Responses to reviews for manuscript **Global Rules for Translating Land-use Change (LUH2) To Land-cover Change for CMIP6 using GLM2**

To Reviewer #1:

Reviewer 1: This is a revision of a previously reviewed manuscript. The authors have done a good job addressing the reviewer comments (which was not a trivial task), but there are still a few things that need clarification before publication. I don't have any major concerns. Please see the comments below for details.

Response: Thanks for all comments. We have made some clarifications accordingly. Please see our point-by-point response below.

Reviewer 1: page 3, lines 19-23: It isn't clear what "inconsistent land-cover translation" means here. Inconsistent with LUH? Inconsistent across ESMs/DGVMs?
It seems that the meaning here is leaning toward inconsistency across ESMs/DGVMs, but both inconsistencies are relevant. So I suggest clearly specifying both.
And "globally consistent" is also ambiguous. A rule that is global in spatial extent? Or a rule that is applied consistently by different folks around the globe? Again, it seems like the latter makes more sense here. That it is a global rule is different issue that also generates uncertainty.
Also, "eliminate added uncertainties" is an overly ambitious claim.
Maybe try "Consistent application of a specified rule for translating…could reduce uncertainties from translation inconsistencies in studying…"

Response: 'consistent' here means ESMs/DGVMs are suggested to use the same rule to translate the given land-use change dataset such as the LUH2. We agree with your suggestion and changed the lines to "*Therefore, consistent application of a specified rule for translating land-use products could reduce uncertainties from translation inconsistency in studying land-use effects through ESMs and DGVMs*".

Reviewer 1: page 4, lines 14-16: Please clarify the relationship to LUH2. These GLM2 runs generate and track the exact same LUH2 data as before, and the additional translational tracking does not affect the LUH2 land use transitions. The translation and tracking of vegetation carbon is an additional capacity.

Response: Very good point. We have added this clarification into the first paragraph of section 2.3. It is "*Note that the modified GLM2 still generate and track the exact same land-use transitions of the LUH2 and has the additional function to track associated land cover change in terms of forest cover and vegetation carbon.*"

Reviewer 1: page 5, lines 17-20 Does this mean that the constant spin-up climate is a 100-year average?
How were the stocks and fluxes calculated during the translation simulations?

Did the spin-up produce a spatial, but temporally static, look-up table for use by the simulations, or was it just for initial conditions?
Or are the simulations also driven by some form of static or time-varying climate that determines carbon fluxes and stocks?
It appears later on page 7 that the spinup contributes to parameters for eq. 7. This should be clarified here.

Response: Yes, the 100-year averaged temperature and precipitation are used and remain constant during the spin-up. They are spatially varied but temporally static. Besides, the GLM2 use them to estimate fluxes and stocks (NPP and B(t) at Eq.7), which is explained at the first paragraph of section 2.3. For better clarification, we have changed the description of climatology generation as "*The annual temperature and precipitation maps from MSTMIP were averaged over 1901 and 2000 to generate the spatially varied and temporally static climatological temperature and precipitation, which was then used to spin up the GLM2 globally at 0.25x0. 25˚ resolution for 500 years.*". Besides, we also added explanation at the paragraph after Eq.7 "*Note that B_0 and NPP_0 are estimated by a statistical model in GLM2 using climatological temperature and precipitation and are constant over simulation period from 850 to 2015.*"

Reviewer 1: page 5, line 30
Is the type of vegetation remaining in the land use categories (5-8) tracked? Or is it just the biomass value that characterizes the vegetation?
Is it assumed that land use categories have no biomass (and no change over time in biomass) if the vegetation has been cleared (this is answered on page 10)?

Response: Vegetation remaining in land-use categories 5-8 is indeed tracked. This vegetation has three pathways: 1) If its land-use type remains the same, its biomass will not grow as explained at the second paragraph of section 2.5, and 2) if it is converted to another type of 5-8, like from crop to managed pasture, its biomass will be cleared; 3) if it is converted back to secondary forest or non-forest, its biomass will continue growing, tracked by Eq.7.

Land-use categories 5-8 have biomass only if they have vegetation that came from primary/secondary land and was not cleared due to translation rule.

Reviewer 1: page 6, lines 11-14. Is this correct for gamma? It seems like it should be the opposite: a 1 value for "O" such that the land use type gains vegetation when no clearing occurs. Clearing means that no vegetation would be gained.

Response: We have modified Eq.2 and replaced γ_{ij} by $(1-\gamma_{ij})$. In this way, gramma is still 1 for X and F indicating no vegetation could be gained in Eq.1, and gramma is still 0 for O indicating amount of a_{ij} vegetation could be gained.

Reviewer 1: page 7, lines 3-4. This needs clarification, as gamma isn't the same as for the reverse of transitions to land use categories. For example, any transition to land use from primary or secondary would generate a loss of vegetation in primary or secondary land, regardless of clearing, which would mean that gamma is always one for eq. 5; the lost vegetation fraction would either be in a land use category, or it has been cleared.

Response: Yes, you are right. Any land-use transitions from primary or secondary would result in vegetation loss in primary and secondary. The lost vegetation could be remained in cropland, pasture or rangeland if translation rules indicate O, or be removed if the rules indicate X/F. We have corrected it by removing γ_{ji} from Eq.5.

Reviewer 1: page 11, line 12. reference table 4

Response: Change made.

Reviewer 1: page 11, line 13. I suggest being specific here, as table 4 shows the results. You don't need the e.g. clause, and you should state that 5 of 8 countries have values within range for rules 1-3 and 4 out of 8 for rule 4 (if i counted correctly)

Response: Good point. We have changed the line to "*The forest cover estimates from Rules 1-4 are generally well within the range of diagnostics. For example, 6 of 8 countries have estimates within the range for Rule 1, 2, and 3, and 5 of 8 countries for Rule 4.*"

Reviewer 1: page 11, line 16. It isn't clear what you mean here by larger difference and what these differences are. I assume you mean differences between rules 1-3 and rule 4.

Response: The difference is between Rule1-3 and Rule 4. We have rephrased it as "*China and Brazil are the two countries where Rules 1-3 and Rule 4 have relatively larger difference between their estimates, the difference between Rule 1, 2, 3 and Rule 4 are 1.17 million and 1.08 million for China and Brazil respectively.*"

Reviewer 1: page 12, line 22. I am not sure that this metric evaluates the heterogeneity. I suggest something like "…best capture carbon density globally…)

Response: It is changed to "According to this comparison, Rules 1-3 best capture the carbon density globally (Figure 8)."

Reviewer 1: page 13, lines 10-11. I suggest rephrasing rangeland part, as currently it isn't clear what the rule does when establishing rangeland. Rather than switching to leaving vegetation, state that for rangeland the rule clears all vegetation only if source land is forest.

Response: Those lines have been changed.

To Reviewer #3:

Reviewer 3: I appreciate that the authors reconsidered the wording throughout the manuscript and added analysis, now presenting a more nuanced discussion of their approach to test different rules for the translation between LUH2 land-use and land-cover for ESMs. However, their main conclusion (=recommendation of rule 1) is not covered by the results of the analysis and sufficient justification for the exclusive recommendation of this rule is still missing. The framing of the manuscript still indicates the opposite, e.g. by the following statement in the abstract:

'Examinations at global, country, and grid scales indicate that the recommended translation rule for CMIP6 models is 1) completely clear vegetation in land-use changes from primary and secondary land (including both forested and non-forested) to cropland, urban land, and managed pasture; 2) completely clear vegetation in land-use changes from primary forest and/or secondary forest to rangeland; 3) keep vegetation in land-use changes from primary non-forest and/or secondary non-forest to rangeland. This confirms the translation rules suggested earlier in the HYDE dataset underlying LUH2.'

(1) The examinations across scales do not exclusively indicate rule 1 (instead rules 2 and 3 are equally likely), which the authors also state in the manuscript and in the reply to the reviewers.

(2) The examinations do not confirm the translation rule suggested by HYDE. Instead, the earlier suggestion from HYDE is used as (the main) justification to pick rule 1 instead of rules 2 or 3.

One way out would be to be very clear about the fact that rule 1 is only recommended to achieve consistent implementation in future simulations (i.e., it would require to be a major point in the discussion and also in the abstract) and this recommendation is NOT a result of the analyses in this manuscript (as these show that with the same arguments also recommendation of rules 2 and 3 could be justified).

In this context, the manuscript would also benefit from a more critical discussion about the downsides of a consistent 'translation rule' (which is not necessarily supported by available data). In my opinion, it is reasonable to aim at a standardized translation between LUH transitions and ESM land cover. But such a standardization always comes at the cost of omitting uncertainties, instead of actually reducing them. If, for example, the 'added uncertainty of 43 PgC in CMIP6' (as stated in the discussions) is avoided by implementing a consistent 'translation rule' this does not necessarily mean that the uncertainty is not there anymore; it might be just not depicted in the ESM results anymore. Only if the authors could show by their analysis that one rule performs significantly better than others, this would be an indication for actually 'reducing' uncertainties.

If the authors do not want to put more emphasis on the consistency aspect and/or highlight the limitations of their results (i.e., basically we do not know about the 'correct' rule), they would need to show with their analysis that rule 1 outperforms the other rules.

In sum, I think it is a useful study/analysis and worth to be published, but requires more nuance in the presentation of results, limitations, and derived conclusions.

Response: We have rephrased the abstract and major content of discussion section according to your suggestions and reworded statements about uncertainty. We do think standardization of land-use data and translation to land-cover is very important and beneficial to model simulations and evaluations in CMIP6, and this is the major point of this study. Therefore, this study discusses possible impacts of translation rule choices on land cover and aims to provide insights into LUH2 implementation for CMIP6 models. Our evaluations suggest Rule 2 gives closer estimates of vegetation carbon to diagnostics than Rule 1 and Rule 3. However, given uncertainties in vegetation carbon diagnostics, we think certainly differentiation of Rules 1, 2 and 3 is difficult in this study. We have discussed limitations at discussion section and revised the statement that a consistent translation rule could eliminate added uncertainty in LULCC emissions. Please see the point-by-point response below.

Reviewer 3: P3 L1-3 The authors did not address the comment on the (non-)existence of 'global transition rules'

Response: We do agree that a global rule may not exist, and implementation of such rule is very likely to oversimplify the translation between land-use changes and land-cover changes. We have stated at the third paragraph of discussion section that global rules may result in errors in land-use translation and discussed the possibility of spatially or temporally varied rules.

Reviewer 3: P3 L5-7 What is the basis for this statement, if it's not supported by literature? Some previous analysis? I think without a reference it is a misleading statement.

Response: We have removed this statement and rephrased this paragraph. This paragraph now emphasizes standardization of LULCC data and consistent translation of LUH2 is important for CMIP6.

Reviewer 3: P4 L1-5 I am sure there are suitable legend translations for ESA CCI land cover as well and it's one of the most up-to-date datasets, but indeed it's not a critical issue.

Response: It will be very interesting and valuable for future work to evaluate these rules with ESA CCI product. We have suggested at the last paragraph of discussion section. that future research could focus on usage of this dataset.

Reviewer 3: P4 L28 While I see that it is difficult to link biomass density to tree density as the authors state, I think it would be worth to give an indication which one of the forest definitions in the literature (and also the ones in the reference maps used for comparison) is closest to this 2 kgC/m² definition. This definition has the potential to affect the results and deserves some attention.

Response: It is difficult to indicate which forest definition is closest to 2 kg C/m^2, because only one definition is used to derive satellite-based tree-cover to forest cover, namely the 30%

threshold. Detailed discussion of the threshold choices is beyond the scope of this study and it is well discussed in Sexton et al 2016 (already cited). Besides, we think comparisons in Fig.3, Fig.4 and Fig.S1 could suggest which reference map best matches the 2 kg C/m² definition. We also pointed out at the last paragraph of section 3.2 that our estimates are closer to GFC than others.

Reviewer 3: P5 L1 The intention to include rules 5-9 is still not clear. Although it might be useful for test/sensitivity runs (also for the ESM community), I think it doesn't make sense to include them if the main purpose of the manuscript is to derive a realistic/recommended translation rule (where these rules by definition are not useful). In the results (incl. tables and figures) they are hardly revisited and rather add confusion to some of the results. In my opinion, the authors should decide to either include all rules in all results/tables/figures or stick to rules 1-4. To concentrate on a different set of rules at different sections of the results is confusing.

Response: As we emphasized at the last paragraph of section 2.2, inclusion of Rules 5-9 could be used to infer individual contribution to land cover change from cropland, pasture and so on, and inclusion of them does not mean they are realistic to be implemented. We still think inclusion of Rules 5-9 will be helpful to answer questions like what likely impacts on forest/carbon from Rules 5-9 are implemented and why we recommend not to use these Rules. We also have added forest cover and carbon density maps of Rules 5-9 to the figure. S6 and S7 are for completeness.

Reviewer 3: P10 L9-11 I see the authors intention to include the whole range of currently available forest reference maps. However, it would be still useful to give an indication which one is closest to the GLM2 forest definition. If we would know, for example, that one of the products has a similar forest definition, this could increase the confidence/justification for one of the rules.

Response: We have added such an indication in terms of spatial pattern at the last paragraph of section 3.2. The reason why to include multiple maps as reference is there is no such a map that undoubtedly has the closest definition with the GLM2. First, all reference maps define forest based on tree cover rather than the GLM2 uses biomass. Second, Figure 2 and 4 suggest different closest maps. The GLC2000 has the smallest difference from the GLM2 in terms of global forest area in Figure 2, but the GFC gives the smallest AAD in Figure 4. Besides, the evaluation of rules is not affected without indication of such reference map. For example, Figure 4 shows Rule 1, 2, and 3 consistently produce the smallest overall difference among Rule 4 and other rules regardless of which satellite-based forest cover is chosen as the reference.

Reviewer 3: P1 L30 Reference biomass is also close for rule 2 and 3.

Response: The abstract has been rephrased.

Reviewer 3: P1 L30 Should it be: '[…] regions with forest cover larger than 50%'?

Response: The abstract has been rephrased.

Reviewer 3: P2 L16 As there is now already a carbon budget update, it might be good to use the latest values/reference. Friedlingstein, P. et al. 2019. Global Carbon Budget 2019. Earth Syst. Sci. Data 11, 1783–1838. https://doi.org/10.5194/essd-11-1783-2019

Response: Change made.

Reviewer 3: P3 L7-9 It is not only the lack of a globally consistent rule, but also the fact that the existence of such a global rule is very unlikely and a large simplification (see original comment P3 L1- 3).

Response: This paragraph has been rephrased in a way of emphasizing importance of consistent rules across models and standardization of LULCC data. We do agree that a global rule is very likely to over simplify the translation between land-use changes and land-cover changes, and we also think particular areas may need different rules. Therefore, we have discussed the possibility of spatially or temporally varied rules and noted readers the simplified rules designed in this study could result in errors at the third paragraph of section 4.

Reviewer 3: P3 L21-23 But also obscures the uncertainty from the lack of process understanding and lack of dedicated spatially explicit treatment.

Response: These lines have been changed as "*Therefore, a consistent rule across models for the LUH2 translation is needed with potential to reduce impacts of LUH2 use inconsistency on studying land-use effects through CMIP6*".

Reviewer 3: P3 L25 'which are then integrated'

Response: Change made.

Reviewer 3: P9 L20 'accounted for in bookkeeping model based studies'

Response: Change made.

Reviewer 3: P9 L29 'should be close to diagnostics'

Response: Change made.

Reviewer 3: P9 L31-33 It's not 'other criteria, such as …', but the only one that is used in the end to identify the recommended rule.

Response: Changed as **"Finally, if several rules have a reasonably good fit to these three diagnostics, other criterion, namely the definition characteristics for managed …"**

Reviewer 3: P10 L17-19 I don't understand what the authors intend to say here?

Response: Removed to avoid confusing.

Reviewer 3: P11 L2-4 Due to these large discrepancies it would be even more helpful to guide the reader with some information about which forest definition (of the reference maps) is closest to the GLM forest definition. (see original comments P4 L28; P10 L9-11).

Response: We have made such indication at the last paragraph of section 3.2.

Reviewer 3: P11 L17-18 And are within the range for Brazil, US, Congo, Indonesia, Peru.

Response: Added "are within range for Brazil, Democratic Republic of the Congo, Indonesia, and Peru". Rule 7 is outside the range for US.

Reviewer 3: P12 L6-14 All the realistic rules (1-4) reduce the pasture anomaly. Is this then just the difference between LUH1 and LUH2 or really a characteristic of the individual rules?

Response: Improvement of LUH2 itself primarily reduces the anomalous emissions by 6 Pg C, and choice of some rules could further reduce the emissions. We also clarified this by adding "*Rule 1 reduces anomalous emissions by 6 Pg C, indicating the sole contribution of the LUH2 to mitigate pasture anomaly*".

Reviewer 3: P13 L3-5 On average and globally. The regional and gridded comparisons (Table 4, Supplements) indicate that this might not hold at the country and grid level. Misleading statement.

Response: These lines have been changed.

Reviewer 3: P13 L6-8 It's actually hard to say if it is 'better' given all the uncertainties in these comparisons.

Response: Changed 'better' to 'closer'.

Reviewer 3: P13 L14-16 Which is also true for rule 2 and 3.

Response: This paragraph has been re-organized.

Reviewer 3: P13 L23-25 The uncertainty is not really reduced by implementing a consistent rule, as long as we do not know, which rule is 'correct'. It's just omitted from evaluation.

Response: This paragraph has been re-organized.

Global Rules for Translating Land-use Change (LUH2) To Land-cover Change for CMIP6 using GLM2

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Abstract.

Anthropogenic land-use and land-cover change activities play a critical role in Earth system dynamics through significant alterations to biogeophysical and biogeochemical properties at local to global scales. To quantify the magnitude of these impacts, climate models need consistent land-cover change time-series at a global scale, based on land-use information from observations or dedicated land-use change models. However, a specific land-use change cannot be unambiguously mapped to a specific land-cover change. Here, ~~various~~ nine translation rules are evaluated based on assumptions about the way land-use change could potentially impact land-cover. Utilizing the Global Land use Model 2 (GLM2), the model underlying the latest Land Use Harmonization dataset (LUH2), the land-cover dynamics resulting from land-use change were simulated based on multiple alternative translation rules from 850 to 2015 globally. For each rule, the resulting forest cover, carbon density, and carbon emissions were compared with independent estimates from remote sensing observations, U.N. Food and Agricultural Organization reports, and other studies. The translation rule previously suggested by the authors of the HYDE 3.2 dataset, that underlies LUH2, is consistent with the results of our e~~Examinations at global, country, and grid scales indicate that the recommended translation rule for CMIP6 models is 1) completely clear vegetation in land-use changes from primary and secondary land (including both forested and non-forested) to cropland, urban land, and managed pasture; 2) completely clear vegetation in land use changes from primary forest and/or secondary forest to rangeland; 3) keep vegetation in land-use changes from primary non-forest and/or secondary non-forest to rangeland. This confirms the translation rules suggested earlier in the HYDE dataset underlying LUH2. According to this rule, contemporary global forest area is estimated to be 37.42·10^6 km², and forest area estimates at global and country scales both stay within the range derived from remote sensing products.~~

~~Likewise, the estimated carbon stock is in close agreement with reference biomass datasets, particularly over regions with 50% forest cover. This rule also mitigates the anomalously high carbon emissions from land-use change observed in previous studies in the 1950s.~~Examinations at global, country, and grid scales. This rule recommends that for CMIP6 simulations, models should 1) completely clear vegetation in land-use changes from primary and secondary land (including both forested and non-forested) to cropland, urban land, and managed pasture; 2) completely clear vegetation in land-use changes from primary forest and/or secondary forest to rangeland; 3) keep vegetation in land-use changes from primary non-forest and/or secondary non-forest to rangeland. Our analysis shows that this rule is ~~indicate that three~~one of ~~nine~~three (out of nine) rules that produce comparable estimates of forest cover, vegetation carbon and emissions to independent estimates, and also mitigate the anomalously high carbon emissions from land-use change observed in previous studies in the 1950s. According to the three translation rules, contemporary global forest area is estimated to be 37.42 10^6 km^2 within the range derived from remote sensing products. Likewise, the estimated carbon stock is in close agreement with reference biomass datasets, particularly over regions with more than 50% forest cover.

1 Introduction

Historical land-use activities have been significantly affecting the global carbon budget in both direct and indirect ways, and changing Earth's climate through altering land surface properties (e.g. surface albedo, surface aerodynamic roughness, and forest cover) (Betts, 2007; Bonan, 2008; Brovkin et al., 2006; Claussen et al., 2001; Feddema et al., 2005; Guo and Gifford, 2002; Pongratz et al., 2010; Post and Kwon, 2000). It has been estimated that, during the past 300 years, >50% of the land surface has been affected by human land-use activities, >25% of forest has been permanently cleared, and 10-44 10^6 km^2 of land are recovering from previous human land-use disturbances (Hurtt et al., 2006). Impacts on the carbon cycle result from several processes among others: deforestation removes natural forest and its corresponding carbon biomass is used for wood products, burning, or decay by microbial decomposition (DeFries et al., 2002). Afforestation/reforestation, in contrast, recovers forest which accumulates carbon but sequestration potential are constrained by water and nutrient availability (Smith and Torn, 2013). Wood harvesting is one of the largest source contributing gross carbon emission by modifying the litter input into various soil pools, stand age, and biomass of secondary forest (Dewar, 1991; Hurtt et al., 2011; Nave et al., 2010)~~–~~. Cumulatively, models estimate that land-use and land-use change have contributed to a net flux ~~190~~205 ± ~~75~~60 Pg C to the atmosphere during ~~1870~~1850-~~2017~~2018 (Friedlingstein et al., 2019)~~(Le Quéré et al., 2018)~~. While emissions from land-use and land-use change only account for 10% of current anthropogenic carbon emissions, they were a dominant contributor to increasing the atmospheric CO_2 above pre-industrial levels before 1920 (Ciais et al., 2014).

Quantification of historical Land-Use and Land-Cover Change (LULCC) is important because it serves as the basis for examining the role of human activities in the global carbon budget and the resulting impacts to Earth's climate system. For

this purpose, LULCC reconstructions enter Earth System Models (ESMs) (Lawrence et al., 2016), Dynamic Global Vegetation Models (DGVMs) (Friedlingstein et al., 2019) (Le Quéré et al., 2018) and bookkeeping models (Hansis et al., 2015) to quantify biogeochemical and biophysical impacts of historical land-use change as part of historical simulates (DECK and CMIP6 historical simulations), future projections (scenarioMIP), impacts studies (ISIMIP), paleoclimate studies (PMIP), land-use

5   specific simulations (LUMIP), and biodiversity studies (IPBES). Considerable efforts have been devoted to modelling historical land-use states (Goldewijk et al., 2017; Kaplan et al., 2009; Pongratz et al., 2008; Ramankutty and Foley, 1999) and land-use transitions (Houghton, 1999; Hurtt et al., 2006, 2011). In particular, the recent Land-Use Harmonization 2 (LUH2) dataset (Hurtt et al., 2017) has been developed to provide global gridded land-use states and transitions in a consistent format for use in ESMs as part of CMIP6 experiments. However, large uncertainties still exist in the carbon/climate studies based on

10   many of the above LULCC products (Chini et al., 2012; Houghton et al., 2012; Pongratz et al., 2014). For example, the Global Carbon Budget reports the spread of cumulative LULCC carbon emission during 1870 1850 2017 2018 estimated by DGVMs is as large as 75 60 Pg C though all models are forced by the LUH2 (Friedlingstein et al., 2019)(Le Quéré et al., 2018). LULCC carbon emissions in CMIP5 have an anomalous spike during the years 1950-1960. These anomalous emission estimates by ESMs (hereinafter referred to as the "pasture anomaly") are caused by an implausible high conversion rate of natural and

15   secondary vegetation to pasture, with the 1950s having double the conversion rate of the 40's or 60's. Because of this, the simulated terrestrial land flux has a two decade delay in the switch from a land carbon source to a land carbon sink compared to observations (Shevliakova et al., 2013).

One reason for the above uncertainties is the lack of a globally consistent rule that translate land-use change estimates into

20   land-cover changes, which is critical for ESM models (Brovkin et al., 2013; Di Vittorio et al., 2018, 2014; de Noblet-Ducoudré et al., 2012). Although land-use changes are generally associated with a change in land cover and carbon stocks, these two changes are not always equivalent (see Figure 1 in (Pongratz et al., 2018)), and the degree of land-cover alteration varies with the types of land-use changes and the location where a land-use change happens. For example, the conversion from forested land to managed pasture and/or cropland tends to be associated with the full removal of native vegetation due to intensive

25   human management, whereas vegetation may be less disturbed during the land conversion from non-forest (e.g. grassland) to rangeland. To enable the inclusion of such land-cover change processes, the HYDE 3.2 dataset has redefined the former pasture category used in CMIP5 into the two sub-categories of "managed pasture" and "rangeland" (with the total being termed "grazing land"). This redefinition intends to suggest different treatments of vegetation and carbon removal in ESMs and DGVMs for these two types of land-use changes (Goldewijk et al., 2017). However, explicit suggestions for land-cover and

30   carbon stock modifications resulting from these new defined land-use types are not yet provided, but are crucial for the translation of land-use change to land-cover change within ESMs or DGVMs. An inconsistent land-cover translation of these land use products within an ESM or DGVM will potentially produce very different land-cover dynamics, which will impact the land surface biophysical and biochemical processes. Therefore, a globally consistent rule for translating land-use products

~~to land-cover change could eliminate added uncertainties from translation inconsistency in studying land-use effects through ESMs and DGVMs.~~

Standardization of LULCC data is critical for CMIP6 to simplify inter-comparison of the ESMs and facilitate model analysis. The CMIP6 requires the LUH2 as standard land-use input for all ESMs, however, the data standardization could be undermined

5 if models implement the LUH2 differently such as applying different rules to translate the LUH2 into land-cover change, which is essential for models. Identifying the consistent rules between models for the LUH2 use is critical for two reasons. First, although land-use changes are generally associated with a change in land-cover and carbon stocks (see Figure 1 in (Pongratz et al., 2018)), these two changes are not always equivalent, and the degree of land-cover alteration varies with the types of land-use changes and the location where ~~a~~ land-use changes ~~happens~~. An inconsistent land-cover translation from the

10 same land-use products will potentially produce variance in land-cover dynamics across models, and in turn impact the land surface biophysical and biochemical processes. Second, the HYDE 3.2 underlying LUH2 has redefined former pasture category used in CMIP5 into the two sub-categories of "managed pasture" and "rangeland" (with the total being termed "grazing land"). This redefinition intends to mitigate the pasture anomaly by suggesting different treatments of vegetation and carbon removal in models for these two types of land-use changes (Goldewijk et al., 2017). However, explicit suggestions are

15 not yet provided for land-cover resulting from these newly defined land-use types. Therefore, a consistent rule across models for the LUH2 translation is needed with potential to reduce impacts of LUH2 use inconsistency on studying land-use effects through CMIP6.

To recommend a ~~a global~~ translation rule for translating historical land-use changes from the LUH2 for CMIP6 models, this

20 study investigates the impacts of land-use change on land-cover by proposing several alternative sets of translation rules, which are then integrated into the Global Land use Model 2 (GLM2) model (Hurtt et al., 2017, 2019) to simulate the forest cover and carbon dynamics. These simulations are then evaluated against estimates of contemporary forest cover and carbon density from remote sensing observations, and the resulting cumulative LULCC carbon emissions are compared with a range of independent estimates. ~~This recommended rule combined with LUH2 could improve estimates of forest area and carbon stock~~

25 ~~at global, country and grid-cell scales when compared to remote sensing data and reduce the 1950s pasture anomaly.~~

2 Methodology

In this study, two key land-cover properties (i.e. forest cover and vegetation carbon) are simulated by combining historical land-use change with translation rules. The historical land-use change information is specified by the LUH2 dataset (v2h, available at http://doi.org/10.22033/ESGF/input4MIPs.1127) which serves as the forcing data for a new generation of

30 advanced ESMs as part of CMIP6. Section 2.1 describes the details of land-use change characterization, and section 2.2 defines each translation rule. The resulting forest cover and vegetation carbon is tracked at each grid cell (0.25×0.25°) for the year 850 to 2015 using methods described in section 2.3 and 2.4. The simulated forest cover and vegetation carbon are then compared

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with multiple published datasets of land-cover , carbon stock, and estimates of land-use change emission (see details in section 2.5).

2.1 Land-use change characterization

The LUH2 dataset was generated with the GLM2 (Hurtt et al., 2017, 2019), which like its predecessors (Hurtt et al., 2006, 2011), estimates annual sub-grid-cell land-use states and transitions by including multiple constraints such as gridded patterns of historical land-use from the HYDE database (Goldewijk et al., 2017), historical national wood harvest reconstructions, potential biomass and recovery rates, and others. Building upon previous work from CMIP5, for which the original LUH1 dataset was used, LUH2 has extended the timespan to 850-2100 and increased spatial resolution to 0.25×0.25˚. In addition, LUH2 includes 12 different land-use types (i.e. forested and non-forested primary and secondary land, cropland of C3 annual, C3 perennial, C4 annual, C4 perennial and C3 nitrogen-fixing, urban, managed pasture and rangeland) and includes transitions between all combinations of these categories.

In LUH2, "primary" refers to land previously undisturbed by any human activities since 850AD, while "secondary" refers to land undergoing a transition or recovering from previous human activities. Global secondary land area was specified as zero in 850. Note that primary and secondary lands are further sub-divided into forested and non-forested grids using a definition based on the potential aboveground biomass density (forested land requiring an aboveground biomass density ≥ 2 kg C/m^2).

2.2 Translation rules

Nine translation rules are proposed (Table 1) to analyse the effects of land-use change on land-cover dynamics, whereby each rule differs in treatment of vegetation cover and vegetation carbon stock during land-use changes. Rules 1-4 all assume complete clearance of vegetation for cropland and vary on vegetation clearance for managed pasture and rangeland. The rules 5-9 are added for analytical purposes, rather than as realistic possibilities. For example, Rule 3 presumes all land-use changes alter land-cover and reduce carbon stock, and this rule would produce the least global forest cover and carbon stock. Rule 1 and 3 differ in treatment of vegetation in non-forested land when converted to rangeland, and the resulting difference between their carbon stocks indicate the impact of rangeland expansion on non-forests, and also tests whether the disaggregation of grazing land into managed pasture and rangeland will address the pasture anomaly issue in 1950-1960. Rule 1 (clearance of all vegetation for cropland and managed pasture, and only forest clearance for rangeland) is in fact the rule suggested in the underlying HYDE dataset and its distinction between pasture and rangeland (Goldewijk et al., 2017). For simplicity, we do not consider partial removal of vegetation in this study; vegetation is either fully removed or fully remains as these land-cover transitions represent the maximum and minimum bounds for land-cover alteration. In this study, the translation rules are applied to all regions and are constant across the whole simulation period. Although the impacts of land-use change on land-cover may vary in different regions, the discussion of region-varied and time-varied translation rules is beyond the scope of this study.

It is important to note that these nine rules are not equally realistic, and the purpose of including Rules 5-9 is to investigate individual or joint contributions of cropland, managed pasture and rangeland expansion on forest and carbon. For example, forest and carbon dynamic resulting from Rule 6 could suggest individual impact of cropland expansion.

5   2.3 Simulation of land-cover change

In this study, land-cover change is simulated by performing a modified GLM2 simulation in which the computed land-use transition rates (using the same methodology as LUH2) are supplemented with a set of translation rules (Table 1) to track forest cover change and carbon dynamics at 0.25º spatial resolution. Note that the modified GLM2 still generate and track the exact same land-use transitions of the LUH2 and has additional function to track associated land-cover change in terms of forest

10   cover and vegetation carbon. GLM2 uses a statistical model to estimate ecosystem stocks and fluxes with temperature and precipitation as inputs (see (Hurtt et al., 2002) for details). The annual temperature and precipitation maps from MSTMIP were averaged over 1901 and 2000 to generate the spatially varied and temporally static climatological temperature and precipitation, which was then used to spin up the GLM2 globally at 0.25x0. 25˚ resolution for 500 years. ~~Climatological temperature and precipitation during 1901-2000 were produced from the MSTMIP (Wei et al., 2014) and used to spin up the~~

15   ~~GLM2 globally at 0.25×0.25˚ resolution for 500 years.~~ The climatology stays as constant over the spin up period, and other environmental factors were not taken into consideration such as CO_2 fertilization, nitrogen limitation and climate variability.

When land is converted to cropland, managed pasture, and/or rangeland, each translation rule indicates that vegetation in primary and secondary may be cleared or remain intact as the result of land-use changes. For example, for a given land-use

20   transition rate from forest to pasture, if the applied translation rule indicates to clear the vegetation completely, then the resulting grid cell vegetation fraction in forest land-use type is reduced equal to the amount of pasture gained. If the rule indicates not to clear vegetation, then only the land-use type will be changed to pasture and the vegetation area will be unchanged, but the vegetation will be influenced by the management in terms of stand age/biomass, which are assumed to cease growing due to pressure from subsequent human management. If this pasture land is further converted to other non-

25   primary and non-secondary land (e.g. cropland, rangeland or urban), the vegetation remaining from previous forest-pasture conversion then will be totally cleared. Therefore, the vegetation fraction existing within the cropland, managed pasture, rangeland and urban of each grid-cell can be tracked via the following equation:

$$f(i, t + 1) = f(i, t) + f^{gained}(i, t) - f^{lost}(i, t), (i = 5,6,7,8) , \tag{1}$$

Where $f(i, t)$ is the fraction of grid-cell that is vegetated in land-use type i (i.e. classes 5-8: cropland, managed pasture,

30   rangeland, urban) at time t, $f^{gained}(i, t)$ and $f^{lost}(i, t)$ are gained and lost vegetation fractions respectively. The vegetation fraction could only be gained in land-use change from primary and secondary land (both forested and non-forested), and be lost in land-use change to any other land use types except forested and non-forested primary land.

6

$$f^{gained}(i,t) = \sum_{j=1}^{4} a_{ij}(1 - \gamma_{ij}), (i = 5,6,7,8; j = 1,2,3,4), \tag{2}$$

$$f^{lost}(i,t) = \frac{f(i,t)}{l(i,t)}\sum_{k=1, k \neq i}^{8} a_{ki}, (i = 5,6,7,8; k = 3,4,\cdots,8), \tag{3}$$

The possible values of i, j and k are 1, 2, ... , 8 representing primary forested land, primary non-forested land, secondary forested land, secondary non-forested land, cropland, managed pasture, rangeland and urban respectively. a_{ij} is the land-use transition fraction estimate by LUH2 from land-use type j (i.e. primary forested land, primary non-forested land, secondary forested land, secondary non-forested land) to land-use type i, γ_{ij} represents the translator factor to convert land-use change to land-cover change, it equals to 1 if the translation rule in Table 1 indicates an 'X' or 'F' for this land-use change. For example, γ_{ij} is 1 for land-use change from primary land (forested, non-forested grids) to cropland in Rules 1 and 2, but 0 for the same type of change in Rules 8 and 9. This translator factor is 1 for all types of land-use change in Rule 3 since all vegetation is cleared during all land-use changes. $l(i,t)$ is the land-use fraction estimate by LUH2 for type i at time t, and this fraction is larger than or equal to its vegetation fraction $f(i,t)$.

Vegetation in primary and secondary land can remain or be lost in land-use changes to cropland, pasture or rangeland depending on translation rules. According to the definition of primary land in the LUH2, its transition to other land-use types is unidirectional, thus primary land could not gain vegetation from any land-use changes. Wood harvest on primary land will result in vegetation loss and a change of land-use type to secondary land, but harvest on secondary land will not change the land-use type. Furthermore, vegetation in secondary land could be gained from harvest on primary land and may be gained through the process of abandonment of cropland, pasture or rangeland depending on translation rules. Note that reforestation but not afforestation is also considered in this study. The former is to re-establish forest on the land which has been forested before, while the latter is an anthropogenic activity to establish forests on land which has never been forested. Thus, the vegetation of primary and secondary land is tracked by the following equation:

$$f(i, t + 1) = f(i,t) - f^{lost}(i,t) + f^{gained}(i,t), (i = 1,2,3,4), \tag{4}$$

$$f^{lost}(i,t) = \begin{cases} \sum_{j=5}^{8} a_{ji}\gamma_{ji} + b_i, & (i = 1,2; j = 5,6,7,8) \\ \sum_{j=5}^{8} a_{ji}\gamma_{ji} & ,(i = 3,4; j = 5,6,7,8) \end{cases} \tag{5}$$

$$f^{gained}(i,t) = \sum_{k=5}^{8} \frac{f(k,t)}{l(k,t)} a_{ik} + b_j, (i = 3,4; j = 1,2; k = 5,6,7,8) \tag{6}$$

Where $f(i,t)$ is fraction of vegetation at land-use category i (primary forested land, primary non-forested land, secondary forested land, secondary non-forested land) at time t. a_{ji} is land-use transition fraction from primary and secondary land to cropland, managed pasture, rangeland and urban in LUH2. ~~γ_{ji} is the translator factor, as is γ_{ij} in Eq. 2; both indicate whether to clear the vegetation during land-use changes.~~ b_i or b_j is wood harvest fraction from primary or secondary (forested or non-forested) land. $f(k,t)$ and $l(k,t)$

are vegetation fraction and land-use fraction in land-use type k (i.e. cropland, managed pasture, rangeland, urban), and a_{ik} is land-use transition due to land-use abandonment.

2.4 Simulation of vegetation carbon dynamics

Vegetation carbon stocks fluctuate through releasing and accumulating carbon in response to natural growing conditions, disturbances, and anthropogenic land-use changes, which can vary widely in terms of their carbon impacts. For land-use changes associated with clearing or harvesting vegetation, the forest biomass is either released immediately (e.g. burning) or stored in soil pools or as timber products (both of which eventually decay over decades). However, when managed land is abandoned and allowed to recover, the vegetation takes up CO_2 from the atmosphere through photosynthesis, resulting in increasing carbon stocks in vegetation and possibly soils. The magnitude of each of these bi-directional carbon flows ultimately determine if the land is a net carbon sink or carbon source. In this study, the temporal dynamics of carbon fluxes after land-use change are simplified, with all biomass (above- and below-ground) being released instantaneously to the atmosphere. Note that the biomass stock change is a rough proxy of actual net land-use change fluxes, for which delayed emissions from litter and soil carbon and product pools needed to be accounted for as well as instantaneous emissions from burning biomass. Changes in soil carbon associated with loss of vegetation biomass are usually associated with carbon losses, but are likely less important than biomass changes, as are net fluxes from product pool changes (Erb et al., 2018).

Similar to land-cover change simulation in section 2.3, if translation rules indicate vegetation clearing at expansion of cropland, managed pasture, rangeland or urban land, vegetation biomass is totally released as a carbon emission, and its age is set as zero. If vegetation is not cleared based on translation rules, the biomass remains but ceases to increase, and the age of this vegetation also remains unaffected, because the age is used in this model only for the calculation of biomass density. Keeping age fixed corresponds to keeping biomass from further growing, which represents the influences of management. If the land is abandoned and converted back to secondary land, a mean age ~~are~~ is calculated over all vegetation with different ages, then the mean age increases year by year and biomass regrows towards equilibrium. Thus, the biomass density in secondary vegetation at time t is calculated for each grid cell using its mean age, potential biomass, and potential NPP:

$$B(t) = B_0\left(1 - e^{-NPP_0 \times G(t)/B_0}\right), \tag{7}$$

Where $B(t)$ is the aboveground biomass density of vegetation at secondary land at time t, and B_0 is the potential aboveground biomass density from the GLM2 model and varied by grid location, and NPP_0 is the potential NPP of the wood fraction that is allocated to cumulate stem and branch biomass annually, and $G(t)$ is the mean age of secondary vegetation. Note that B_0 and NPP_0 ~~is~~ are estimated by a statistical model in GLM2 using climatological temperature and precipitation and are spatially varied but temporally constant over simulation period ~~from~~ of 850 to 2015. Above- to below-ground biomass ratio is assumed as 3:1 when converting aboveground biomass to total biomass (above- and belowground), and biomass density is converted to carbon by a ratio of 0.5.

Plants cultivated by human management (e.g. crops and orchards) are not tracked in this study; zero biomass is assigned to cropland, managed pasture, rangeland and urban use types. However, carbon is tracked for vegetation remaining from primary or secondary due to the translation rules, as well as lands that convert from human management back to natural lands. Thus, the total carbon stocks in this study are expected to be lower than other estimates (Houghton, 2003; Saatchi et al., 2011), especially in the grids with a higher fraction of non-primary and non-secondary land-use.

2.5 Diagnostics for evaluating translation rules

To evaluate which translation rules best translate land-use changes to land-cover changes, the simulation results were compared with contemporary forest cover and carbon density maps from remote sensing observations and other estimates, as well as LULCC carbon emissions from other studies using different models. Contemporary values of forest cover and carbon density are used for two reasons. First is the lack of multiple diagnostics of forest cover and carbon density across the whole simulation period (i.e. 850 to 2015). Second is that contemporary values could potentially reflect cumulative error in converting land-use change to land-cover change since 850. We assume that if a translation rule produces a best match with the diagnostic maps of forest cover and carbon density, then it would also produce the best estimate for the historical period.

Diagnostics of contemporary forest cover consist of six widely used satellite-based land-cover and tree coverage datasets (Bartholomé and Belward, 2005; Bicheron et al., 2008; DeFries et al., 2000; Friedl et al., 2010; Hansen et al., 2010; Loveland et al., 2000) (see Table 2) and the Global Forest Resources Assessment (FRA) 2015 (FAO, 2015). In Table 2, GLC, GLC2000, GlobCover and MODIS LC are land-cover datasets rather than tree cover and were produced based on different classification schemes resulting in different land-cover legends. Prior to being used as diagnostics in this study, they needed further reclassification of their land-cover legends into a common representation of forest canopy cover at the same spatial resolution (0.25˚) by the following procedures: First, the GLCC, GLC2000, GlobCover and MODIS LC were converted to tree cover fraction based on Table S1 at their native resolutions (Song et al., 2014). Then, all six datasets were resampled to 1 km resolution and translated to a binary (forest versus non-forest) map by applying a 30% tree-cover threshold (Sexton et al., 2016). Through counting the percentage of pixels marked as forest within each 0.25x0.25˚ grid cell, six global gridded forest cover maps at 0.25º spatial resolution were generated, and resulting global forest area of each dataset are shown in Table 2. As these satellite-based datasets were developed from different sensors (e.g. AVHRR, SPOT-4, MERIS, MODIS, Landsat) and models (regression trees, decision tree, clustering labels and random forests), an averaged map (hereinafter referred to as 'Averaged satellite-based forest cover') was generated in accompany with the six forest cover maps to examine spatial pattern of contemporary forest cover simulated by each translation rule. In addition, since FAO only reports national forest cover (not spatially explicit), these data were only used for comparison at the country level.

Carbon density maps are employed as the second metric to evaluate the translation rules. Two datasets were employed: the IPCC Tier-1 biomass carbon map for the year 2000 (Ruesch and Gibbs, 2008) and a pantropical biomass map (hereinafter referred to as the Baccini's product (Baccini et al., 2012). The former, a global above- and below-ground carbon density map, is created by dividing the globe into 124 carbon zones by land-cover, continental regions, eco-floristic zones, and forest age

5 and assigning each zone a unique carbon stock value. The latter is estimated by combining ground plots, GLAS LiDAR observations and optical reflectance of MODIS. This dataset employs the empirical relationship between aboveground biomass and tree diameter at breast height and estimates aboveground biomass density for pantropical regions (40˚S-30˚N). Both carbon density maps were resampled to 0.25˚ before evaluation.

10 In addition, the ability of the translation rules to reproduce LULCC carbon emissions is also assessed. The estimates of LULCC carbon emissions were compiled from published papers (Table 3) (Houghton, 2010; Houghton and Nassikas, 2017; Le Quéré et al., 2018; Pongratz et al., 2009; Reick et al., 2010; Shevliakova et al., 2009; Stocker et al., 2011). These studies have significant discrepancy in emissions estimates as they employed various methods (e.g. book-keeping methods and different process-based models), LULCC datasets, and considered different types of land-use change activities. They also differ in

15 treatment of environmental change, for example, (Pongratz et al., 2009; Reick et al., 2010; Shevliakova et al., 2009; Stocker et al., 2011) include effects of evolving climate or atmospheric CO_2 concentration on LULCC emissions, which is not accounted for in bookkeeping model based studies (Houghton, 2010; Houghton and Nassikas, 2017). In this study, only the range of these estimates during the pre-industrial and industrial periods are chosen to evaluate the translation rules. We posit that the recommended translation rule should not produce anomalous carbon emissions that are outside the compiled range.

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In summary, the GLM2-based estimates of forest cover and carbon density in the year 2000 and LULCC carbon emissions during the periods 850-1850 and 1850-2000, based on nine different translation rules are compared with the above three types of diagnostics (i.e. contemporary forest cover/area and carbon density maps, LULCC emissions). The final recommended translation rules should produce: 1) the forest cover with the smallest difference with diagnostic maps at global, country and

25 grid scale, the total forest cover at global and country level should be comparable to the range of diagnostics, and spatial pattern should also be closed to diagnostics; 2) the closest carbon density map compared to diagnostics with the smallest difference, comparable spatial pattern and total carbon stock as well; and 3) reasonable LULCC carbon emissions within the range from other diagnostic estimates and minimizing the anomalous emissions during 1950-1960. Finally, if several rules have a reasonably good fit to these three diagnostics, other criteria, such as the definition characteristics for managed pasture and

30 rangeland has handled in HYDE (Goldewijk et al., 2017) will also be taken into account in identifying the recommended rule.

3 Results

3.1 Potential forest cover and biomass carbon

The GLM2 estimates global vegetation carbon stock (including above- and belowground) in 850 as 718 Pg C, and the resulting potential biomass map is shown in Figure 1a. For comparison, global potential vegetation carbon stock was estimated as 557

5 Pg C in (Kucharik et al., 2000), 772 Pg C in (Pan et al., 2013) and 923 Pg C in (Sitch et al., 2003). Forested land in GLM2 is defined as land which has aboveground potential biomass of at least 2 kg C/m^2 (Hurtt et al., 2006, 2011). With this definition, global potential forest area was estimated as 47.82 million km^2, and the resulting potential forest cover map is shown in Figure 1b. For comparison, global potential forest area was estimated as 48.68 million km^2 in (Pongratz et al., 2008), and potential forests and woodlands area was 55.3 million km^2 in (Ramankutty and Foley, 1999).

10 ### 3.2 Forest cover evaluation

The global gridded forest cover maps resulting from Rules 1-~~4~~ 9 in 2000 are generally consistent in forest extent with satellite-based observations (shown in Figure 2 and Figure S6). For example, they all estimate high forest cover in tropical rainforests and northern boreal forests but low cover in Western USA, Eastern Europe and Central Asia. As Rules 1, 2, and 3 only differ in whether to clear vegetation and carbon in the conversion from non-forest to pasture or rangeland, the forest cover resulting

15 from Rules 1, 2, and 3 are the same. All rules of 1-~~4~~ 9 consistently estimate higher forest cover than the averaged satellite-based forest cover in West Siberia and South China, and lower forest cover in African savannas and East Siberia, Western Mexico and Argentina. Separately, Rules 4, 6, 7, 8 and 9 shows larger forest cover than Rules 1, 2, 3 and 5~~3~~ in South and Southeast of Brazil and Tiber in China. ~~The spatial pattern of negative bias in estimated forest cover of Rules 1-4 well corresponds to where the GLM2 model and Satellite-based datasets disagree the presence of forest.~~

20

The total area of global forest in 850 amounts to 47.82 million km^2 according to the GLM2 model (Figure 1b and Figure 3a) when all forested lands were in a primary state by definition and decreased thereafter (Figure 3a). Forest loss has accelerated since the beginning of the Industrial Revolution and shows relatively high annual change rates (shown in Figure 3c). The translation rules produce a wide range of global forest cover in 2000 from 37.42 to 45.89 million km^2. In Rules 1, 2, and 3, the

25 global forest is lost at the highest rate due to all land-use change activities on forested land resulting in the clearing of forest, and only 37.42 million km^2 of global forest is left in 2000 under these three rules. In contrast, under Rule 4 forest remains during rangeland expansion, and this would result in greater forest cover (e.g. 41.80 million km^2 in 2000, Table 4). The forest losses in Rules 6, 8, and 9 indicate the individual contribution of cropland, manged pasture and rangeland expansion. For example, rangeland and cropland expansion results in the most and second most of forest loss with an area of 4.34 million km^2

30 and 4.06 million km^2 respectively during 850-2000.

Six satellite-based forest cover datasets and FAO data report the global forest area around the year 2000 ranging from 35.66 to 42.74 million km^2. One of major reasons underlying the discrepancy in global forest area is the difference in defining 'forest', particularly in the regions with intermediate tree cover (Sexton et al., 2016). The global forest area in the year 2000 resulting from the translation rules are compared to the range of seven diagnostic estimates (Figure 3b). The forest cover based

5 on Rules 6, 8 and 9 is beyond the range of the diagnostics, indicating that these rules underestimate the impacts of land-use change on land-cover and overestimate the global forest existing in the present day. The excessive remaining forest cover in these three rules also rejects these rules' assumptions that only a particular type of land-use change would alter the land-cover. In contrast, Rules 1-4, 5 and 7 produced estimates of global forest area within the range of diagnostics.

10 The forest cover estimation from translation rules are further compared with diagnostic datasets at the country level (Table 4). In the diagnostic forest cover datasets, three-fourths of global forest cover lies within eight countries: the Russian Federation, Brazil, Canada, United of States of America, China, Democratic Republic of the Congo, Indonesia and Peru. The forest cover estimates from Rules 1-4 are generally well within the range of diagnostics. For example, 6 of 8 countries have estimates within the range for Rules 1, 2, and 3, and 5 of 8 countries for Rule 4 ~~for most of the eight countries (e.g. Brazil, Indonesia,~~

15 ~~and United States of America) in terms of forest area and slightly overestimated in the Russian Federation and Canada, where the estimates of Rules 1-3 are closer to the upper bound of the diagnostics than Rule 4~~. China and Brazil are the two countries where Rules ~~1-4~~ 1-3 and Rule 4 ~~shows~~ have relatively larger difference ~~in~~ between their estimates, ~~forest area and~~ the difference between Rules 1, 2, 3 and Rule 4 are 1.17 million and 1.08 million for China and Brazil respectively. Rule 5 and 7 overestimated forest area of China, Russian Federation and Canada though their global forest areas are within the range of diagnostic and are

20 within range for Brazil, Democratic Republic of the Congo, Indonesia, and Peru.~~.~~

These comparisons evaluate the resulting gross forest cover of the translation rules at global and country level. Further examination at the grid level is also needed. Since the FAO report only provides national forest cover, the averaged satellite-based forest cover map and each of the six satellite-based forest cover maps were used to calculate the average of absolute

25 difference across global grids (Figure 4) respectively. Rules 1, 2, and 3 consistently produce the smallest overall difference than Rule 4 and other rules regardless of which satellite-based forest cover is chosen as the reference. The average absolute difference (AAD) of Rule 1, 2, 3 is under 90 km^2 comparing to the averaged satellite-based forest cover map, and even smaller comparing to the GFC. The smallest difference of all rules across six reference forest maps indicate the GLC2 may have more similar spatial distribution to~~with~~ the GLM2 estimate. Regional comparison of average of absolute difference (Figure S1)

30 suggests Rules 1, 2, 3 give better estimate of forest cover at the north and south temperate zones (i.e. 60°N ~ 23°N and 23°S ~ 60°S) than tropical zone (23°N ~ 23°S). All rules have similar AAD at 60°N ~ 90°N zone.

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3.3 Evaluation of carbon dynamics

The net carbon emissions of the nine translation rules were calculated over two periods (850 to 1850 and 1850 to 2000) and compared to other studies (Table 5). Rules 1-4 produced similar patterns to other studies, specifically that global carbon emissions of 1850-2000 are twice as large as that of 850-1850. However, the emissions estimates of each period varied among

5 Rules 1-4, from 55 to 77 Pg C during 850-1850 and from 142 to 185 Pg C during 1850-2000, due to the assumptions for clearing vegetation during land-use change. For example, Rule 3 produced the largest emissions as the carbon in both forested and non-forested land is released for all land-use changes, and Rule 1 produces fewer emissions since the vegetation is not cleared and carbon is not released when non-forested land is converted to rangeland. In general, Rule 1, 2, 3 and 4 estimated comparable emissions with other studies, while the emissions of the Rules 6-9 are out of range (Table 5).

10

Carbon emissions from pasture expansion were calculated for LUH1 (Hurtt et al., 2011) and this is used as a baseline to assess the improvement of translation rules on the pasture anomaly. Rules 1-4 estimate fewer emissions during this decade and decrease the anomaly between 4 to 10 Pg C. Rule 1 reduces anomalous emissions by 6 Pg C, indicating the sole contribution of the LUH2 to mitigate pasture anomaly. In LUH1, the anomalous emissions spike during 1950-1960 mainly arises from

15 overestimating the emissions from pasture expansion, especially in three regions (i.e. Africa, East, South and Central Asia, and North America). The carbon flux from expansion of managed pasture and rangeland in LUH2 was reduced at global (Figure 5) and regional (Figure 6) scales in simulations based on Rules 1, 2, and 3. Note that the pasture land in LUH1 corresponds to rangeland and managed pasture together in LUH2. Rule 2 reduces more anomalous emissions than Rule 1 (reduced 6 Pg C in Rule 1 and 7 Pg C in Rule 2), because Rule 1 completely clears vegetation when transitioning to managed

20 pasture, whereas Rule 2 only removes vegetation if the preceding land cover is primary or secondary forest.

Rules 1-4 generally capture the spatial pattern that carbon density in tropical rainforest regions is much higher than northern boreal forests (Figure 7). These four rules overestimate carbon density at high latitudes of the Northern Hemisphere, in South China and in the Amazon rainforests but underestimate density across much of Sub-Saharan Africa, Mexico and the

25 Southwestern part of the United States (Figure S2 and Figure S3). To further examine the spatial pattern of estimated carbon density, the estimates from all rules were compared to the carbon density maps of IPCC Tier-1 (above- and belowground) globally and the Bacchini's dataset (only aboveground) at the pantropical scale by calculating averaged absolute difference (Figure 8). According to this comparison, Rules 1-3 best capture the carbon density heterogeneity globally (Figure 8). Regional comparison of the IPCC Tier-1 biomass map and rule estimates indicate Rules 1-4 have comparable AAD of carbon density

30 at the zone of 90°N ~ 60° N, the AAD difference between four rules is largest at 23°S ~ 60°S, followed by 23°N ~ 23°S and 23°N ~ 60°N (Figure S4). Carbon density estimates of Rules 1-3 were further examined at regions where their estimates have difference (shown in Figure S5a). The spatial pattern (Figure S5c-S5f) and histogram (Figure S5b) of carbon density difference between rules and IPCC Tier-1 biomass estimates shows that all of these three rules underestimate carbon density and more

grids are less underestimated in Rules 1-2 than Rule 3. The underestimation is expected because biomass of human cultivated vegetation is not tracked, and nor is growth of natural vegetation on cropland and pasture and rangeland. However, uncertainty level of the IPCC Tier-1 biomass should be taken into account when determining rule performance. Three bias levels of IPCC Tier-1 biomass map (i.e. ±10%, ±20% and ±30%) were considered (Figure S5b). At these levels of uncertainty in the reference,

5 Rules 1-3 could not be distinguished in performance. Finally, the carbon stock comparison between Rules 1-3 (Figure 9) shows these three rules underestimate carbon stock at low forest fraction, but give better agreement with diagnostics as forest fraction increases.

4 Discussion and Conclusions

This study quantified the result~~s~~ of multiple alternative translation rules for estimating the potential effects of land-use change

10 on land-cover utilizing the LUH2 dataset, and the underlying land model embedded in it (GLM2). The evaluations of forest cover and carbon ~~at both global, country and grid level jointly~~ indicate that Rules 1-3 on average and globally outperform other rules and are able produce the closest estimates of contemporary forest cover and carbon to ~~global~~ diagnostics. The evaluations also confirm that prior recommendation of translation rule from HYDE 3.2 (Goldewijk et al., 2017) corresponding to the Rule 1 could produce comparable estimates of forest cover and vegetation carbon relative~~s~~ to diagnostics. Differentiation between

15 Rules 1-3 depends largely on estimates of ~~forest~~ vegetation carbon because these rules produce equivalent estimates of forest cover. Comparisons of carbon stock and gridded difference in carbon density have shown that Rule~~s 1~~2 ~~and 2~~ produce~~s~~ ~~better~~ closer estimates of carbon density than Rule~~s~~ 1 and 3 relative to diagnostics~~references~~. However, given underlying uncertainty of the carbon density reference map, the difference between Rules 1, 2 and ~~3~~3 is small implying the differentiation of these rules is not possible in this study based on the difference alone~~Factoring in the uncertainty in the carbon density reference~~

20 ~~map~~. ~~, and prior recommendation from HYDE 3.2 (Goldewijk et al., 2017), Rule 1 is recommended for model implementation, namely removes all vegetation when establishing cropland, urban land, or managed pasture, and leaves all vegetation when establishing rangeland only if the land is previously non-forested.~~

A key feature of this study is to explicitly link land-use change and land-cover change and to provide~~s~~ insights into the

25 consequences of ~~rule choices of~~choosing different land-use translation rules in ESMs. This study quantitively characterizes historical land-cover change using the same underlying model of the LUH2, namely the GLM2. Estimates of forest cover and vegetation carbon between translation rules could provide information about sensitivities of ESMs to the LUH2 implementation. For example,

30 ~~A key feature of this study is to explicitly link land-use change and land-cover change and to suggest a suitable method to incorporate the LUH2 land-use transition dataset into ESMs and DGVMs. With recommended translation rule from this study and the LUH2, historical land-cover change could be reconstructed over the period of 850-2015~~focus on LUH2 implementation

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in CMIP6 models. With Rules 1-3, and the LUH2, historical land-cover change could be reconstructed over the period of 850-2015 and and the resulting the resulting contemporary forest cover and carbon density are comparable to independent estimates. Furthermore, this study also provides insights into the potential discrepancy in LULCC emissions estimates from ESMs/DGVMs if different rules are implemented.uncertainty attribution of LULCC emissions estimates from ESMs and DGVMs. Table 4 despite of same land-use transitions from the LUH2, in this study indicates choices of RRules 1-4 could result in a difference of 43 Pg C in still have a difference of 43 Pg C in LULCC emissions during 1850-2000 for the same model. ThisSuch difference solely from land-use translation accounts for about 24% of the range of estimated vegetation carbon changes during 1850-2005 between CMIP5 models The CMIP5 models estimate vegetation carbon changes during 1850-2005 in a wide range of -151 to +27 Pg C, which is contributed by different implementations of land-use change as well as inter-model uncertainty of strength of the CO_2 fertilization (Jones et al., 2013). Another feature is the relatively extensive evaluation of the LUH2 translation with multiple diagnostic datasets. The diagnostic datasets used in this study could serve to evaluate ESMs such as forest cover range at global and country level. Besides, this study also emphasizes the necessarity of improving vegetation carbon estimates, especially in regions with low forest cover or vegetation carbon in order to further differentiate translation rules. Table 4 in this study indicates differences in choice of Rules 1-4 result in an uncertainty of 43 Pg C in LULCC emissions during 1850-2000 and it is about 24% of the uncertainties in estimates of vegetation carbon changes in CMIP5. Therefore, in addition to uncertainties stemming from inter-model difference in potential vegetation cover and biomass as well as effects of CO_2 fertilization, an added uncertainty of 43 Pg C could be expected in CMIP6 solely from inconsistent choices in Rules 1-4 and it could be larger when other rules are implemented.

In additional to the nine rules designed in this study, many other designs of translation rules designs are possible for LUH2 implementation in CMIP6 models such as spatially or temporally varied rules. It is important to note that the designed translation rules of this study are spatially and temporally constant meaning land-use changes at different regions or years will result in the same land-cover change for a given translation rule and given land-use transitions. This simplification may result in errors in land-use change translation because impacts of land-use change on land-cover could vary by regions and time. Combination of spatially/temporally varied rules and LUH2 may produce better estimates of forest cover and carbon density than these nine rules of this study. However, spatially/temporally varied translation rules will potentially add complexity to the LUH2 implementation in ESMs. Meanwhile, identification of such rules is sophisticated and also , and it requires diagnostics with historical coverageless uncertainty. Uncertainties in these diagnostics should be small enough in order to differentiate various translation rules. and historical coverage, especially in carbon density maps which are not available.

The estimated forest cover and carbon dynamics are subject to the several assumptions being made,
When considering translation rules, it is important to note that the results of this study may depend on the the land-use change dataset being used, the land-cover properties being evaluated, reference datasets, and the models. This study used the LUH2

dataset because of its required used in CMIP6 and widespread used in other studies. The land cover properties addressed here include two critical variables (i.e. forest cover and carbon stock) due to their biophysical and biogeochemical significance. Multiple datasets based on remote sensing and other sources were selected for evaluation with the intention to provide a robust reference. The use of GLM2 model was selected to provide the most internally consistent treatment of these issues given its

5   role in producing the LUH2 dataset. Given these considerations, it is possible that different results could be obtained for different systems. Although multiple of satellite-based land-cover datasets were included, they disagree the presence or absence of forest over low forest cover regions such as shrublands and semi-arid savannahs, and the discrepancies due to technical challenges and disagreement of forest definition. In addition, global vegetation carbon mapping is still challenging and uncertain mainly because of indirect proxies of biomass and paucity of in situ measurements and observations from space.

10   ~~Combined uncertainties from forest cover and~~Uncertainties in vegetation carbon diagnostics ~~may~~ limit the evaluation of translation rules such as differentiation of Rules 1-3~~, especially in locations where forest cover or vegetation carbon is low~~. Furthermore, dynamics of forest cover and vegetation carbon from past to present interact with climate change and increasing atmospheric CO_2, which are not considered in this study. Finally, the carbon emission estimates using the same translation rules and land-use change dataset may be different using other ~~carbon models~~ESMs/DGVMs.

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Future research is needed to investigate both the robustness of these findings, and potentially identify even better implementations. The CMIP6 LUMIP study is designed to quantify some of these effects (Lawrence et al., 2016) through model inter-comparison. Additional work on translation rules should include possible spatial/temporal varying rules, partial land clearing, and more land cover variables (e.g. forest age, height, soil carbon, energy balance) and focus on ~~differentiation~~

20   ~~of~~Rules 1-3 differentiation with better diagnostics such as ~~the~~ annual land-cover maps from ~~the~~ ESA Climate Change Initiative (CCI) (Lamarche et al., 2017) and lidar-based aboveground biomass from NASA's Global Ecosystem Dynamics Investigation (GEDI) mission (Dubayah et al., 2020).~~..~~

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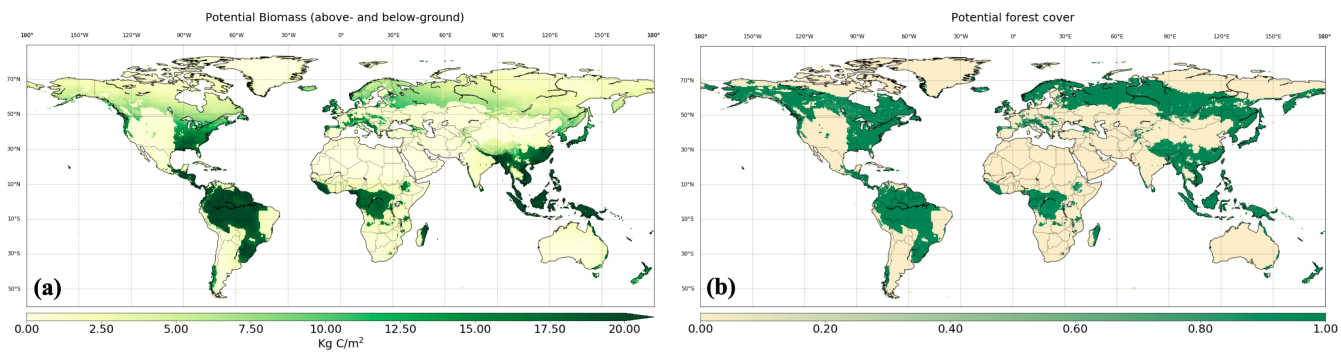25

Figures & Tables

Figure 1. Potential biomass density (a) and potential forest cover (b) in 850 estimated by GLM2 model.
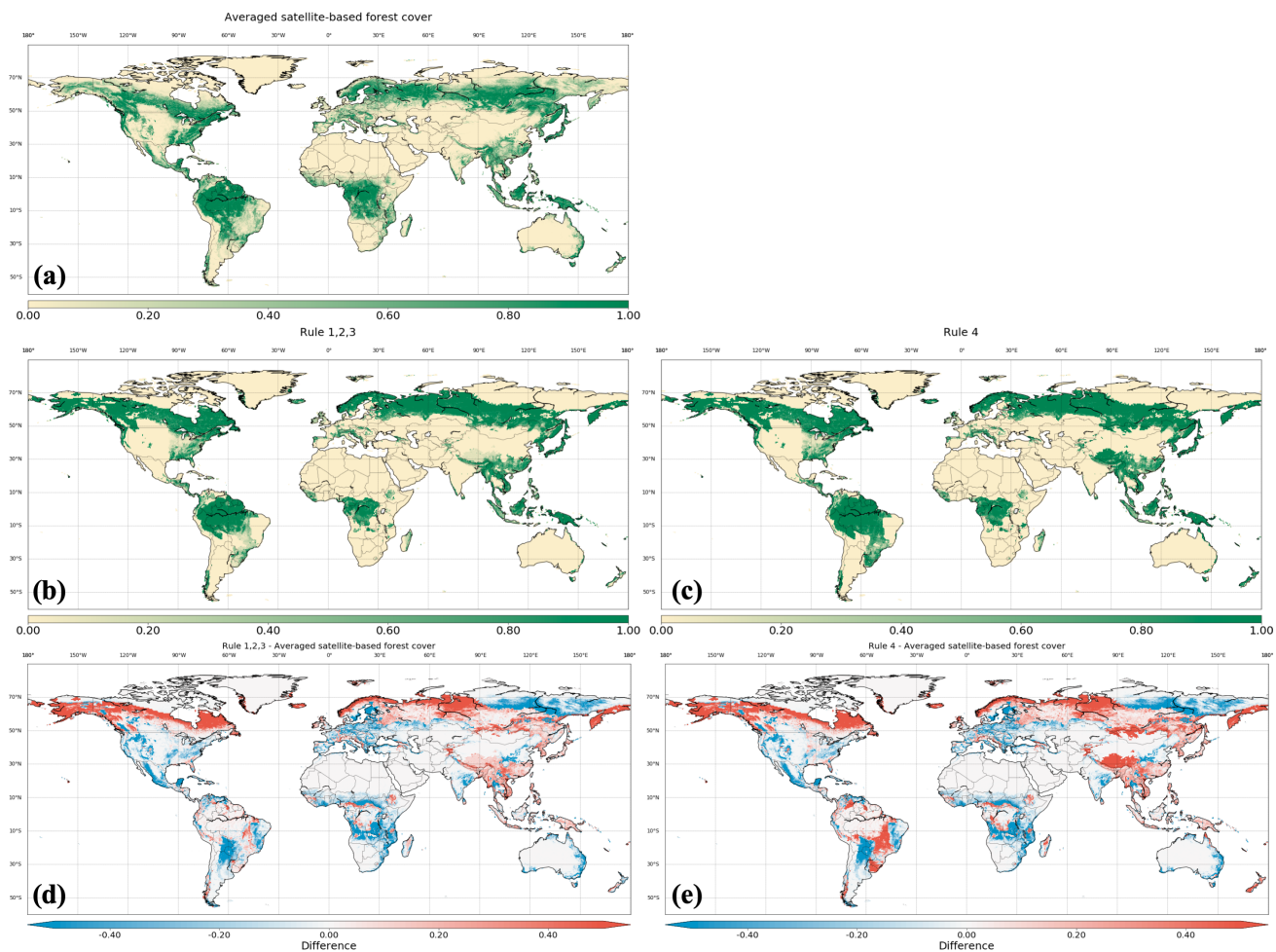
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Figure 2. Forest cover in 2000 from the Averaged satellite-based forest cover in (a), Rule 1, 2, 3 in (b) and Rule 4 in (c). (d) and (e) are maps of forest cover difference between (b) and (a), and (c) and (a) respectively.

Table 1. Rules for vegetation clearance during cropland, pasture and rangeland expansion. 'X' indicates complete removal of vegetation if the primary and secondary land state is altered. 'O' indicates no vegetation removal when land-use change occurs. 'F' indicates that vegetation is only removed if the preceding land cover is forested primary or forested secondary land.

5

Transition Rule	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6	Rule 7	Rule 8	Rule 9
->Crop	X	X	X	X	X	X	O	O	O
->Managed pasture	X	F	X	X	O	O	X	X	O
->Rangeland	F	F	X	O	X	O	X	O	X

Table 2. Summary of land cover products used in this study including six satellite-based datasets and FAO FRA report.

Product	Global Forest Area (10^6 km^2)	Time	Publication	Data Type/Classification Scheme
GLCC	40.89	1992-1993	Loveland et al. 2000	Land Cover (IGBP)
GLC2000	38.22	1999-2000	Bartholome et al. 2005	Land Cover (GLC 2000)
GlobCover	35.66	2004-2006	Bicheron et al. 2008	Land Cover (GlobCover)
MODIS LC	41.05	2001	Friedl et al. 2010	Land Cover (IGBP)
1 Kilometer Tree Cover Continuous Fields (TCCF)	42.74	1992-1993	DeFries et al. 2000	Tree Percentage
Global Forest Change (GFC)	41.71	2000	Hansen et al. 2010	Tree Percentage
FAO	40.55	2000	FRA 2015	National Censuses

Table 3. Summary of carbon emissions due to LULCC from available studies at pre-industrial and industrial period.

| Reference	Time span	Carbon Emissions (Pg C)	LULCC types
Pre-industrial Period			
Reick et al., 2010 (bookkeeping model)	1100-1850	80	Cropland/Pasture Change
Reick et al., 2010 (DGVM)	1100-1850	47	
Pongratz et al., 2009	850-1850	53	Cropland/Pasture Change
Stocker et al., 2011	until 1850	69	Cropland/Pasture Change, Urban
Industrial Period			
Houghton 2010	1850-2005	156	Cropland/Pasture Change, shifting cultivation in tropics, and wood harvest
Houghton and Nassikas, 2017	1850-2015	145	Cropland/Pasture Change, shifting cultivation in tropics, and wood harvest
Shevliakova et al.,2009	1850-2000	164 - 188	Cropland/Pasture Change, shifting cultivation in tropics, and wood harvest
Pongratz et al.,2009	1850-2000	108	Cropland/Pasture Change
Reick et al.,2010 (bookkeeping model)	1850-1990	153	Cropland/Pasture Change
Reick et al.,2010 (DGVM)	1850-1990	110	Cropland/Pasture Change
Stocker et al., 2011	1850-2004	164	Cropland/Pasture Change, Urban
Le Quéré et., 2018	1850-2014	195	Cropland/Pasture Change, shifting cultivation in tropics, and wood harvest
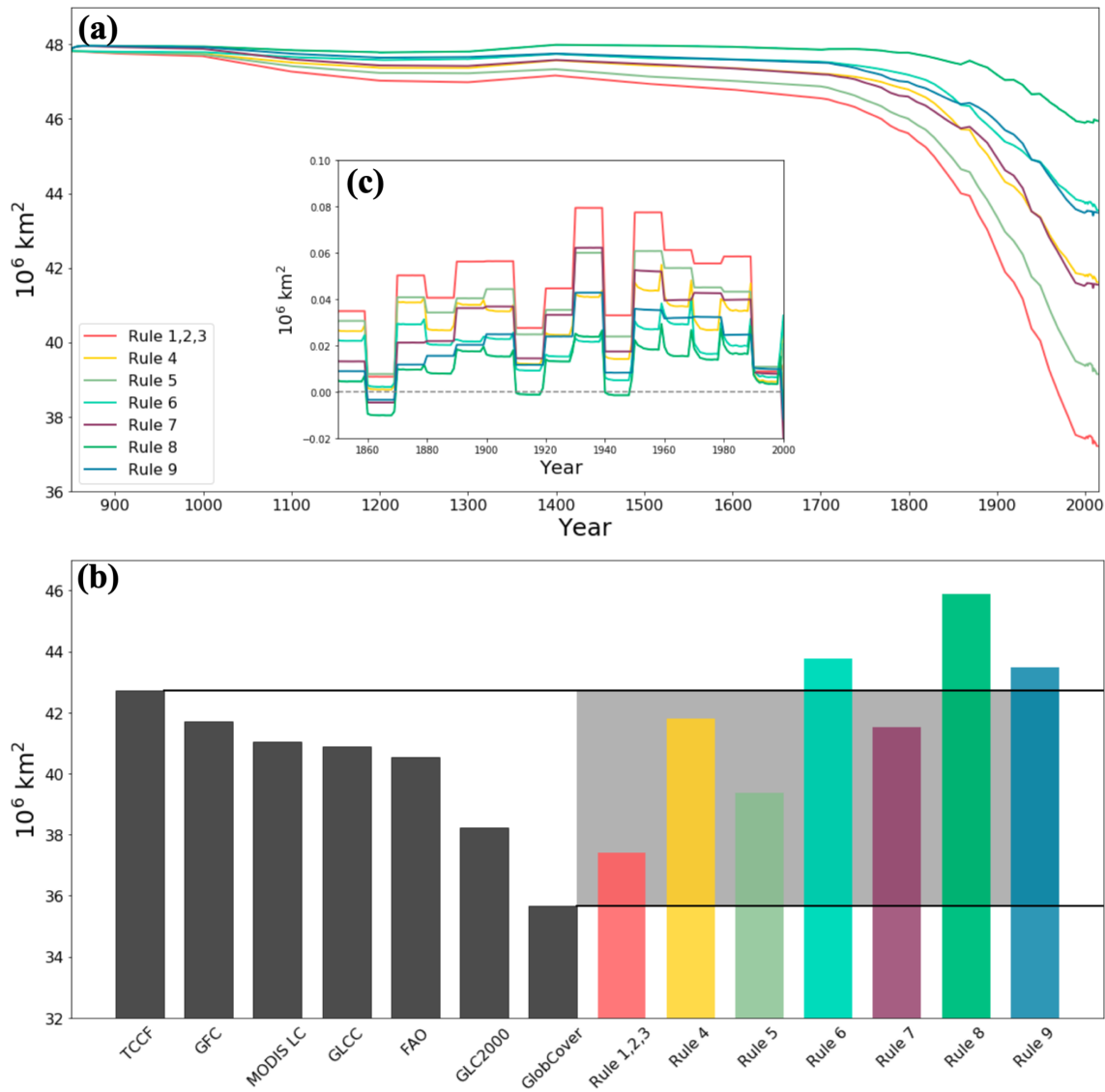
Figure 3. (a) Global forest area resulting from translation rules from 850 to 2015; **(b)** Comparison of global forest area in 2000 between remote sensing and FAO (shown as black bars) and results of translation rules (colored bars); **(c)** Annual change rate from 1850 to 2000. Positive value indicates the forest loss.

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Table 4. Forest area (10^6 km^2) in 2000 of eight countries with the largest forest area, and all other countries combined ('Others'), estimated by the 9 translation rules, range compiled from satellite-based datasets and FAO report.

| Country	Forest Area (10^6 km^2)							Range from satellite-based products and FAO
	Rule 1, 2, 3	Rule 4	Rule 5	Rule 6	Rule 7	Rule 8	Rule 9	
Russian Federation	8.72	9.15	8.80	9.23	9.01	9.44	9.10	6.65-8.62
Brazil	4.61	5.69	4.89	5.96	5.05	6.12	5.33	4.19-5.92
Canada	5.59	5.63	5.59	5.64	5.76	5.81	5.77	3.27-4.36
United States of America	2.81	2.94	3.06	3.19	3.62	3.76	3.87	2.65-3.36
China	2.04	3.22	2.44	3.61	2.45	3.63	2.85	1.34-2.14
Democratic Republic of the Congo	1.57	1.61	1.60	1.64	1.63	1.67	1.66	1.57-2.11
Indonesia	1.30	1.33	1.36	1.38	1.58	1.60	1.64	0.99-1.64
Peru	0.76	0.78	0.78	0.80	0.77	0.79	0.79	0.69-0.79
Others	10.02	11.47	10.86	12.31	11.63	13.08	12.48	12.21-17.08
World	**37.42**	**41.80**	**39.38**	**43.76**	**41.52**	**45.89**	**43.48**	**35.66-42.74**

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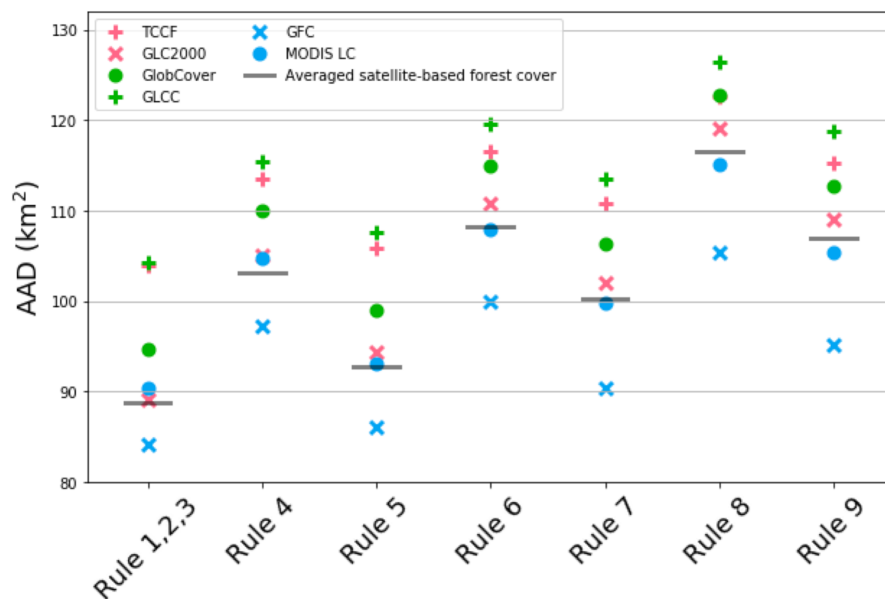
Figure 4. Global average of absolute difference in forest area between maps estimated by translation rules, and each of the six satellite-based forest cover maps as well as the averaged satellite-based forest cover map.

Table 5. Summary of LULCC carbon emissions estimated by the 9 translation rules and those from other studies in Table 3

Translation Rule	Carbon Emissions Estimation (Pg C)			Emission Range from Table 3		Estimation using LUH1
	850-1850	1850-2000	1950-1960	850-1850	1850-2015	1950-1960
Rule 1	72	175	20			
Rule 2	70	170	19			
Rule 3	77	185	22			
Rule 4	55	142	16			
Rule 5	63	146	17	47-80	108-195	26
Rue 6	41	104	11			
Rule 7	28	107	13			
Rule 8	5	65	7			
Rule 9	13	67	7			

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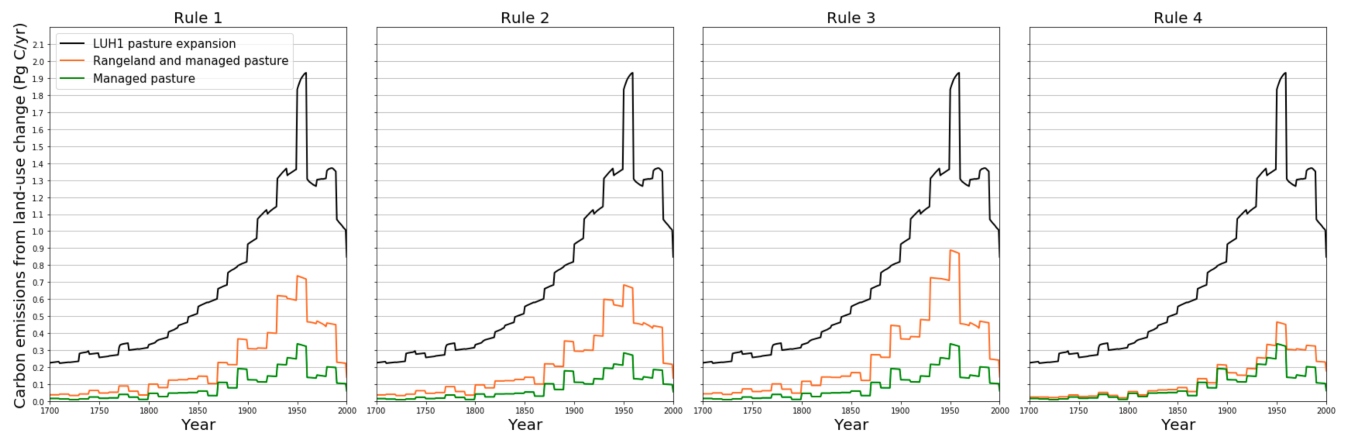
Figure 5. Carbon emission due to vegetation (forests and non-forests) removal in expansion of managed pasture and rangeland. Black line represents emissions from pasture expansion in LUH1. Orange and green lines represent emissions from expansion of managed pasture and rangeland and from expansion of just managed pasture respectively in LUH2. Note that the pasture category in LUH1 corresponds to managed pasture and rangeland together in LUH2.
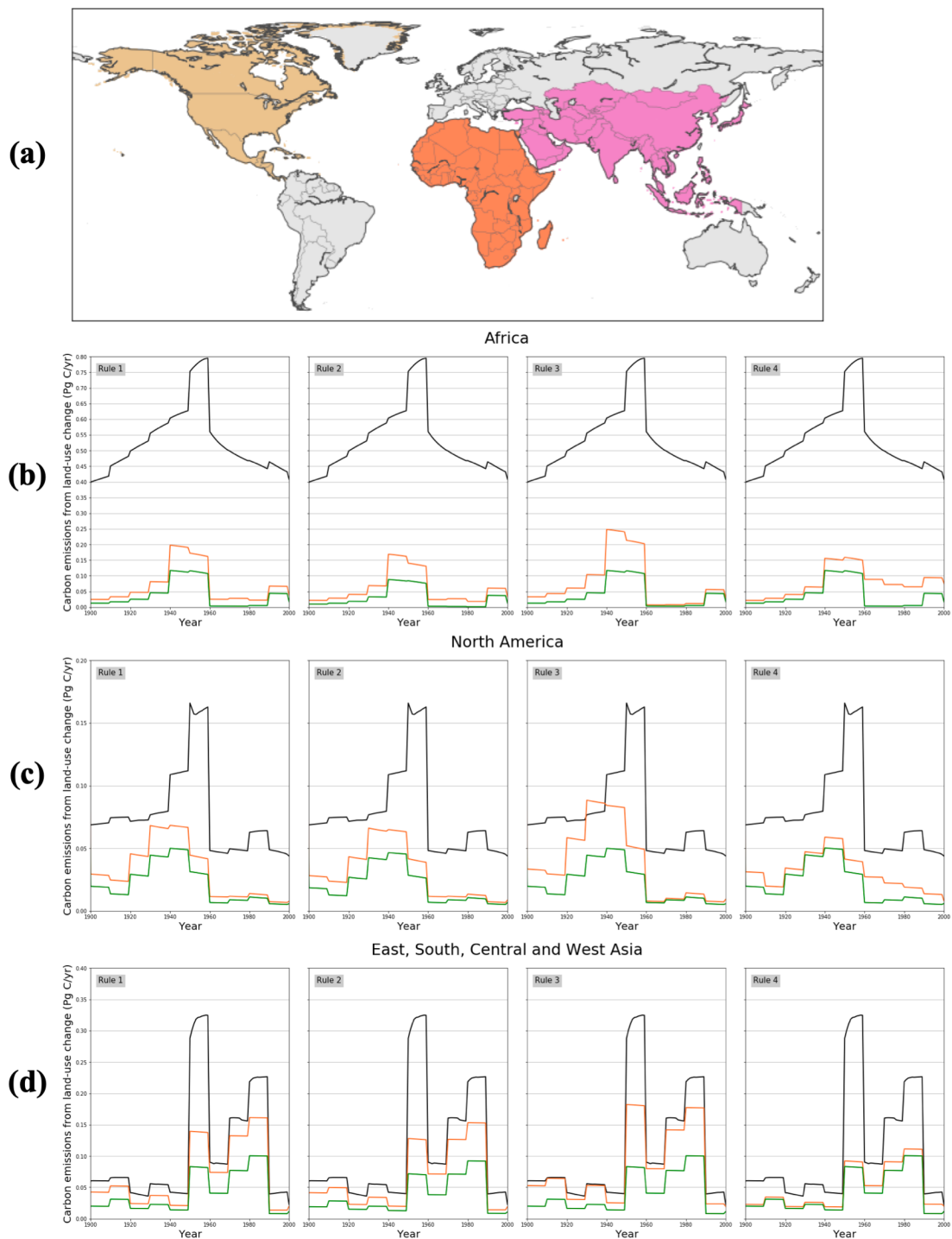
Figure 6. As in Figure 5 but three regions: (b) Africa; (c) East, South, Central and West Asia; (d) North America. (a) illustrates the defined boundaries of (b) - (d).
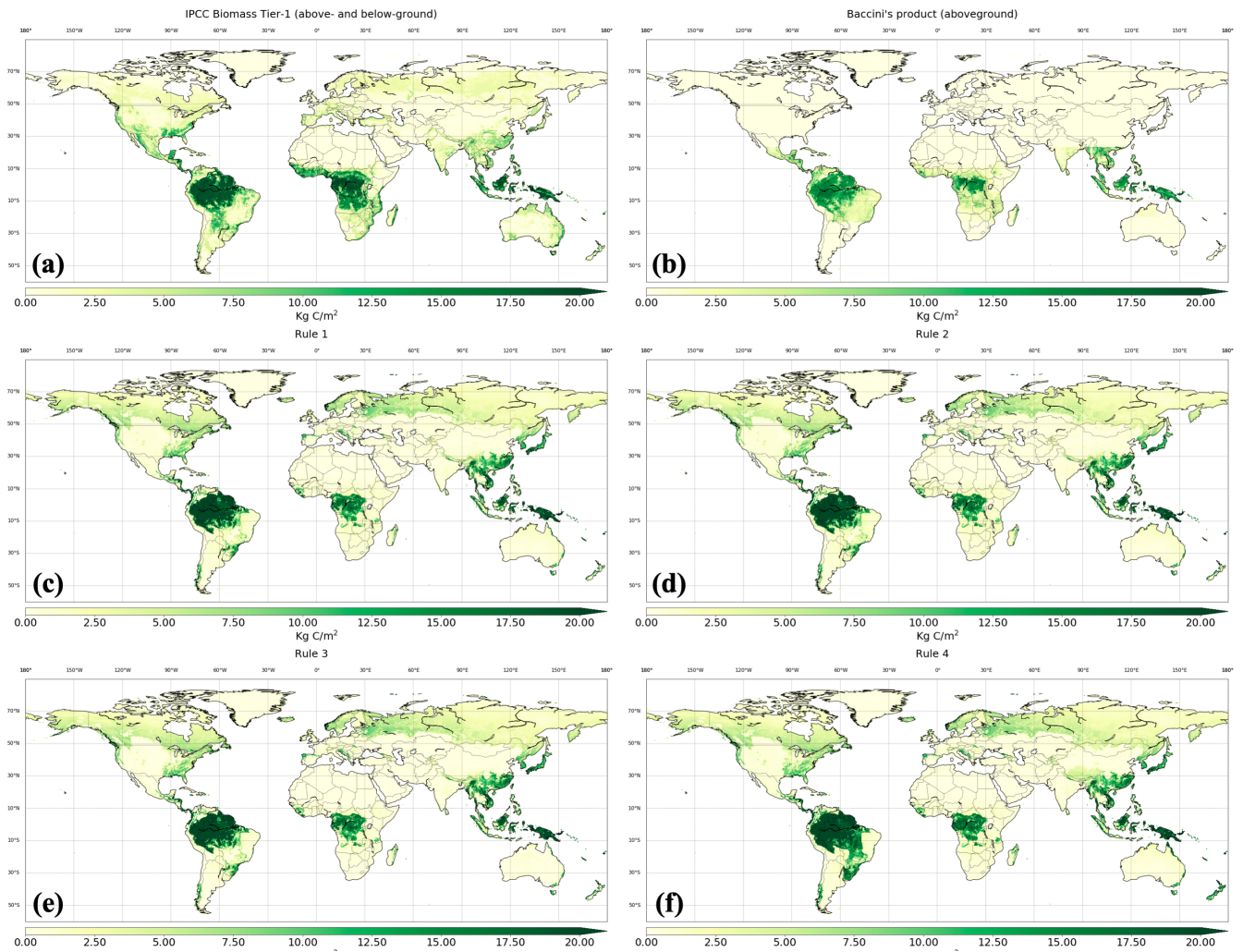
Figure 7. (a) IPCC Biomass Tier-1 density; (b) Baccini's product (only aboveground) at pantropical; global carbon density (above- and below-ground) maps estimated by Rules 1-4 from (c) to (f).
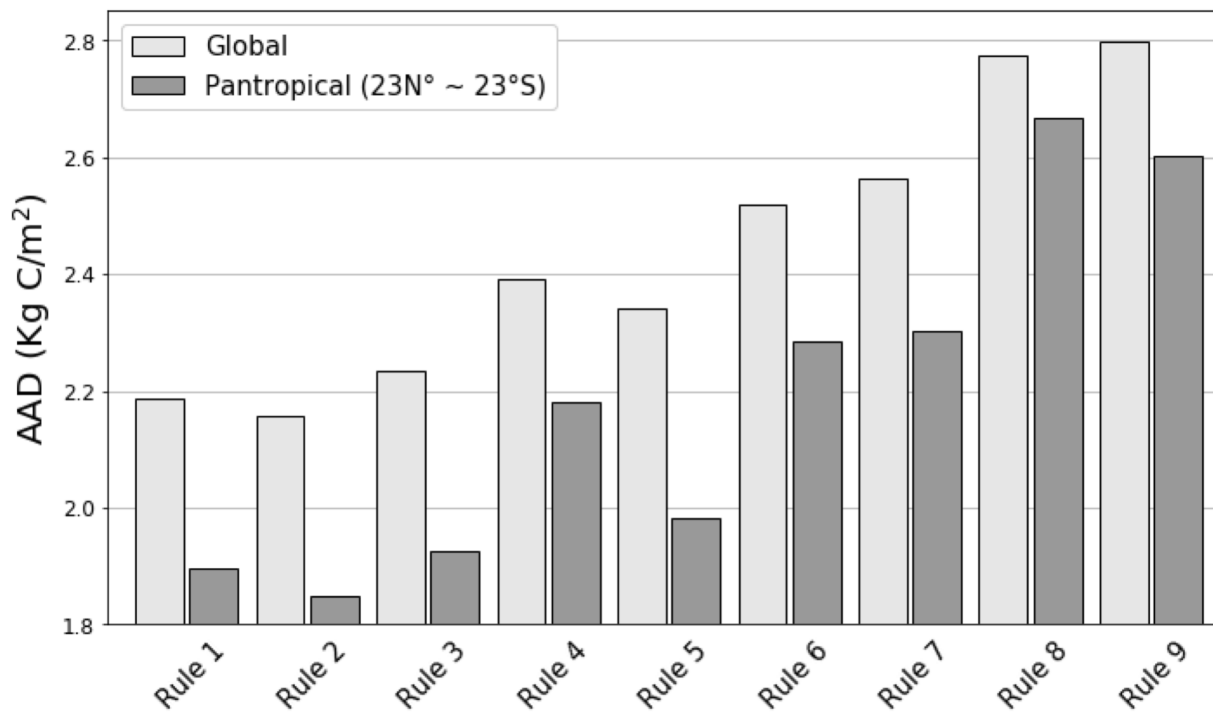
Figure 8. Average of absolute difference in carbon density between estimations of the 9 translation rules and two diagnostic maps: global comparison with IPCC Tier-1 biomass density map (incl. above- and below-ground); tropical comparison with Baccini's carbon density map (only aboveground).
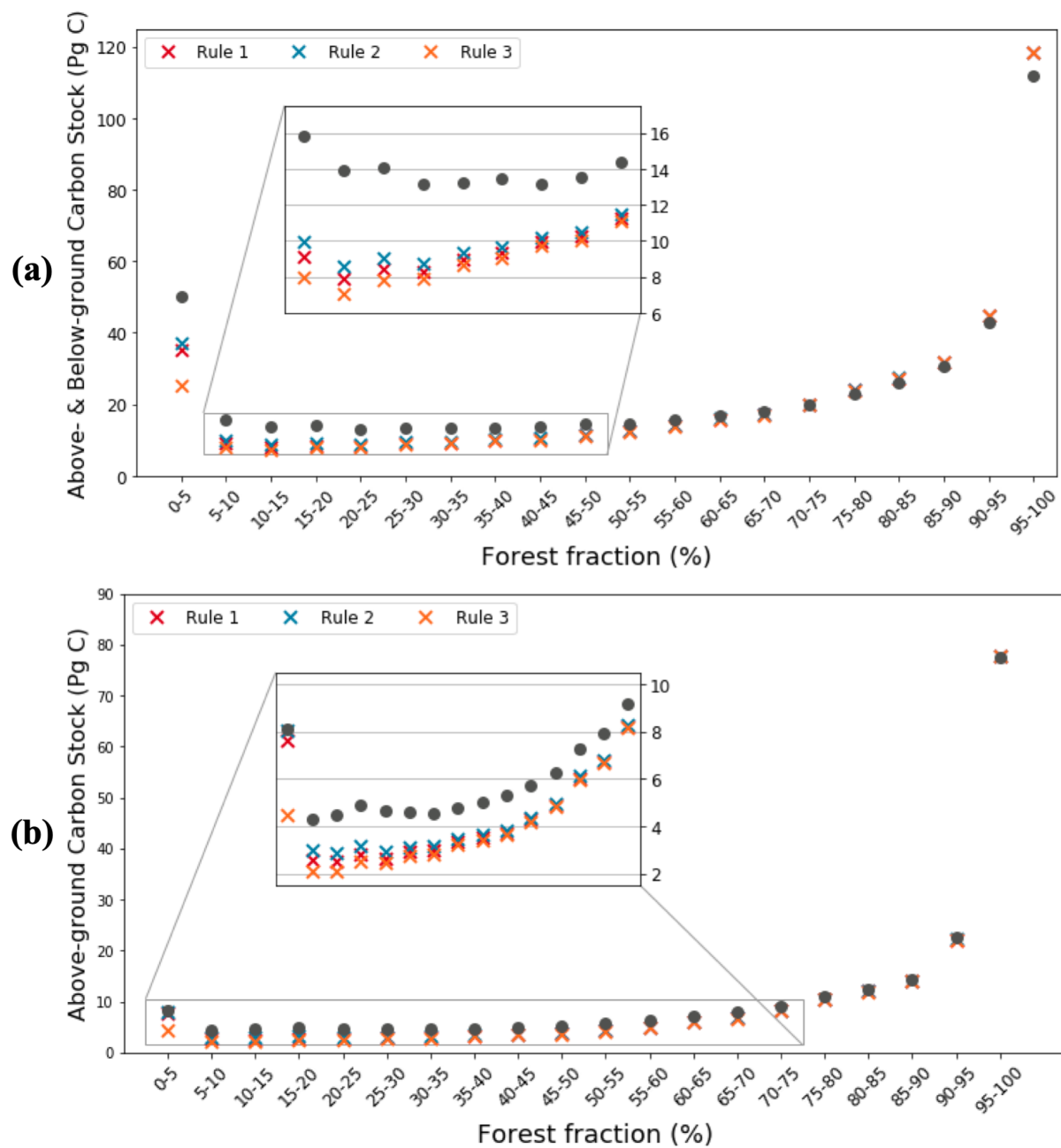
Figure 9. Total carbon stock grouped by forest fraction from the averaged satellite-based forest cover map. (a) global (above- and below-ground); (b) pantropical (aboveground).