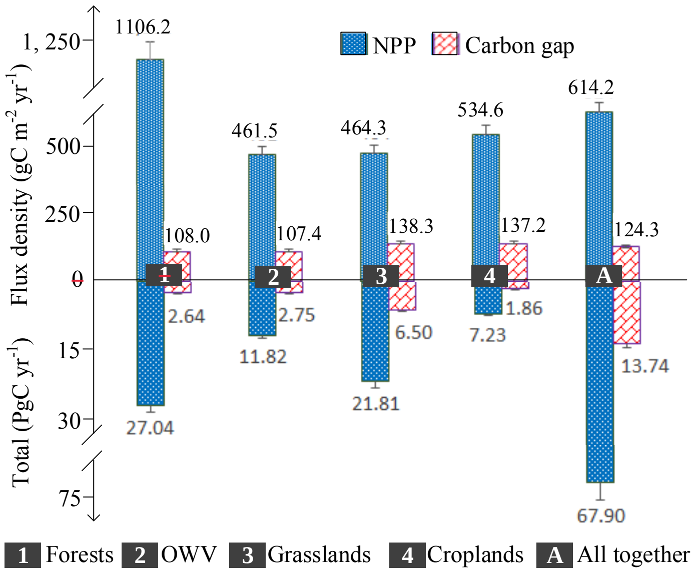


Fig. 3 | Comparison of the carbon gap and NPP across biomes. The statistics summarize the carbon gap and NPP (total and flux) of the global vegetated area (see more on the definition of the vegetated area in *SI Table S3*).

Grasslands and croplands lead the carbon gap density, reaching 138.3 and 137.2 gC m^{-2} yr^{-1}, respectively (Fig. 3). Forests show rather limited potential in the carbon gap, only 107.99 gC m^{-2} yr^{-1} in the flux and 2.64 PgC yr^{-1} in the total, though the NPP flux of is almost double of the averaged (1,106.2 gC m^{-2} yr^{-1} vs. 614.2 gC m^{-2} yr^{-1}) and the total NPP of forests is more than 1/3 out of all together (i.e., 27.04 PgC yr^{-1} vs. 67.9 PgC yr^{-1}). The other woody vegetation (OWV), though presenting much lower NPP flux and total NPP, shows a carbon gap flux and total carbon gap comparable to those of forests, which are 107.4 gC m^{-2} yr^{-1} and 2.75 PgC yr^{-1}, respectively. Because grasslands cover the largest area (46.97 million km^2, *SI Table S4*) and present the highest carbon gap flux, i.e., 138.3 gC m^{-2} yr^{-1}, the total carbon gap accounts for nearly half of the all summed total, reaching 6.5 PgC yr^{-1}. Croplands can sink atmospheric CO_2 with the adoption of improved context-specific land management[33]. Croplands show relatively high carbon gap flux, 137.2 gC m^{-2} yr^{-1}. However, croplands cover the least land area (13.52 million km^2), making the total carbon gap the lowest, i.e., 1.86 PgC yr^{-1} only.

~~The higher carbon gap fluxes in grasslands and croplands indicate that they have a quicker or more sensitive response to human activities (i.e., updated LMPs), compared to the forests and OWV. For grasslands and croplands, the improvement (or degradation) of vegetation productivity may take a shorter period to appear (e.g., within a calendar year) once LMPs are updated. Conversely, apart from abrupt intervention from human activities such as massive reforestation or deforestation[10], forests and OWV vegetation may take a relatively longer time to show up the effect from updated LMPs. Thus, grasslands and croplands have the advantage of showing immediate benefit, i.e., increased carbon sequestration, from implementation of OLMPs; on the other hand, it requires a long-term plan to improve carbon sequestration for forest and OWV ecosystems.~~

The carbon gap flux presents a strong clustering pattern, which is reflected by the comparison between the accumulative carbon gap and the accumulative sliced vegetated area using the carbon gap flux from low to high (Fig. 4 and *SI Fig. S8*). On average, ~50% of the total carbon gap comes from only ~15% of the global vegetated area. The finding implies that, in terms of OLMP implementation, only a small part of the prioritized vegetated area, i.e., ~15% of total vegetated coverage, would add more 6.87 PgC yr^{-1} (i.e., 50% of the total carbon gap) in vegetation productivity.

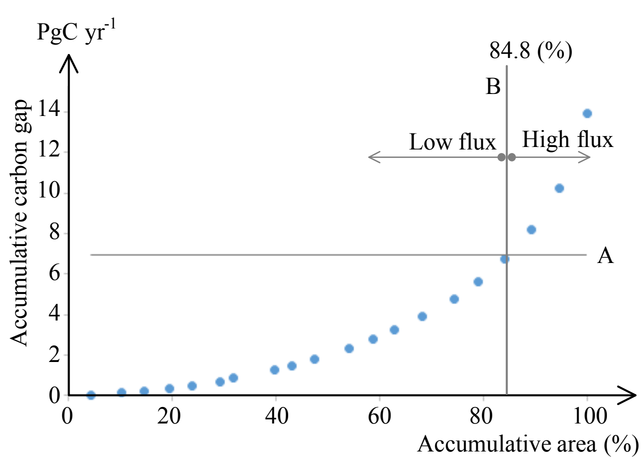


Fig. 4 | Accumulative total carbon gap against accumulative total vegetated area. The whole vegetated area is first sliced into sub-areas using the percentiles of carbon gap flux (from low to high) at an interval of 5%, i.e., 0~5%, 5~10%, …, 95~100% and the accumulated area in the order of the percentiles is depicted on the X axis The corresponding accumulated total carbon gap is shown on the Y axis. The horizontal line (A) shows the location of half (50%) the accumulative total carbon gap. The vertical line (B) denotes the location of the separator that divides the accumulated areas into two equal parts (low flux side and high flux side), where both sides collect half (50%) of the total carbon gap. The high flux side, while representing only ~15% of the total area, collects half of the total carbon gap.

Human activities strongly affect the carbon gap

We examine the relationship between the carbon gap and the population, as human density is a good indicator of human activities[34]. The world population varies substantially over the space between continents/regions (Fig. 5 and *SI Table S5*). South Asia, East Asia, and South-East Asia present the most densified population, followed by moderately populated South-east Asia, Europe, and Africa. At the continental level, there ~~exists~~ no clear link between the carbon gap flux and population density (Pearson's correlation coefficient r=0.27; see *SI Table S5*). However, strong consistency is found between them within the continental/regional scale, as revealed by the statistically significant and positive slope (β coefficient of the independent variable) for all the continents (Table 1 and *SI Fig. S9*). The findings suggest that the areas with intensive human influences are more likely to observe high carbon gap flux which is primarily observed in the densely populated areas (Fig. 1 and Fig. 5). As a case of human activities, updating land management practices (LMPs) can alter vegetation NPP in terrestrial ecosystems, either positively or negatively[23,32]. The study verifies that human activities have generally increased the carbon gap in the past two decades and thereby policy interference should focus more on those highly populated areas.

Table 1 | Regression between carbon gap flux and population density

Continent	Slope (□)	t-value[a]	-95%[b]	+95%[c]	R^2
Europe	12.48	9.48*	9.71	15.24	0.83*
Africa	11.29	9.95*	8.82	13.76	0.89*

Australia	79.92	15.14*	68.16	91.68	0.96*
East Asia	6.53	6.80*	4.47	8.59	0.77*
North Asia	145.76	8.96*	110.86	180.66	0.85*
South Asia	2.69	4.23*	1.31	4.06	0.59*
South-east Asia	5.14	3.75*	2.23	8.05	0.47*
South-west Asia	11.49	3.48*	4.56	18.42	0.40*
Central Asia	12.51	11.54*	10.21	14.81	0.89*
North America	20.78	36.28*	19.54	22.06	0.99*
Central America	14.16	4.17*	7.01	21.28	0.49*
South America	28.16	10.02*	22.16	34.15	0.87*

* Significance level=0.01, [a] the t-value for the slope (□), showing significant ($p<0.01$) and positive (slope>0) for all the continents/regions, [b] 95% lower and [c] 95% upper bound for the slope

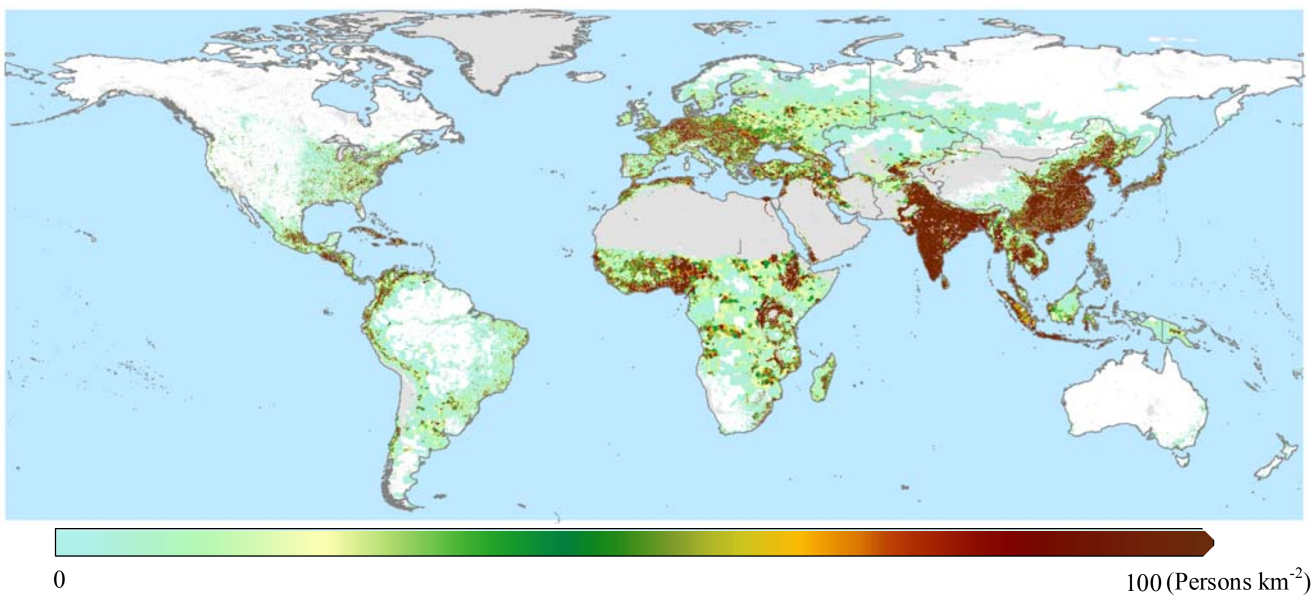


Fig. 5 | Distribution of world population density. Grey background is non-vegetated (see biomes definition in *SI Table S3*) that is excluded from analysis and white areas show population density 0.

Discussion

We estimate that ~1/5 more carbon, totaling 13.74 PgC yr^{-1}, could be added to the current NPP from global terrestrial vegetation if the identified OLMPs get implemented, resulting in a net effect of reducing 3.5~4.0 PgC yr^{-1} from the atmosphere. On average, the carbon gap flux is 124.3 gC m^{-2} yr^{-1}, with significant variations among the continents/regions and the vegetation biomes. Central America and South-east Asia present the highest carbon gap flux, reaching 348.3 and 260.7 gC m^{-2} yr^{-1}, respectively. Grasslands shows the most potential in the improvement of carbon sequestration, with a carbon gap flux of 138.3 gC m^{-2} yr^{-1} and total carbon gap of 6.5 PgC yr^{-1}. Half of the total carbon gap concentrates in ~15% of the vegetated area that particular policy-making attention needs to focus on. In other words, localtion-dependent OLMPs are suggested to proritize to fill the carbon gaps particularly in the ~15% areas.

OLMPs correspond to one or a set of LMPs that have historically proved to be able to produce higher NPP_{CR} (≥90th percentile of NPP_{CR}) at locations within an environmentally (climatically and non-climatically) homogeneous neighborhood. Modeling the carbon gap and identifying the candidates of OLMPs provide a critical reference to implement the OLMPs in practice. This study has mapped the carbon gap and itendified the OLMPs that present potential of carbon sequestration improvement from terrestrial vegetation. Nevertheless, there are a few concerns that may cause uncertainties, requiring further imporvement.

First, the referenced target NPP, i.e., NPP_{CR}^{90th}, could come from optimal LMPs that induce extra GHGs emissions, e.g., N_2O (for instance, fertilizer application in croplands). As a result, the net effect in mitigating GHGs through implementing OLMPs in some areas could be overestimated. Second, while land management optimization targets higher NPP (and vegetation carbon sequestration), implementation of OLMPs for ecological benefits (i.e., more NPP and carbon sequestration) may contradict with other socio-economic needs, e.g., maximizing the production of grains or other edible produces. Furthermore, implementing OLMPs could involve extra input (e.g., labor or other resources), which offsets the willingness to implement the OLMPs widely. Under those cases, the land management optimization can reduce the target potential NPP standard (NPP_{CR}^{90th}), e.g., from 90th percentile to a lower expection, which will result in more candidates of OLMPs. Lastly, while the segmentation of the biophysically homogeneous zones from the perspectives of landscape-vegetation-soil (LVS) probably places the most important basis for assessments of the carbon gap, some other factors affecting vegetation productivity are not included, inevitably introducing uncertainties in the finaly result. Because the detailed biophysical and socio-economic datasets (including LMPs) are rarely available at global scope, the uncertainties raised from the above concerns are challenging to address in this work. We suggest that further assessment of enhancing vegetation productivity through OLMPs be conducted at a national scale with the support of detailed socio-economic contextual datasets and biophysical datasets. Nevertheless, the potential of improving carbon sequestration through OLMPs is confirmed, though designing practicable schemas for OLMPs implementation requires multiple participations from both governments and private vectors to work together.

Methods

We divide the factors affecting vegetation carbon sequestration into three categories[17]:

1) Climate impact (typically precipitation and temperature)
2) Other non-climatic environmental factors, including landforms (L), vegetation (V) types, and soil (S) property
3) Human-related land management practices (HUMAN)

Once the differed impact on vegetation carbon sequestration from the climatic (1) and non-climatic (2) is excluded, the difference in the carbon sequestration from vegetation will be solely attributed to HUMAN impact (3).

Our main objective is to assess how much more carbon (termed as carbon gap) can be realistically achieved by updating HUMAN only from global terrestrial vegetation, without converting land use and land cover vegetation biomes. We use publicly available time-series of datasets to analyze the carbon gap. Data sources come from Google Earth Engine (GEE). Data preprocessing and analysis are also performed on the GEE computing platform. There are four groups of data sources involved, namely climate-related variables, (non-climate) physical environmental variables, net primary productivity (NPP), and world population. Those datasets, if not at the scale of 500m, are uniformly be resampled to a resolution at 500m. We hypothesize that NPP variations are related to climatic, non-climatic factors, and human activities (including land management practices). The following explains the steps of data processing and analysis methods.

Region segmentation of homogeneous natural environments to detach non-climate impacts on NPP variation. Region segmentation is performed by overlaying the layers of landform（L）, vegetation type (V), and soil type (S) to derive homogeneous zones, known as homogeneous LVS zones so that all locations (image pixels) in an LVS zone will have the same LVS# of landform, vegetation, and soil type.

In other words, over the pixels within the same LVS zone, the impact from the non-climate environmental factors on the internal NPP variation is uniform. Thus, any NPP variation within an LVS zone is attributed to varied climatic and HUMAN impacts only.

The three environmental factors are chosen for LVS segmentation because of the following considerations. First, landform properties are often used to represent the spatial variability of hydrological, geomorphologic, and biological processes[35]. Here we use the classified landform cover from European Soil Data Centre (https://esdac.jrc.ec.europa.eu) to indicate landform variations, which include 16 labels dynamically classified by an unsupervised nested-means algorithm based on three geometric criteria (including slope, surface texture, and local convexity) from the Shuttle Radar Topography Mission 30m (SRTM30) digital elevation data[36]. Second, the International Geosphere-Biosphere Programme (IGBP) land cover classification schema of MODIS MOD12Q1 (asset id=MODIS/006/MCD12Q1 in GEE) is taken to map vegetation (biome) distributions. According to the IGBP land cover classification system, there are 17 labels, out of which 13 are closely related to vegetation cover types. Five of them (13# urban and built-up lands, 15# snow and ice, 16# barren, 17# water bodies, and 11# permanent wetlands) are excluded from further analysis (*SI Fig. S6*; *SI Table S4*). Thus, the 12 land cover classes play a vital role in sinking CO_2 from the atmosphere. Lastly, Harmonized World Soil Database (HWSD, ver. 1.2, http://www.fao.org/soils-portal) is the most up-to-date world soil map that incorporates a data table of 48,148 soil profile descriptions related to the various soils associated with each mapping unit, at a spatial resolution 1-km at the equator[37]. Thus, soil type classes from FAO-90 code (SU_Code90), which includes 194 labels, are used for mapping soil type cover.

Rectifying the climatic impact on NPP. NPP dataset provides a direct indicator to carbon sequestration from vegetation. The MODIS MOD17A2H product (V6) is a cumulative 8-day composite at 500m spatial resolution. MOD17A2H includes a layer of net photosynthesis (PSN), an indicator of Net Primary Productivity (NPP) reflecting the spatiotemporal variations in vegetation carbon sequestration.

In terms of the climatic factors, precipitation and temperature are the most important elements because both of them were confirmed to alter NPP and thus carbon uptake from vegetation[38]. Theoretical NPP has been modeled purely from climatic conditions; the empirical Miami model is considered the first one that computes potential NPP (PNPP) using monthly precipitation and temperature and is often used as a baseline for model comparison[39]. The modeled PNPP exhibits significant spatial variations, reflecting spatial heterogeneity of the impact of the climatic factors.

For discriminating varied climate impact on NPP in an LVS zone, a location-dependent relative contribution (RC) was devised to sasses the climate impact on potential NPP (PNPP), which is mapped by the Miami model. The Miami NPP model takes the form[38],

$$\mathrm{PNPP} = \lambda \times \min\{\frac{3{,}000}{1+e^{1.315-0.119t}}, 3{,}000 \times (1-e^{-0.000664p})\} \quad (1)$$

where t is the annual average temperature (°C), p is the annual precipitation (mm) and λ is a conversion coefficient (0.50 for woody ecosystems and 0.45 for herbaceous) that converts dry matter to carbon unit (gC m^{-2} yr^{-1}). TerraClimate derived from climatically aided interpolation by combining WorldClim dataset and Climatic Research Unit (CRU) Time-Series (TS) dataset has been widely applied for mapping regional and global ecological parameters[40]. It provides monthly precipitation and maximum/minimum temperature at the spatial resolution of 2.5 arc minutes. Eq. 1 describes the relationship between PNPP and two climatic variables, p and t. RC at location i in an LVS zone g is defined as the difference between PNPP at the location and the averaged PNPP of the whole g, namely,

$$RC(i,g)=PNPP(i,g)-PNPP_{Mean}(g) \qquad (2)$$

where $PNPP_{Mean}(g)$ is the mean PNPP of all locations in g, $PNPP(i,g)$ is PNPP at i in g, $RC(i,g)$ is the difference between PNPP at i and the mean PNPP in g (i.e., $PNPP_{Mean}(g)$) due to within-group variation of the climate impact. The rationale is that more favorable climate conditions at a location i will result in a positive and higher $RC(i,g)$ and vice versa. The NPP difference due to the climate variations can be reflected from RC on a location basis in an LVS zone. To offset the difference of the climate impact for all locations within an LVS zone g, climate-rectified NPP (NPP_{CR}) at any location i in g can be derived using the function,

$$NPP_{CR}(i,g)=NPP(i,g)-RC(i,g) \qquad (3)$$

The internal variation of the computed NPP_{CR} across all the locations in the LVS zone g is attributed to HUMAN impact only. Thus, after the climate rectification, NPP_{CR} should be free of climate influence over all locations in each LVS zone and have a constant value if there is no differed HUMAN impact. If spatial variation of NPP_{CR} within each LVS zone is observed, it is most likely attributed to HUMAN influence, i.e., the difference in land management practices (LMPs). Furthermore, the locations (pixels) showing relatively very high NPP_{CR} values can be regarded as practicing good LMPs, which suggests that an introduction of the LMPs can sequester more carbon; thus, these good LMPs can be deemed as the optimal LMPs (OLMPs) under similar environmental conditions over this LVS zone. In other words, through human policy and management interventions, LMPs at locations (pixels) with lower NPP_{CR} in the LVS zone could be replaced by the OLMPs to increase the NPP_{CR} to a higher level.

Computing carbon gap by distance-constrained (DC) zonal analysis. The OLMPs and carbon gap are processed for each location. The carbon gap for a given location is computed as the gap from its current NPP_{CR} to a target NPP level that is statistically referenced from NPP_{CR} of locations under identical environmental contexts (i.e., in the same LVS zone). We develop a distance-constrained zonal analysis to evaluate the target NPP level. Zonal analysis computes a set of statistics (e.g., maximum, median or minimum value) from the input values of NPP_{CR} within a zone[41]. The maximum zonal NPP_{CR} (NPP_{CR}^{Max}) is the highest NPP_{CR} that corresponds to the best land management practice (BLMP) in the zone; if BLMP is adopted, it will present the highest carbon gap. However, a zonal statistic defined as 90^{th} percentile, or NPP_{CR}^{90th}, from the input vector of NPP_{CR} is computed as the referenced target NPP level in this study. The selection of NPP_{CR}^{90th} instead of NPP_{CR}^{Max} in an LVS zone can exclude exceptionally high NPP_{CR} values, which are likely outliers resulting from noisy data and are hardly achievable by other locations even in the same LVS zone. Thus, the zonal statistic NPP_{CR}^{90th} provides a more robust reference as the target potential NPP level and the LMPs at locations showing $NPP_{CR} \geq NPP_{CR}^{90th}$ will be referenced as the OLMPs for other locations in a similar environmental contexts.

The appraisal of the NPP_{CR}^{90th} for a location is fulfilled from locations labeled as the same LVS#

within a local neighborhood. It is argued that the variations of NPP_{CR} at locations within an LVS zone are attributed to the differences of HUMAN impacts (i.e., LMPs). It is also aknowledged that other omitted factors may impose unneglectable impact on vegetation carbon sequestration, which could produce certain uncertainties in the isolation of HUMAN impact. Thus, the determination of OLMPs is preferably performed at a local scope. In other words, LMPs at locations too far away from the currently examined location could be affected by too many heterogeneous economical, social, and political factors. Furthermore, locally referenced OLMPs are more practical for policy implementation and make it possible for on-site checkout. A window size specifies a local neighborhood surrounding a given location *i*, in which the NPP_{CR} values at all the locations with the identical LVS# in this window are taken as input to compute the NPP_{CR}^{90th}. To decide the window size, a stratified random selection is made to sample 5000 points in the vegetated land with the sample size weighted by the area of each of the biome types. The samples' histogram shows peak NPP_{CR}^{90th} along the distance, which presents a relatively stable stage when the distance is over 20 km from the piecewise linear function fitting (*SI Fig. S1*). Hence, the carbon gap at location *i* is computed as the difference between the current NPP_{CR} and the NPP_{CR}^{90th} within the 20km window in the environmentally homogeneous zone (i.e., LVS zone).

$$\text{Carbon gap}_i = \max(0, NPP_{CR}^{90th} - NPP_{CR}^{i}) \qquad (4)$$

where NPP_{CR}^{90th} corresponds to the statistic of the 90^{th} percentile for NPP_{CR} input at all locations labeled ~~as~~ as the same LVS# in the distance-constrained neighborhood, NPP_{CR}^{i} is NPP_{CR} for location *i*, and max is the function for getting the maximum value from the two input 0 and $NPP_{CR}^{90th} - NPP_{CR}^{i}$, meaning that if the NPP_{CR} at the location *i* is less than the NPP_{CR}^{90th}, the carbon gap will be equivalent to NPP_{CR}^{90th} minus NPP_{CR}^{i}; otherwise the land management practice (LMP) at location *i* has already reached the level of carbon sequestration under OLMP and no extra space of carbon sequestration is available (i.e. carbon gap_i=0, if $NPP_{CR}^{i} \geq NPP_{CR}^{90th}$). The carbon gap flux and NPP flux are shown in Fig. 1 and *SI Fig. S2*. The annual changes in the carbon gap and NPP are summarized in *SI* Table 4. The ratio map of carbon gap density to NPP density is shown in *SI Fig. S3*. The carbon gap and NPP (total and flux density, respectively) among the biomes and continents/regions are compared in *SI Fig. S7*.

Effect of reducing atmospheric CO_2 from the carbon gap. The resultant carbon gap suggests an increase of NPP 13.74 PgC yr^{-1} with OLMPs implemented (*SI Table S2*). When considering the possible increase in soil heterotrophic respiration (R_H), the improved NPP's net effect (i.e., the carbon gap) on reducing atmospheric CO_2 is less than this total NPP. Previous studies show that the total amount of R_H is largely proportional to NPP; for example, the previous study showed that the ratio of R_H to NPP was 0.71[14]. A meta-analysis on RH from the available dataset estimated that the global weighted mean R_H was 457 ± 139 g C m^{-2} yr^{-1} [42]. Our study indicates that the average NPP over the study years is 614±35 g C m^{-2} yr^{-1} (*SI Table S2*), suggesting that the ratio of R_H to NPP is 0.74 (=457/614), which is reasonably close to the previous study[14]. Assuming that the ratio of R_H to NPP is between 0.70~0.75 (though the ratio is subject to vary on a broader scope under climate changes), an increase of NPP (the total carbon gap) 13.74 PgC yr^{-1} is estimated to reduce 3.5~4.0 PgC yr^{-1} from the atmosphere.

Correlation analysis between total carbon gap and total NPP. The relationship between the total carbon gap and total NPP at the global scale is revealed by Pearson's correlation analysis on the two variables, i.e., total carbon gap and total NPP for each continent/region, resulting in Pearson correlation coefficient r=0.98 (Fig. 2). The relationship between the carbon gap flux and NPP flux at the sub-continental/regional level is performed by slicing the carbon gap density into partitions based on the ordered percentiles of the carbon gap flux (from low to high) at an interval of 5%, i.e., 0~5%, 5~10%, …, 95~100% for each continent/region (*SI Fig. S4*). Comparison between the total carbon gap and total NPP for two typical regions, i.e., amazon rainforests and the rainforests of Africa, is further illustrated in *SI Fig. S5*.

Analyzing the distribution pattern of the carbon gap. For each of the 12 continents/regions, the carbon gap flux is grouped based on the sliced percentiles (from low to high) at an interval step of 5%, i.e., 0~5%, 5~10%, …, 95~100%. The vegetated area and total carbon gap within each percentile are then computed. The points denoted by the accumulative vegetated area and the accumulative total carbon gap in each percentile are used to reveal the carbon gap's clustering pattern (*SI Fig. S8*). The maximum accumulative total carbon gap is divided into two half-half sections by a horizontal line, i.e., low flux density and high flux density. The global clustering pattern in the carbon gap distribution is similarly derived (Fig. 4).

Regression analysis between carbon gap and population density. For each of the 12 continents/regions, the carbon gap density is grouped based on the sliced percentiles (from low to high) at an interval step of 5%, i.e., 0~5%, 5~10%, …, 95~100%. We then compute the accumulative total carbon gap and accumulative total population. The relationships between the accumulative total population and the accumulative total carbon gap are graphed by the sliced percentiles. Linear regressions are fit for the partitions with the accumulative total carbon gap set as the dependent variable and the accumulative total population for each percentile as the independent variable (Table 1 and *SI Fig. S9*).

The world population data comes from the Gridded Population of World (Ver. 4), which models the distribution of the global human population for the years 2000, 2005, 2010, 2015, and 2020 on 30 arc-second grid cells. A proportional allocation gridding algorithm, utilizing millions of national and sub-national administrative units, is used to assign population counts to 30 arc-second grid cells[43]. The averaged population density and carbon gap flux within each continent/regions is summarized in *SI* Table S5.

Code availability. The carbon gap processing Python code on Google Earth Engine, along with all the datasets, is available for download from Pangea at https://github.com/zysha123/carbongap/blob/master/code_wld_nature.py.

Data availability. The modeling results, in the form of the global carbon gap, are available at https://github.com/zysha123/carbongap. The different datasets used to compute the carbon gap for this study are publicly available and described in Supplementary Information (*SI*) along with links. Any other materials generated for this study are available from the corresponding author on reasonable request.

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Acknowledgements

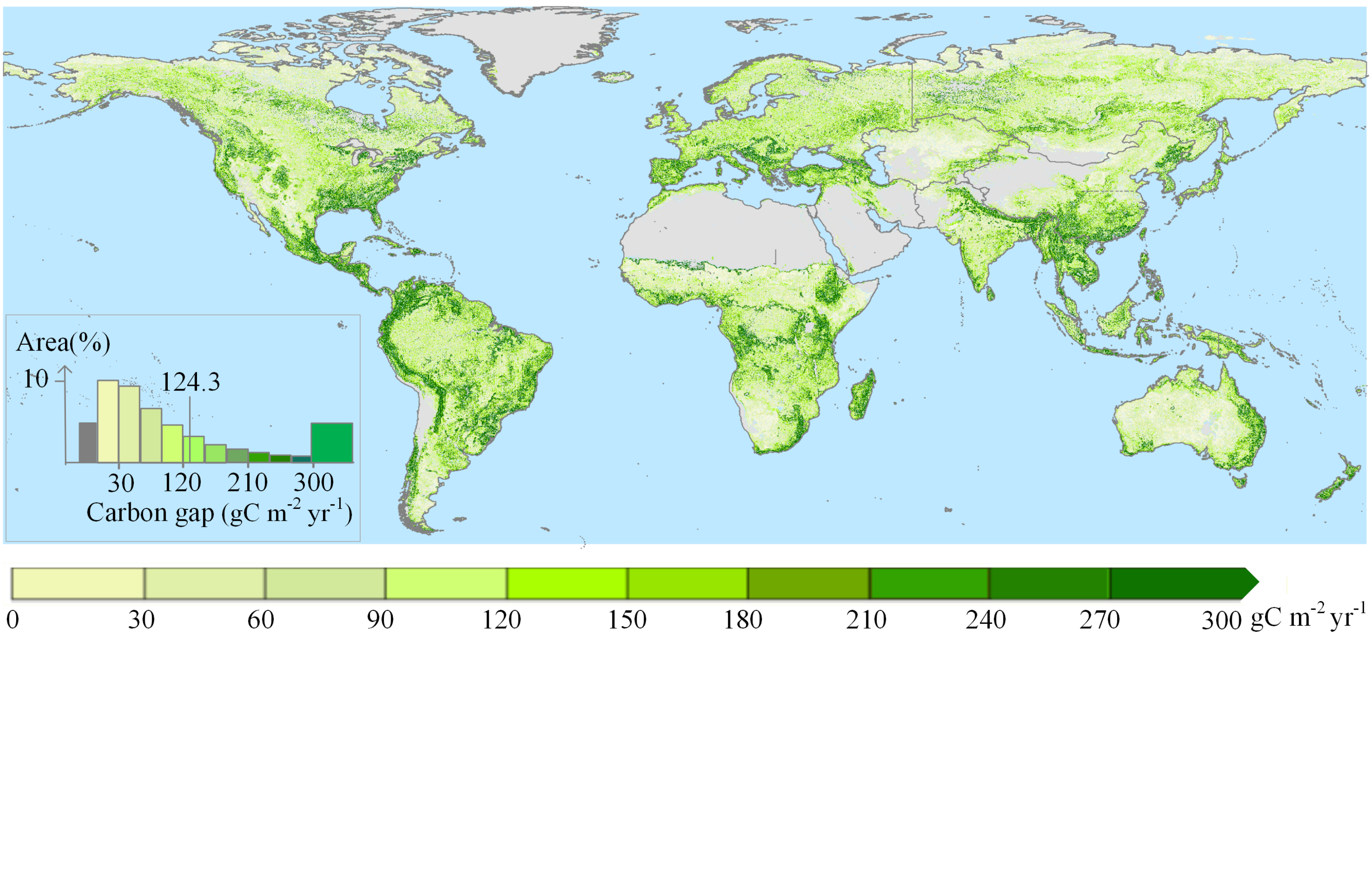
TBD

Author contributions

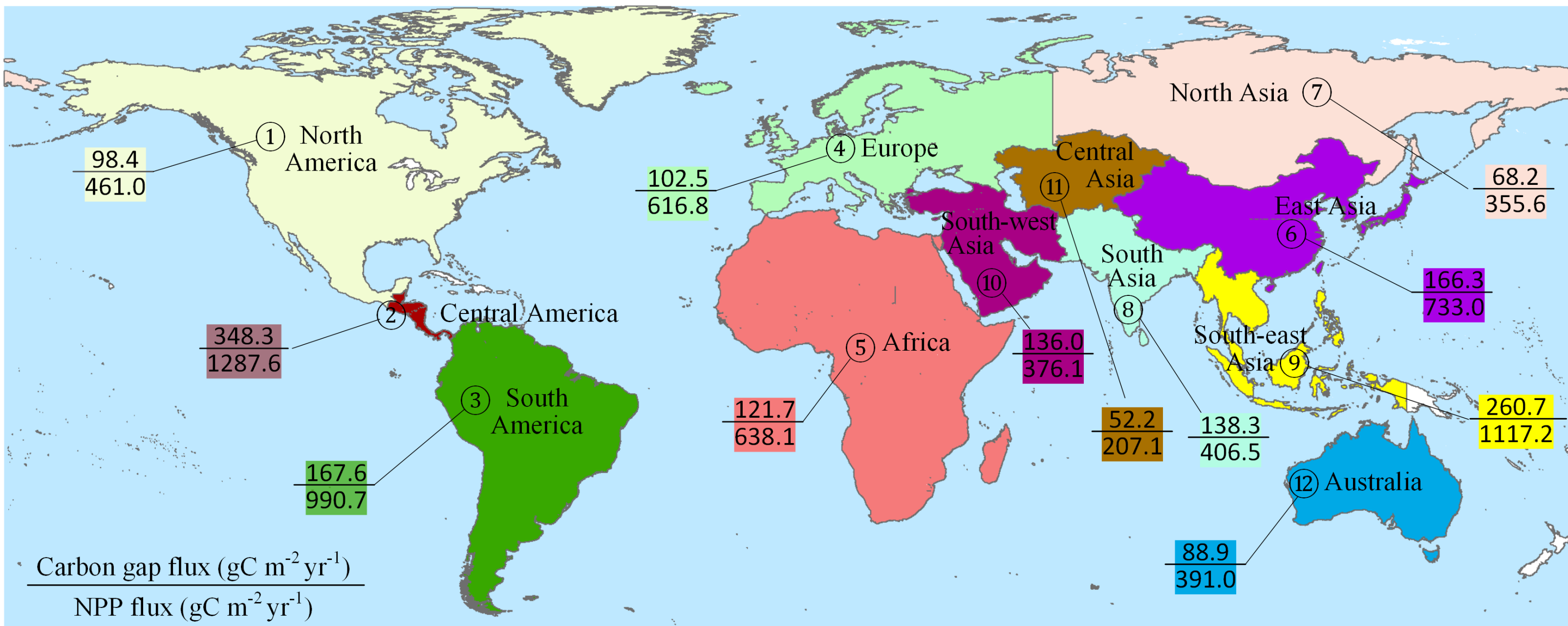
Z.S., Y.X. Y.B. and R.L. conceived the modelling framework to estimating the carbon gap. Z.S. and H. L. realized (coded) the carbon gap modelling on Google Earth Enging and conducted the data analyses. Z.S. wrote the manuscript. Y.X. and Y.B revised the manuscript. X.Z., J.L and X.L participated in the modeling and computation. J.L. reviewed the data and results. All authors provided feedback on the manuscript.

Competing interests

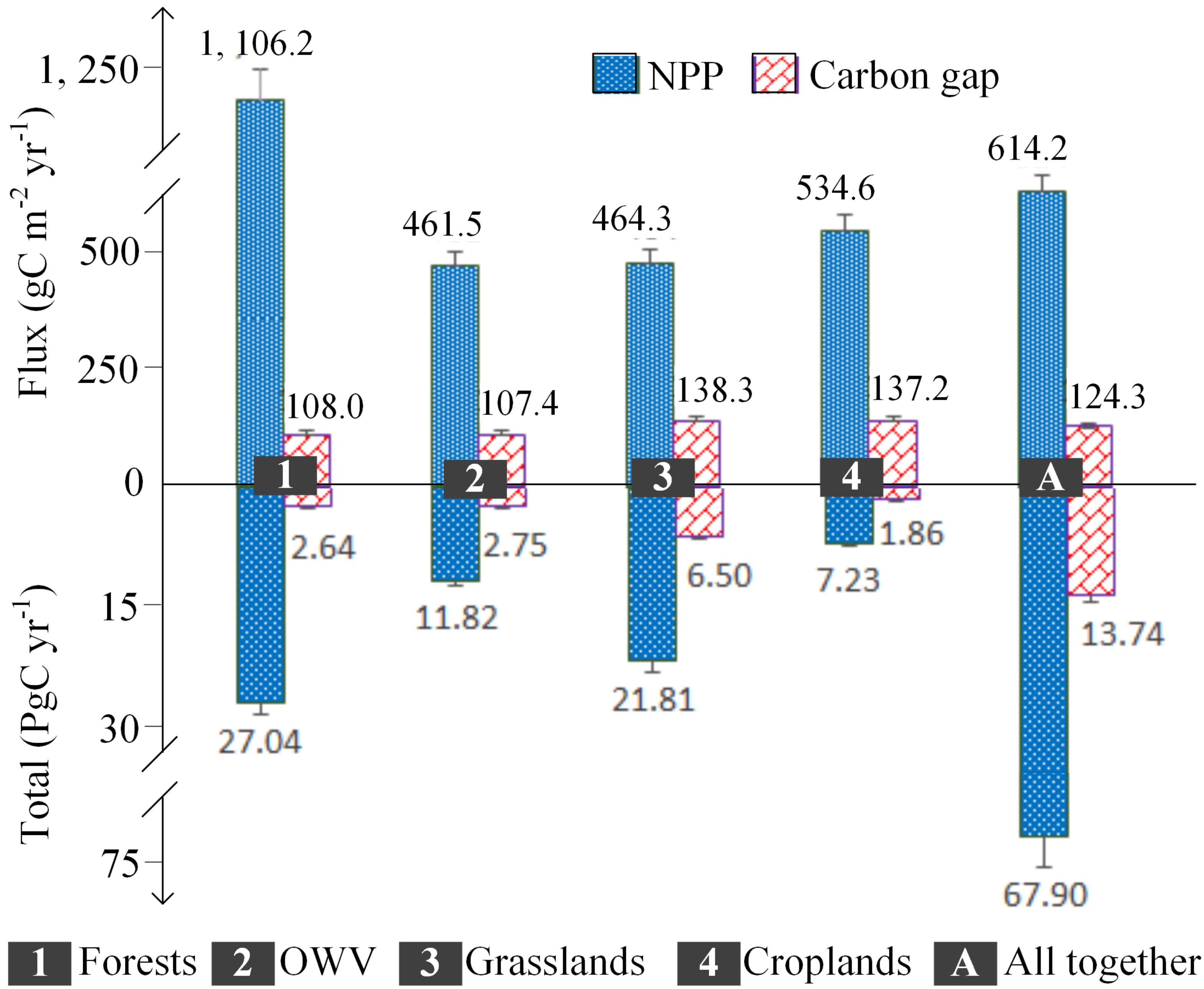
The authors declare no competing interests.



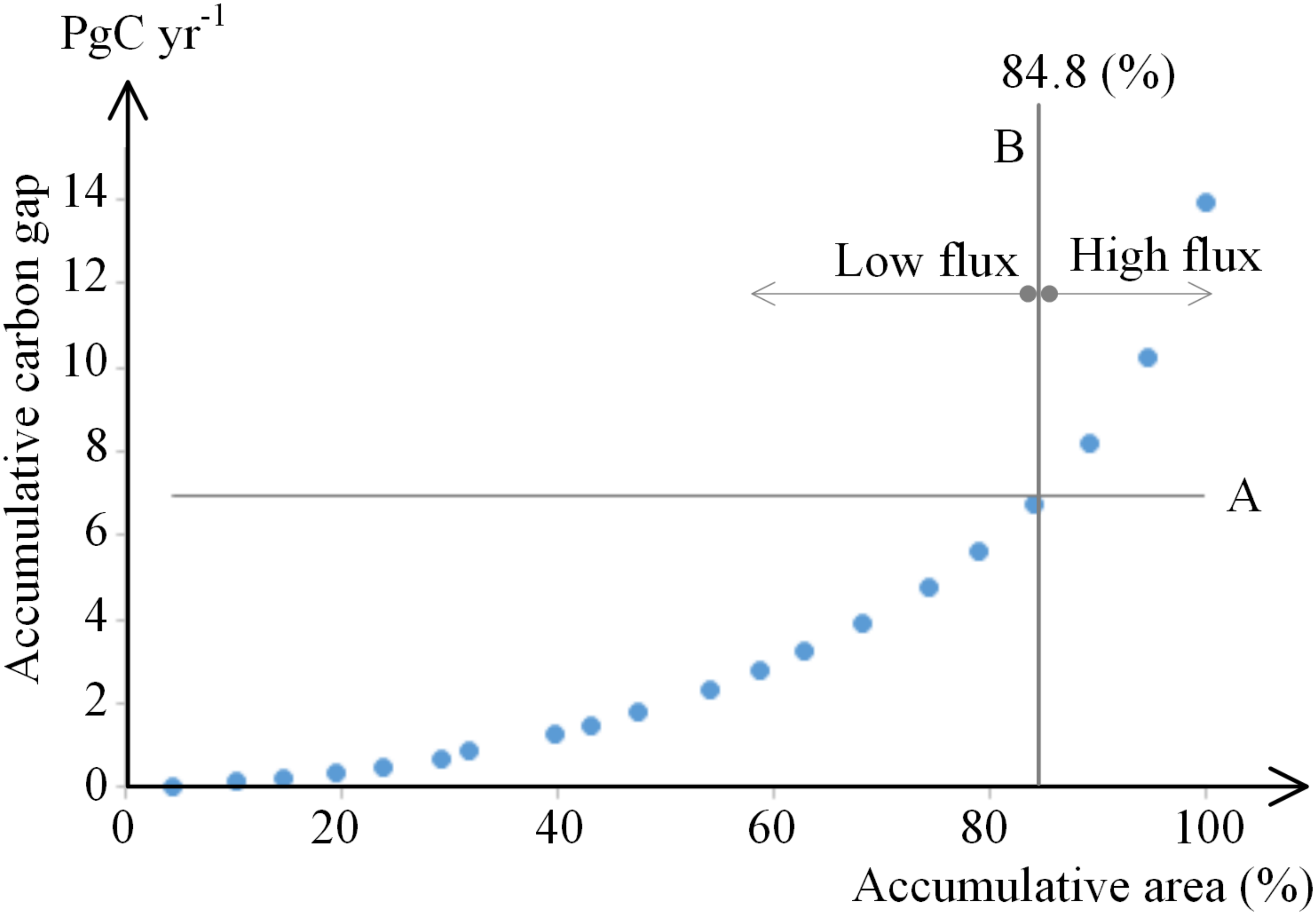
Area(%)
10
124.3
30
120
210
300
Carbon gap (gC m-2 yr-1)
0
30
60
90
120
150
180
210
240
270
300
gC m-2 yr-1



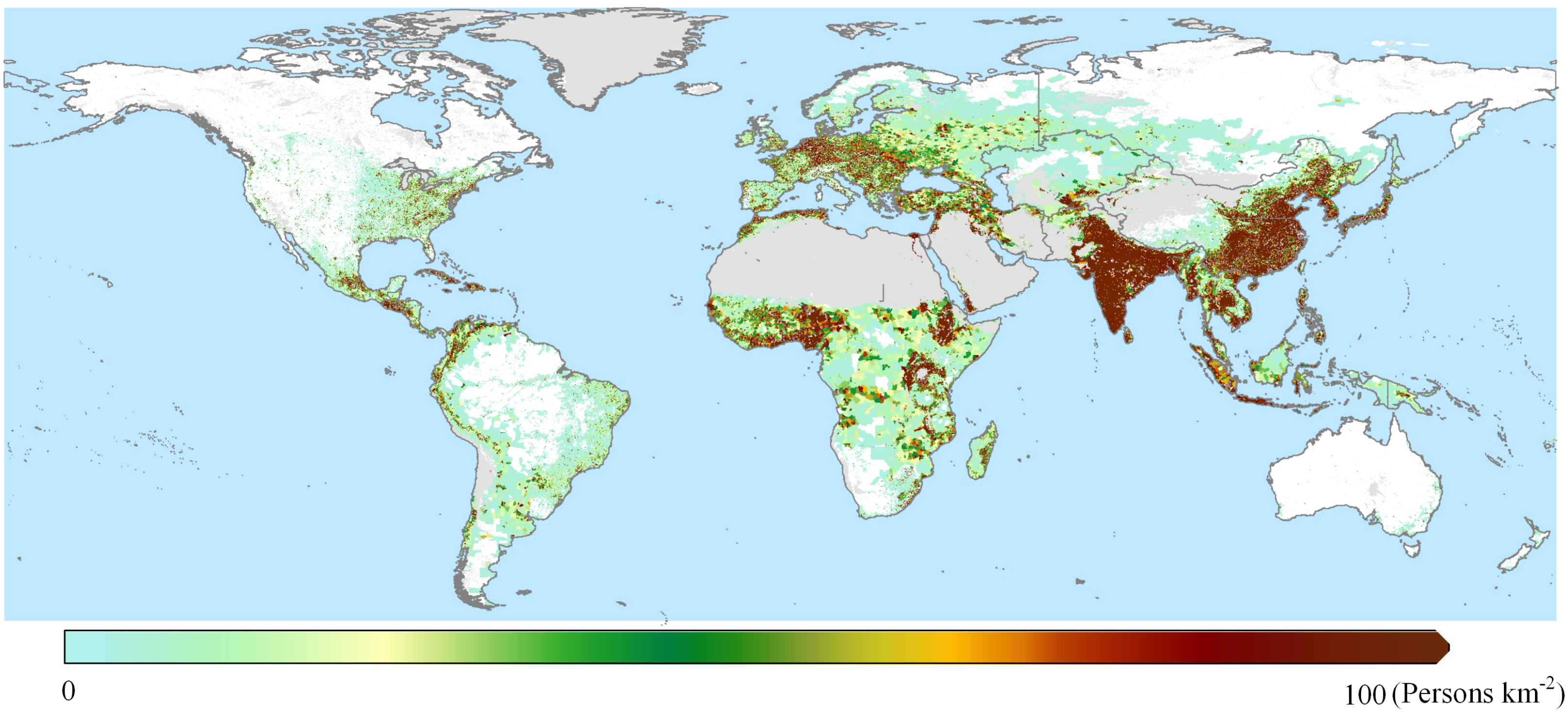
Continent#	1	2	3	4	5	6	7	8	9	10	11	12	Total
Veg. area ($10^6 \times km^2$)	18.89	0.50	16.58	9.24	19.51	11.66	13.28	4.03	4.26	1.93	3.18	7.49	110.54
Carbon gap ($PgC\ yr^{-1}$)	1.86	0.17	2.78	0.95	2.37	1.94	0.91	0.56	1.11	0.26	0.17	0.67	13.74
± std.	0.17	0.01	0.21	0.05	0.13	0.10	0.06	0.02	0.07	0.02	0.01	0.05	/
NPP ($PgC\ yr^{-1}$)	8.71	0.64	16.43	5.70	12.45	8.54	4.72	1.64	4.76	0.73	0.66	2.93	67.90
± std.	0.82	0.04	1.31	0.39	0.83	0.42	0.29	0.09	0.25	0.06	0.09	0.33	/



OWV: other woody vegetation



PgC yr-1
Accumulative carbon gap
84.8 (%)
B
Low flux
High flux
A
0
2
4
6
8
10
12
14
0
20
40
60
80
100
Accumulative area (%)


0
100 (Persons km-2)

Rebuttal/Response Letter to Reviewers

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Increasing terrestrial carbon sink by adopting OLMPs is a strategy proposed by many previous studies to offset anthropogenic carbon emissions. Because of the difficulty in collecting global-scale land management data, these studies are all regional scale. Instead, Sha et al. propose a method that relies on remote sensing and geographical data to assess global-scale terrestrial carbon sink potential from vegetation with OLMPs. In my view, if the method is validated, this can become a masterpiece in the scientific literature. However, my foremost concern is also the validity of the method.

Response: Thank you for the comments. We have done our best to handle the concerns following your specific questions.

Question: The authors suggested that by subtracting RC from NPP (Eq. 3), they can obtain a new variable NPP_CR whose internal variation across all the location in the LVS zone can be fully attributed to human factors. Or in other words, NPP_CR should be constant within each LVS zone if there is no differed human impact. From what has been presented, I am not sure whether this statement is true, even though it should be very easy to verify. For example, the authors can examine whether the correlation between NPP_CR and climate drivers (such as temperature and precipitation) is close to zero.

Response: The raised question is much appreciated and reminds us to rethink the role of climate rectification in the assessment of the carbon gap. We reevaluated the assumptions in the modeling and made correlation analysis between NPP_CR and the climate drivers. However, statistically the correlation between NPP_CR and climate drivers is not close to zero, as the climate rectification on NPP will not change the nature of their correlation level. We are providing the details and explanations below.

We have the following modeling assumptions,

1) NPP is jointly affected by 1) climate impact, 2) LVS (landscape-vegetation-soil) environmental or biophysical factors, and 3) HUMAN activities (land management practices, LMPs).
2) Over a homogeneous LVS segmented zone, the climate factors and HUMAN factors are the most important ones explaining the NPP variation in an LVS zone. Climate's potential impact on vegetation productivity in an LVS zone can be indicated by climate-driven NPP models such as Miami (Eq. 1), called potential NPP (PNPP).

3) The variation of NPP due to climate factors in an LVS zone can be measured by a statistic called Relative Contribution of climate factor (RC). RC is the difference between PNPP at a location in an LVS zone and the averaged PNPP of the whole zone, which can be calculated by Eq.2.
4) RC is designed to rectify the relative impact of climate in an LVS zone by removing RC from NPP to derive the climate-rectified NPP, called NPP_CR (Eq. 3). The variation of NPP_CR over an LVS zone is then attributed to HUMAN influence.

The above assumptions were reasonably made based on the literature review. At the same time, we fully understand that these model assumptions are not exhaustive. The internal variation of NPP_CR in LVS zones may not be fully isolated for HUMAN impact. We have made extensive discussions in the Discussion section in this revised version. We hope that our revision could clarify the concern.

As for the question raised here, NPP_CR will be theoretically correlated to the climate factors if NPP is correlated to the climate factors. In this study, Eq. 3 specifies NPP_CR(i,g)=NPP(i,g)-RC(i,g) in an LVS zone g. Clearly, NPP(i,g) correlates to the climate factors (precipitation or temperature). Based on Eq. 2 (Hypothesis 3) RC(i,g) is also correlated to precipitation and temperature. RC(i,g) only represents local PNPP variations for its mean PNPP over an LVS zone. Therefore, RC(i,g) is designed to reduce local variations of the impacts of the climate factors on NPP, but does not cancel the impacts of the climate factors on NPP. Consequently, NPP_CR(i,g) could remain correlated to the climate factors. In summary, the correlation between NPP_CR and precipitation (and temperature) will not approach zero.

We further use a simulated scenario to explain our analysis (though it is the same for real applications). In the below diagram (Figure 1), we show an LVS zone that is consisted of 6×6 pixels. We use precipitation as an example. Figure 1(a) and (b) are the precipitation and NPP, and Figure 1(c) is the RC distribution, which is derived from the Miami model (by Eq. (1) and (2)). Figure 1(d) is NPP_CR computed by Eq. (3). We can see that NPP is strongly affected by precipitation and that the correlation between NPP and precipitation is 1.0 (perfectly correlated) and that higher precipitation corresponds to higher NPP (shown in (a) and (b)). The correlation between RC and precipitation is also 1.0 (perfecty correlated, see (a) and (c)). After RC rectification, it is clear that the varied impact from precipitation has been largely removed (d), which is less spatially varied compared to (b). The result shows that the correlation between NPP_CR and precipitation is also 1.0 (Figure 1(a) and (d)), even when the spatially varied impact from precipitation has been rectified. Thus, we prove the nature of correlations, i.e., the Pearson correlation coefficients between NPP and the climate factors and between NPP_CR and the climate factors are not changed.

Precipitation

(a)

810	820	830	840	850	860
820	830	840	850	860	870
830	840	850	860	870	880
840	850	860	870	880	890
850	860	870	880	890	900
860	870	880	890	900	910

NPP

(b)

210	220	230	240	250	260
220	230	240	250	260	270
230	240	250	260	270	280
240	250	260	270	280	290
250	260	270	280	290	300
260	270	280	290	300	310

RC

(c)

-45	-36	-27	-18	-9	0
-36	-27	-18	-9	0	9
-27	-18	-9	0	9	18
-18	-9	0	9	18	27
-9	0	9	18	27	36
0	9	18	27	36	45

NPP_CR

(d)

255	256	257	258	259	260
256	257	258	259	260	261
257	258	259	260	261	262
258	259	260	261	262	263
259	260	261	262	263	264
260	261	262	263	264	265

Figure 2 Diagrams showing the relationships between the climate factors (precipitation as an example), NPP, RC and NPP_CR

Question: The key result of this study (Figure 1) may further support my suspicion. Figure 1 shows that in most of cases, regions with high carbon gap density are those with high elevation gradient (such as Andes and Himalayas). Studies have shown that large biodiversity exists in these regions due to the variation of climate with altitude. The meteorological and soil data used by the authors are very likely not able to resolve this spatial variability. As a result, the large internal variation of NPP_CR in these regions is incorrectly attributed to human impact. But in reality, it is not.

Response: We agree that the data adopted has a critical impact on the estimated carbon gap. We assume that LVS, i.e., landforms, vegetation cover and soil, and climate variations and human impact affect NPP in terrestrial ecosystems. An LVS zone is supposed to be homogeneous in biophysical environments, but this assumption could be challenged on several occasions. First, the data sources, including landform data from the European Soil Data Centre, vegetation cover from MODIS, and soil data from Harmonized World Soil Database, all contain uncertainties. It is unlikely to fully resolve the spatial variability in meteorological data and soil (and landforms and vegetation cover) related to NPP. However, those data sources are the most suitable ones that we could get currently for the global scale study. Second, the landforms, vegetation cover, and soil properties are complex and consist of many descriptive properties, making it difficult to segment entirely homogeneous LVS zones. Therefore, an LVS zone is "relatively" homogeneous. We believe that the proposed modeling framework is scientifically correct. More high-quality data available in the future will enable us to provide more unbiased results.

In this revised version, we have updated the text in the Discussion section by acknowledging the limitations, particularly the assumption of the homogeneous biophysical environments from LVS segmentation. We suggest high-quality data, particularly at a national scale, is essential to reducing the uncertainties in the estimated carbon gap.

Question: The only evidence the authors provided to prove that the calculated carbon cap is caused by LMPs is the strong positive correlation between carbon gap and population density. But in my view, this strong positive correlation can also have other explanations irrelevant to OLMPs in Table S1. For example, high population density can increase the spatial heterogeneity of land surface, which eventually increases the internal variation of NPP_CR. Here, I have an example. Region A uses a single crop system that needs fewer people to care about and has lower internal variation of NPP_CR. Region B of the same area has different crops that needs more people to care about and has higher internal variation of NPP_CR. As illustrated, the lower carbon gap in A is not the result of OLMPs rather the result of the spatial homogeneity. To validate the method, I suggest the authors to do more detailed comparison using their method between regions where the data of LMPs exist.

Response: We concur that high population density likely induces high spatial heterogeneity of land surface, which could lead to a considerable internal variation of NPP_CR and thus a higher carbon gap. We assume that human activities cause the internal variation of NPP_CR. In some cases, human activities (e.g., favorable soil tillage or vegetation restoration programs) improve NPP, and others (e.g., overgrazing in grasslands) decrease NPP; both cases tend to induce a considerable NPP_CR internal variation and higher carbon gap. The current study also assumes that OLMPs refer to historical datasets, and the estimated carbon gap is inter-annually dynamic. For the example illustrated in the question, since Region A is characterized by a uniform HUMAN intervention, no OLMPs will be iendtified due to its spatial homogeneity.

However, from the historical perspective, assuming that a new land management practice (LMP) is introduced in the next year, an improved NPP (i.e., higher variation in NPP_CR in the zone) will be observed. In other words, that introduced LMP will be identified as OLMP, and the carbon gap will increase. In brief, the historical perspective of OLMP is critical for identifying the internal variation of NPP_CR in local communities.

In this revised version, we added a validation through a detailed analysis of the grassland in Inner Mongolia, China. We reported the validation design and results in the Methods section and supplementary information (Figs. S10 and S11). We have proved that OLMPs can potentially improve NPP and thus the carbon gap in the grassland, though more validation is still needed in other ecosystems. The validation data file has been shared at github https://github.com/zysha123/carbongap

Specific comments
1. References cited in the supplementary are missing.

We are sorry to have the references missed in the supplementary, and now those are provided in the revision.

2. There are many grammar errors in the manuscript. It may be helpful to ask native speakers to proofread it.

We have invited native speakers from our colleagues and made a substantial revision in the language.

3. L344: Is “sasses” a typo?

Sorry for the mistake, “sasses” has been updated to “assess.”

Reviewer #2 (Remarks to the Author):

I would like to congratulate the authors for choosing a topic of high importance in the current climate context because: 1) shows that it is possible to reconcile adequate land use practices with climate goals without 2) expanding production areas (which would also affect biodiversity and sustainable development goals) or compromising food production. The text is clear, the established methods are well detailed (with good assumptions and justifications for the choice of parameters) and allow others to reproduce the study. However, I understand that there are some structural inconsistencies in results item (for example, between lines 99 and 118) and the authors should provide a deppen discussion (such as the implications of the results for the fulfillment of the Nationally Determined Contributions of the Paris Agreement - more details in the attached document). For these reasons, I suggest the authors to revise the manuscript to address specific concerns before a final decision is reached.

Response: We are grateful for the valuable and detailed comments, especially those marked in the attached document. We have addressed the comments one by one (as shown in responses to the attached document). We added a new paragraph to discuss the implications of the results concerning the fulfillment of the Nationally Determined Contributions in the Discussion section. We illustrated the carbon gaps for the four countries/regions, namely, China, USA, EU28, and India, which are the most carbon emitters or/and have the largest population (Supplementary Table S6). We hope the revisions could better present the findings and implications of the study.

Reviewer #3

Remarks to the Author

The manuscript presents a global-scale study of a novel concept called as carbon gap. The methodology is sound, and the data interpretations are thoroughly and suitably justified. I would recommend acceptance with minimal revisions. Some comments are as follows:

-Ln 192 Since croplands show one of the highest potential, it is worth discussing options to improve C sequestration in this landform. Tillage and afforestation are suggested. I recommend including a brief discussion about cover crops as well.

Response: Thank you for the valuable comment. We understand that OLMP takes many forms and have included the application of cover crops as OLMPs options in the Discussion section in this revised version and Supplementary Table S1.

-Deforestation and reforestation are important processes that can affect carbon sequestration in the short and long-term. The authors need to highlight more of the influence of these factors. As of now they've been mentioned only once (Ln. 208)

Response: We have highlighted the influence of reforestation in the Discussion section in this revised version.

-Ln 255 and Fig. 5. Central America and SE Asia also have the lowest correlation with respect to population density. This relationship should be highlighted and explained.

Response: Our study indicates that R^2 between population (POP) and carbon gap (GAP) for all continents is statistically significant, though it varies between them. The relatively low correlation between population (POP) and carbon gap (GAP) in Central America and SE Asia (and SW Asia) is reflected in SI Fig. S9. While the exact reasons are unknown, we believe that the natural resources (LVS variations) and local demographic patterns (clustered or dispersed population) explain the POP-GAP relationship. For example, in Central America, the area presenting the highest carbon gap (top 5% percentile) corresponds to a population density of 60.3/km^2 (SI Fig. S9(k)).

In this revised version, we have supplemented further notes for the R^2 variation, emphasizing that "the goodness of fit of the regression model (R^2) differs probably due to the varied spatial patterns of population distribution and the different biophysical environments reflected by LVS factors."

-Ln 326-Wetlands are unfortunately not considered in the study. These have been shown to play an important, though variable, part in global carbon dynamics. In terms of LMPs these have received a lot of attention and must be briefly addressed.

Response: We agree that wetlands have an essential part in global carbon dynamics. However, our analysis and related studies in the literature suggest that wetlands are susceptible to hydrological processes, resulting from variations of water depth, hydrologic alterations, sediment and turbidity, and even of transferred pollutant elements. We excluded wetlands in the analysis because the impact on NPP from those hydrological processes is hard to model. Furthermore, the wetlands area covers only about ~1% of total land (see SI Table S3); thus, excluding wetlands has no significant impact on the globally estimated carbon gap patterns.

This revised version has updated texts related to wetlands in two locations, including "Region segmentation of homogeneous natural environments to detach non-climate impacts on NPP variation" in the Methods section and the last paragraph in the Discussion section.

-Minor: The manuscript has a lot of grammatical errors. Authors need to address these before re-submission

Response: Thank you very much for pointing out the errors, and we have asked an English native speaker to double-check our revisions.

25th Nov 21

Dear Professor Xie,

Your manuscript titled "Assessing global terrestrial carbon sink potential from vegetation with optimal land management" has now been seen by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. In particular, we ask that you provide better clarity on the limitations of the approach identified for your calculated carbon gap and provide an in-depth discussion of the potential influence of spatial heterogeneity (please see Reviewer #1's comments for more detail). At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table". Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

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Editorial Board Member
Communications Earth & Environment

Dr Clare Davis
Associate Editor
Communications Earth & Environment

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I am satisfied by the responses for my first and third questions but not convinced by the response for my second question. My core concern is that most of the carbon gap calculated by the method is caused by spatial heterogeneity not induced by human activities. Let us take the carbon gap density of China, India and EU countries in Figure 1 as examples. From the spatial variability of the carbon gap density, I do not see any clue that it has correlation to human activities. For example, in the Eastern plain regions of China, the plain regions of India and the plain regions of France, Germany and Poland, the carbon gap density is very low but human activities are very intense. For this, the authors have not given convincing explanations. To overcome the low carbon gap induced by homogeneous LVS landscapes, it may be necessary to use a reference NPP_{CR}^{90th} beyond local neighboring grid cells, for example national or continental-scale reference NPP<sub>CR</sub^{90th}.

In addition, I have several new comments.
Page8: "Furthermore, within each continent/region, the carbon gap density (Fig. 1) and NPP density (SI Fig. S2) do not correlate well" << Is it expected because the carbon gap density is controlled by NPP variability but not absolute values.

Page14, last paragraph: The discussion in this paragraph is baseless. I do not see any results from the study support it.

Page18: "Excluding wetlands should have no significant impact on the globally estimated carbon gap" << Although I support to exclude wetlands in the analysis because the current method does not work for it, I do not agree with this statement. Wetlands, especially peatlands, can store a disproportionally large amount of carbon and some recent high-profile studies showed that management practices matter for the carbon sequestration of wetlands (Leifeld et al., 2019, Nature Climate Change).

Page20, Equation 4: A NPP_{CR}^{90th} constrain should also be added to limit the impact of unrealistic low NPP values.

Reviewer #2 (Remarks to the Author):

I would like to congratulate the authors for carefully reviewing the manuscript in order to make the piece a relevant contribution to the science of sustainability.

Reviewer #3 (Remarks to the Author):

The authors have sufficiently addressed my comments in the revised version. I recommend 'Accept'.

REVIEWERS' COMMENTS:

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I am satisfied by the responses for my first and third questions but not convinced by the response for my second question. My core concern is that most of the carbon gap calculated by the method is caused by spatial heterogeneity not induced by human activities. Let us take the carbon gap density of China, India and EU countries in Figure 1 as examples. From the spatial variability of the carbon gap density, I do not see any clue that it has correlation to human activities. For example, in the Eastern plain regions of China, the plain regions of India and the plain regions of France, Germany and Poland, the carbon gap density is very low but human activities are very intense. For this, the authors have not given convincing explanations.

Response: We thank you for the comment. We are sorry that we did not explain the difference in the carbon gap across different regions, particularly those highly populated plain regions as mentioned above.

The study confirms that the human activities may critically affect the carbon gap, but at the same time, the carbon gap is also constrained by the NPP_CR, as shown by Eq. (4). Eq. 4 suggests that the carbon gap is not higher than the NPP_CR_90^{th}. In other words, the ultimate carbon gap will be low when the NPP_CR of the local neighboring window is low (and therefore, the derived NPP_CR_90th is low). The NPP density in the Eastern plain regions of China, the plain regions of India and, the plain regions of France, Germany and Poland (Fig. 1) is low (see Supplementary Fig. 2). Correspondingly, the carbon gap density in these plain regions will not be high. One explanation is that these plain regions have long been cultivated. These regions' crop production management practices are well optimized and fit their environments. In other words, these regions have realized OLMPs to some extent. Therefore, the NPP variability is very limited in these regions.

In this revised version, we updated the text in the results section and methods section. In the result section, we provide explanation in the section "Human activities strongly affect the carbon gap", as the following

"At the same time, the impact on the carbon gap from human activities is not independent of the biomes distribution, which is noticeably observed in the plain region of the Eastern China and some plain regions of India presenting the most densely populated but relatively a lower carbon gap flux (Fig. 5 and Fig. 1). Those plain regions show relatively low NPP flux (Fig. 5 and Supplementary Fig. 2), and thus the carbon gap density will also be low (see Methods). One explanation is that these plain regions have long been cultivated. These regions' crop production management practices are well optimized and fit their environments. In other words, these regions have realized OLMPs to some extent. Therefore, the NPP variability is very limited in these regions."

In the methods section (the paragraph under Eq. 4), we emphasize that "The carbon gap is not only dependent on the NPP_CR variability but also constrained by the level of NPP_CR. It is reasonable that areas with a low NPP (and accordingly NPP_CR) density cannot be expected to have a higher carbon gap density."

To overcome the low carbon gap induced by homogeneous LVS landscapes, it may be necessary to use a reference NPPCR90th beyond local neighboring grid cells, for example national or continental-scale reference NPPCR</sub90th.

Response: Extending the size of the local neighborhood may improve the NPP_CR_90th and thus the carbon gap in some regions. Because we applied 90th percentile and when the scale increases, the 90th threshold of NPP_CR does not always increase along with the increase of the scale. Our analysis showed that ~20km is an optimal scale for computing the NPP_CR_90th, as shown in "Computing carbon gap by distance-constrained (DC) zonal analysis." in the Method section. More importantly, from the perspective of the convenience of implementation, adopting the national or continental-scale reference will make the identified OLMPs (Optimal Land Management Practices) much harder to transfer from one location to another (it is harder to transfer an OLMP from a different country/province than from a nearby village).

In addition, I have several new comments.
Page8: "Furthermore, within each continent/region, the carbon gap density (Fig. 1) and NPP density (SI Fig. S2) do not correlate well" << Is it expected because the carbon gap density is controlled by NPP variability but not absolute values.

Response: We agree that the carbon gap density is primarily controlled by NPP variability but is also affected by NPP_CR_90th derived from NPP_CR. The carbon gap will be low in the areas characterized by low NPP_CR (and thus low NPP_CR_90th). On the contrary, for those areas with high NPP_CR and (thus high NPP_CR_90th), the carbon gap could be high, though the ultimate result is also subject to NPP variability. Therefore, we cannot exclude the possibility that the carbon gap is correlated to the NPP density at the continental scale. In a word, the carbon gap density is related to both NPP variability and NPP density.

Page14, last paragraph: The discussion in this paragraph is baseless. I do not see any results from the study support it.

Response: The discussion in this paragraph is our interpretation of the OLMP's implication in improving carbon sink potentials based on several references concerning the management of agriculture, forestation, and land conservation. We hope to convince that the optimal land management can play a critical role in improving carbon sink potentials through this discussion. More importantly, we reiterate that the two concepts developed in this manuscript, the 90^{th} NPP_{CR} and the local neighborhood of ~20km, make it feasible to implement optimal land management.

Page18: "Excluding wetlands should have no significant impact on the globally estimated carbon gap" << Although I support to exclude wetlands in the analysis because the current method does not work for it, I do not agree with this statement. Wetlands, especially peatlands, can store a disproportionally large amount of carbon and some recent high-profile studies showed that management practices matter for the carbon sequestration of wetlands (Leifeld et al., 2019, Nature Climate Change).

Response: we agree that improved management on wetlands will significantly increase carbon sequestration of the wetlands. Due to the limitations in this study (data availability and complicated factors affecting NPP of wetlands), we were unable to include it. Since the area in wetlands is small, the overall impact at the global scale will not be dramatic, although the carbon gap density could be very high for wetlands. In this revised version, we reworded "no significant" to "limited impact." We also made revisions to the limitation of excluding wetlands in the Discussion.

Page20, Equation 4: A NPPCR90th constrain should also be added to limit the impact of unrealistic low NPP values.

Response: In this study, the low NPP values corresponding to non-vegetated (land cover types 13, 15-17) have been excluded from the studies because we only consider vegetated areas (defined by the land cover types from IGBP). Thus, we think that the impact of unrealistic low NPP values should be small.

We have updated the text in this revised version to emphasize that those non-vegetated areas were not included in computing NPP_CR90th.

Reviewer #2 (Remarks to the Author):

I would like to congratulate the authors for carefully reviewing the manuscript in order to make the piece a relevant contribution to the science of sustainability.

Reviewer #3 (Remarks to the Author):

The authors have sufficiently addressed my comments in the revised version. I recommend 'Accept'.