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

To Reviewer #1:

Reviewer 1: The authors present an analysis of how various land conversion rules affect forest area and biomass carbon over the historical period, when applied to the LUH2 land use data. The results are compared with several available data sets, and they find that while a few different rules may be reasonable, the rule corresponding to definitions of source land use data appears to be the most reasonable one to use. They conclude by recommending full clearing of vegetation for cropland, urban, and managed pasture and clearing only for rangeland, when applying LUH2 data to ESMs and DGVMs.
Overall response I, and I think many others, will be happy to see these results published. This is a necessary step toward improving estimates of LULCC effects on the earth system. The paper is relatively clear, but some additional clarification and discussion are needed. Please see the details following these main concerns:

Response: Thank you very much for your comments which are very conductive to improve the manuscript. We have carefully revised the manuscript accordingly. Note that 'transition rule' has been renamed as 'translation rule' throughout the manuscript to avoid confusion with LUH2 land-use transitions. Please see our point-by-point response below.

Reviewer 1: 1) The methods describing how vegetation fraction and land-use fraction are tracked (section 2.3) are not complete.

Response: Please see details in relevant comment below.

Reviewer 1: 2) While there is some discussion of "forest area" vs "forest/tree cover," it is still unclear which metric is being used and discussed in the comparisons.

Response: Only forest cover/area were simulated and compared between model and reference datasets. We have clarified what metrics are used at the last paragraph of section 2.5.

Reviewer 1: 3) Please include discussion of the analytical rule results. You present the numbers, but do not tell us what they mean in terms of how particular transitions affect forest area and carbon dynamics.

Response: We have added discussions of Rules 5-9 at results section.

Reviewer 1: 4) It would be useful to see regional comparisons for carbon.

Response: Regional comparisons of carbon density estimate has been added as Figure S4.

Reviewer 1: Specific suggestions and comments: Abstract page 1, line 23: "optimal" is a strong word here for a global transition rule. "most reasonable global transition rule. . ." may be more appropriate

Response: We have changed 'optimal' to 'recommended'.

Reviewer 1: page 1, line 23: "optimal" is a strong word here for a global transition rule. "most reasonable global transition rule. . ." may be more appropriate

Response: We have changed 'optimal' to 'recommended'.

Reviewer 1: page 2, lines 9-10: this is a misleading statement not supported by the inappropriate reference (which is also quite old). it isn't necessarily the case that recovering or planted or re-planted forest has lower potential biomass many plantations or managed forests have higher growth rates than unmanaged forest, and in time could easily match or outgrow unmanaged biomass levels furthermore, the reference is about available land for afforestation, and does not compare afforested stands with corresponding primary stands. there are several recent papers that estimate carbon sequestration potential of forests. here is one example: griscom et al 2017: natural climate solutions in PNAS, oct 31 2017 vol 114 no 44 11645-11650

Response: We have revised these line as "*Afforestation/reforestation, in contrast, recovers forest which accumulates carbon but sequestration potential are constrained by water and nutrient availability (Smith and Torn, 2013)*", and the reference discusses ecological limit on sequestration potential of afforestation/reforestation.

Reviewer 1: page 2, lines 18-22: awkward sentence that is difficult to read. split it up and bring the examples out of the parentheses

Response: It has been revised as "*For this purpose, LULCC reconstructions enter Earth System Models (ESMs) (Lawrence et al., 2016), Dynamic Global Vegetation Models (DGVMs) (Le Quéré et al., 2018) and bookkeeping models (Hansis et al., 2015) to quantify biogeochemical and biophysical impacts of historical land-use change …* ".

Reviewer 1: page 5, lines 22-23: are there other factors not taken into consideration? is the climatology constant or does it vary with time? be specific here - state exactly what factors are or are not included

Response: The climatology is produced by averaging temperature and precipitation of MSTMIP 1901 and 2000 and remained as constant over the spin up period. We have reorganized these lines.

Reviewer 1: page 5, lines 26-29: what tree density or how much tree canopy cover will give 2 KgC/m^2? what defines potential forest area in the two comparison studies?

Response: It is difficult to link biomass density to tree density as their relationship may strongly vary with tree species and also locations, and there are many different definitions of forest in the literature. The threshold value of 2 kg C/m^2 potential biomass was used for consistency with prior studies and GLM2/LUH2 (see references below).

Hurtt GC, Pacala SW, Moorcroft PR, Caspersen J, Shevliakova E, Houghton R, Moore B (2002) Projecting the Future of the US Carbon Sink. Proceedings of the National Academy of Sciences of the United States (PNAS)/ 99(3): 1389-1394.

Hurtt GC, Frolking S, Fearon MG, Moore B, Shevliakova E, Malyshev S, Pacala SW, Houghton RA (2006), The underpinnings of land-use history: three centuries of global gridded land-use transitions, wood harvest activity, and resulting secondary lands. Global Change Biol 12:1208–1229

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Reviewer 1: page 6, lines 5-28: These equations are incomplete, and therefore confusing. Transitions from types 5-8 to 5-8 are not included for f-gained. As such we do not see that these types of gains account for the f/l ratios of the losing types 5-8. Transitions from types 1-4 to 1-4 are not included for losses or gains. Doesn't harvest move primary to secondary land? Are there any gamma factors for these transitions? Also, wouldn't abandoned ag land move to secondary first, then from secondary to primary? For this path from ag to secondary to primary, how is the abandoned ag vegetation fraction tracked over time?

Response: As the example of forest-pasture transition (the 2nd paragraph of section 2.3) explains, vegetation remaining in pasture will be cleared when the land is further changed to non-primary and non-secondary land. Similarly, vegetation remaining in cropland, rangeland or urban will also be cleared when the land is changed to cropland, pasture, rangeland and urban. Therefore, vegetation fraction could only be gained from land use changes from type 1-4. This is why $f^{gained}(i,t)$ in Eq.2 only includes land use changes from types 1-4. To avoid confusion, we clarify this before Eq.2.

Wood harvest from primary land does move vegetation to secondary, and there is no gamma factor for it. We have fixed the Eq. 5 and 6. Note that vegetation in cropland, pasture or rangeland could be back only to secondary land, there Eq.6 only apply to forested and non-forested secondary land. We have clarified this at the paragraph before Eq.4.
Besides, regarding the path you gave, the first part from abandoned ag to secondary is tracked in the Eq. 3 and 6, but the rest part that from secondary to primary is invalid in LUH2 according the definition of primary land in LUH2. Specifically, primary will not be reconverted once any land-use changes occur, thus your path will stop as secondary land.

Reviewer 1: Furthermore, there are corresponding equations for l(i,t+1), correct? But they are different because they track the land use transitions upon which the vegetation changes (without the gamma parameter that alters vegetation cover). This distinction and relationship between the two needs to be made clear.

Response: $l(i, t)$ is land-use fraction from LUH2 for type *i* at time *t*. This is no need to track land use fractions as LUH2 provides time series for them. Changes are made at the paragraph after Eq.3.

Reviewer 1: page 6, lines 20-21: f(i,t) could also be equal to l(i,t)

Response: Yes, we have revised it as "*this fraction is larger than or equal to its vegetation fraction* $f(i, t)$*.*"

Reviewer 1: page 6, lines 22-23: "these" is confusing. maybe delete "these" and make "land-use" at the end plural.

Response: We have rephased the whole paragraph that describes how vegetation in primary and secondary land is tracked.

Reviewer 1: page 7, line 21: considering annual creation and discard of wood products and decay in landfills, these emissions can grow to be quite large over time.

Response: We agree that emissions from wood product could be very large. However, we think using biomass change as proxy of land-use change emissions in this manuscript has already included the emissions you mentioned, since wood products accumulate carbon from harvest, deforestation and other activities, and this accumulation could be reflected in vegetation carbon changes.

Reviewer 1: page 7, lines 22-32: This does not appear to account for different areas of secondary land within a grid cell with different ages. Similarly to my comment above, if cropland is abandoned and has half natural secondary veg and half crop veg, there can be at least three different ages of secondary land in the cell. The number of different ages will grow with each transition. How is this dealt with? When does secondary become primary land again? Does primary land always have biomass density of B0?

Response: GLM2 does not account explicitly for the complete age distribution within secondary lands. When a fraction of secondary is newly created either from abandoned cropland or from harvested primary land, the mean age of the secondary land will be re-computed, and then it increases year by year to track biomass growth. Besides, primary land always has B_0, and once land use change occurs, it will never come back to primary land because of the primary land definition. We added description at the 2nd paragraph of section 2.4 to clarify the computation of mean age.

Reviewer 1: page 8, line 25: do you expect a 30% tree cover threshold to correspond with GLM's 2 KgC.m^2 threshold? Also, are the >30% pixel areas used for the values in table 2, or are the values in table 2 pre-threshold tree cover fractions that were calculated?

Response: Threshold value of 30% is discussed in Sexton et al., 2016 and its resulting forest area is comparible to FAO report. This value was used to convert tree cover to binary maps of forest and non-forest at 1km resolution, then we counted the forest area based on the 1km binary maps and reported global forest area of satellite-based dataset in Table 2. We have clarified this at the 2nd paragraph of section 2.5.

Reviewer 1: page 10, lines 4-28: What numbers are you comparing here and in figures 3-4 and table 4? Are the six-dataset numbers the tree cover or the forest with cover >30%? What does GLM's biomass threshold represent in relation to these metrics? Also, there are a couple of other tree cover estimates that are much lower: see meiyappan and jain 2012 frontiers in earth science 6(2):122 and Li et al 2018 earth system science data, 10:219.

Response: Only forest area/cover with a tree-cover threshold >30% of six satellite-based datasets are used in section 3.2 "Forest cover evaluation". We have clarified what metrics are used for evaluation at the last paragraph of section 2.5.

The lower global forest area estimates of meiyappan and jain 2012 may due to definition of forest, as they state in the second paragraph of section 4 "Comparisons with other studies". Moreover, the values of their test-case in the Table 5 is very comparable to the Table 2 of our manuscript.

The inclusion of six datasets as diagnostics in our manuscript is to avoid biased evaluation because of choosing a particular dataset. It will be very helpful to investigate the causes why satellite datasets report different forest cover, but it beyond the scope of our manuscript.

Reviewer 1: page 11: Can you make regional comparisons of LULCC emissions with info from the sources in table 3?

Response: As most of studies in Table 3 do not provide regional or gridded estimates, it is difficult to compare the regional LULCC emissions. However, we do compare the emissions from pasture and rangeland expansion for Rule 1-4 at different regions in Figure 6.

Reviewer 1: page 11, lines16-25: It would be helpful to see regional comparisons of carbon stock here.

Response: we have added Figure S4 for comparing carbon density at different latitudinal bands.

Reviewer 1: page 12, lines 11-13: up to this point you report that rules 1-3 have the same forest area dynamics, which makes sense because forest is always cleared in all three rules. but here you state that there are differences between rules 1 and 2 for forest area. please clarify why this is the case, and if they are different it needs to be noted early on, even if the differences are negligible.

Response: Rule 1,2, 3 should have the same forest area and only differ in carbon density, we have reorganized the results, discussion and conclusions section.

Reviewer 1: page 12, lines18-30: This is repetitive of your methods. It would be more useful to have discussion of the alternative rules, which you include in your figures/tables, but do not comment on at all.

Response: We have reorganized the discussion and conclusions, also analyzed Rules 5-9 at results section.

Reviewer 1: Figure 2 Only the results for rules 1-4 are shown, not all 9 as in the caption

Response: Right, we have fixed it.

Reviewer 1: Table 5 Do you mean compared with studies from table 3?

Response: Yes, it should be 'Table 3'. Change made.

Reviewer 1: Figures 5 and 6 I don't see the black dashed line. is it hidden?

Response: As Rules 1 and 3 have same treatment for land-use changes from primary and secondary land to managed pasture, the resulting emissions are very closed to each other, thus back dashed line almost completely overlapped blue dashed line. We have recreated Figures 5 and 6 by splitting each rule into individual plot.

Reviewer 1: Figure 8 I suggest plotting them in rule # order - rules 1 and 2 appear to be switched

Response: Change made.

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

To Reviewer #2 Eddy Robertson:

Reviewer 2: The paper provides a useful assessment of how the choice of implementation of landuse data can affect the simulation of tree cover and carbon emissions. A more detailed description of the model used is needed to allow better interpretation of the results. A clearer justification of the choice of optimal transition rule is needed. Key uncertainties in the model simulation need to be discussed, in order to assess whether the results show the optimal transition rule for all models or simply for GLM2. I have also suggested a few minor corrections.

Response: Thank very much for your time on reviewing our paper. Your comments are very helpful for us to improve the paper. We have carefully addressed your comments, please see the detailed responses below. Note that 'transition rule' has been renamed as 'translation rule' throughout the manuscript to avoid confusion with LUH2 land-use transitions.

Reviewer 2: P5, L21: Please provide more detail about the Miami model and the simulation of carbon stocks.

– What inputs does the Miami model use? Does it use climate data? What is the MSTMIP climatology?
– Is the Miami model a process-based model or a statistical model?
– What time period is being simulated? What period does the MSTMIP climatology cover? Does the model use CO2 concentration from the year 850, or is CO2 concentration simply not a factor the model can consider?

Response: The GLM2 estimate carbon stocks and fluxes using a statistical model which take temperature and precipitation into account. The input is from MSTMIP by averaging temperature and precipitation during 1901-2000. Since this model does not take CO_2 into consideration, CO_2 concentration is not used at all. We have reorganized these lines and clarified these questions at the first paragraph of section 2.3.

Reviewer 2: Discussion: The paper should comment on the significance of uncertainty in the map of potential carbon stocks, for example if the global total potential carbon stock were only 557 Pg C, do you think a different transition rule would be optimal?

– Related to the above point, is whether different rules are best for different ESM, because they will simulate different potential carbon stocks. Please comment.

Response: We added a discussion of this issue to the Discussion. Briefly, our goal was to provide a reference set of translation rules for this reference land-use dataset. However, we note that it is possible to obtain different results with different models using the same translation rules. The CMIP6 Land Use Model Inter-comparison Project (LUMIP) has organized an inter-comparison of model results using this forcing dataset (Lawrence et al 2016).

Reviewer 2: P5, L26 and discussion: Why was 2 kg C/m2 chosen to define a forest? Is using 2.2 kg C/m2 equally justifiable and if so, might this lead to a different transitional rule being optimal?

Response: The threshold value of 2 kg C/m2 potential biomass was used for consistency with prior studies and GLM2/LUH2 (see references below).

Hurtt GC, Pacala SW, Moorcroft PR, Caspersen J, Shevliakova E, Houghton R, Moore B (2002) Projecting the Future of the US Carbon Sink. Proceedings of the National Academy of Sciences of the United States (PNAS)/ 99(3): 1389-1394.

Hurtt GC, Frolking S, Fearon MG, Moore B, Shevliakova E, Malyshev S, Pacala SW, Houghton RA (2006), The underpinnings of land-use history: three centuries of global gridded land-use transitions, wood harvest activity, and resulting secondary lands. Global Change Biol 12:1208–1229

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Reviewer 2: P10, L27 and figure 4: Disagreement with the average satellite-based forest cover does not mean that the model is not consistent with (i.e. within the range of) the ensemble of satellite-based forest cover. Please can you at least mention this possibility. You could account for this uncertainty, perhaps by adding an uncertainty bar to figure 4 showing the errors relative to the TCCF and GLC2000 datasets.

Response: Good suggestion. We have recreated the Figure 4 by comparing rule estimates to each of the six datasets as well as to the average satellite-based forest cover. The new Figure 4 still suggests Rules 1, 2, 3 outperform Rule 4 in terms of gridded forest cover as long as the same satellite-based dataset is used as the reference.

Reviewer 2: Figures 5, 6 and 9: Please add results from rule 4 to figures 5, 6 and 9. I don't know why you have stopped considering rule 4.

Response: We stopped considering Rule 4 because it has relatively large bias than Rules 1-3 in forest cover and vegetation carbon estimates. However, we have included Rule 4 again in our recreated Figure 5 and 6.

Reviewer 2: Discussion: More justification is needed for you choice of optimal rule. I agree that, all else being equal, using rule 1 is best because it is consistent with HYDE 3.2. It's fair to exclude rule 4 because it produces too much tree cover (table 4) and compared to the other rules it has twice the carbon stock error in the tropics (Figure 8). However, in the discussion you need to more clearly state why rule 4 is excluded. I don't know why rule 3 has been excluded, please can you justify this choice?

Response: We have added detailed justification at the results section.

Reviewer 2: Discussion: Will the choice of rule matter less in future simulations? Is there less range-land expansion in future?

Response: We believe discussion of impacts of rule choices is very helpful, however our experiments and diagnostics really limit this kind of analysis, therefore we only state that this study only aim to propose a recommended rule for translation of historical land-use change to land-cover change in the introduction.

Reviewer 2: P2, L18-22: This sentence needs to be made clearer. I also think that you are underselling the importance of LUH2, it is not only used in land-use specific model simulations, it is a key input to the DECK and historical simulations as well as for future projections (scenarioMIP). Additionally, you could mention that it is used to simulate the biophysical effects of land-use change as well as the biogeochemical effects.

Response: We have rephased these lines to appropriately credit the significance and importance of the LUH2 for the reasons you mention. The revised sentence is "*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) (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 specific simulations (LUMIP), and biodiversity studies (IPBES)*"

Reviewer 2: P3, L11-15: This sentence needs to be made clearer.

Response: We have reorganized this part by removing some irrelevant description. The revised sentence is "However, explicit suggestions for land-cover and 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".

Reviewer 2: P8, L1: What is the "wood fraction?"

Response: The fraction of NPP is allocated to cumulate stem and branch biomass annually. We have added explanation for it.

Reviewer 2: P13, L4: Please remove reference to the "Miami-LU model" and replace with "Miami model" or "GLM2," as appropriate.

Response: We have replaced 'Miami-LU' by 'GLM2'.

Reviewer 2: Caption of Table 5: Should refer to table 3 not table 4?

Response: Yes, it should be 'Table 3'. Change made.

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

To Reviewer #3:

Reviewer 3: The manuscript entitled Global Transition Rules for Translating Land-use Change (LUH2) To Land-cover Change for CMIP6 using GLM2 by Ma et al. aims at recommending a global transition rule for translating LUH2 land-use forcing into land-cover changes in CMIP6 models. The authors simulate land-use induced land-cover changes based on a set of translation rules using the GLM2 model and prescribed LUH2 land-use transitions. Subsequently, emerging present-day forest cover, biomass density, and LUC emissions are evaluated against published estimates. The authors conclude by recommending a rule where all vegetation is cleared upon cropland/pasture expansion and only forest vegetation is cleared upon rangeland expansion.

The paper is technically correct, well written, timely in providing recommendations how to translate land-use forcing into land-cover changes for CMIP6 and the content is generally suitable for publication in GMD. I am wondering, however, if the conceptual design of the study is valid in the context of the large uncertainties that exist in the reconstruction of historical land use. Likewise, I do not think that the main conclusion ('optimal' rule being rule 1) is supported by the results presented. The wording ('optimal transition rule', 'accurate quantification', […]) is not suitable in the context of large uncertainties. Rather than claiming an 'optimal' transition rule, I suggest a framing towards recommending a 'consistent' translation rule for implementation of land use in ESMs/DGVMs. A consistent treatment in ESMs/DGVMs would eliminate added uncertainty and complexity from different treatment in each model. If this is 'optimal' (or and 'optimal' global rule even exists), is difficult to judge with available data and not shown by the contents of this manuscript. The reproducibility of the analysis presented is questionable, especially as neither the code of GLM2 (though stated in the code and data availability section) nor any documentation of the model is publicly available at the moment.

Response: Thanks for your comments which have helped us improve the manuscript. We have revised the manuscript including changing word of 'optimal' to 'recommended' and strengthening the justification of rule determination at result section by adding spatial analysis and regional comparisons. Note that 'transition rule' has been renamed as 'translation rule' throughout the manuscript to avoid confusion with LUH2 land-use transitions.

Regarding the comment of the conceptual design, we agree that large uncertainties exist in current land-use modelling products, and it is difficult or even impossible to propose globally 'optimal' rule to translate land-use change to land-cover change regardless of the land-use dataset. Therefore, we have modified the last paragraph of introduction section to clarify the goal that recommended through our evaluation only guide the implementation of LUH2 (historical part) in CMIP6. Besides, we agree with your point that "globally consistent rule could eliminate added uncertainty and complexity from different treatment in each model", we have added this at end of the second last paragraph of introduction section.

Reviewer 3: Conceptual design. One of the main (implicit) assumptions in the manuscript is that the land-use transitions from LUH2 are 'correct', although these transitions are affected by large uncertainties and necessarily based on many assumptions. Given also the presented results that show simulated forest cover (and mostly also carbon emissions) in the range of previously published results for rules 1-4 (and partly even for the 'analytical' rules), I am wondering how valid any conclusions drawn regarding an 'optimal' translation rule can be. Without evaluation if any of the reference estimates is 'better' than others, I cannot see why Rule 1 is more 'optimal' than Rule 2, 3, or 4 (as long as they are all within the range). Moreover, if we can see only this small discrepancy already with assuming LUH2 data as 'correct', how do the authors think, would this evolve, if accounted for uncertainties in the land-use reconstruction? For example, how would the LUH2 high and low estimates change the results? How would prioritizing another land-use type in the allocation of land-use transitions in GLM2 (if this still exists like in GLM) change the results? And in conclusion: Does it even matter which of the rules is applied in an ESM/DGVM given these probably much larger effects from the mentioned uncertainties (besides of being consistent across CMIP6 models)?

Response2: Given the role of LUH2 as required forcing dataset, our goal was to determine the best translation rules given these data to inform and standardize the use in future modeling studies. To address uncertainty, we now include estimates of uncertainty in key reference datasets. We show that given this uncertainty, it is not technically possible to differentiate performance between some of the possible alternative rule choices. However, here we do confirm that Rule 1 performs among the best through these analyses consistent with the HYDE recommendation, and therefore have increased the confidence in recommending its standard usage. While LUH2 does provide a historical high-low, we focus here on the reference dataset only due to its required usage in model forcing. The Land-Use Model Inter-comparison Project (LUMIP) is organized to compare model performance using this forcing dataset.

Reviewer 3: Wording/Framing. Closely related to the comment above, I do not think that the wording in the manuscript is appropriate at many instances. The authors should avoid terms like 'accurate', 'optimal', etc. in the context of historical land-use change and its translation to land-cover change. As the authors state correctly in their discussions, globally valid transition rules probably do not exist and I would encourage the authors to rather emphasize the underlying uncertainties than trying to hide them behind strong words. Instead of claiming to derive 'optimal' rule(s), it would be more useful to recommend a 'reasonable rule' that should be used consistently across CMIP6 models.

Response: Very good suggestion. We have removed these adjectives where possible.

Reviewer 3: Conclusions. The main conclusion (=recommending rule 1) is not supported by the results presented. For all of the proposed diagnostics (forest cover, biomass density, carbon emissions), all of the rules (1-4) are within the range of the diagnostics (sometimes even some of the analytical rules which are supposed to be idealized/unrealistic), and all of them are far from 'accurately' translating land-use change to land-cover change as the authors claim. The fact that on average one of the rules is closer to an averaged reference map does not provide justification that one of the four rules is superior over the others. The authors need to provide more justification why they recommend rule 1 and/or 2 based on the results presented here. Personally, I do not think this is possible without either defining a 'best/most suitable' reference map (e.g., based on GLM2 forest definition) or extended (spatial) analysis to identify regional characteristics of the different rules. Generally, the discussion/conclusion section needs to be strengthened, as in its current form it mainly repeats methods/results instead of discussing the findings of the analysis.

Response: We largely agree and have re-framed the analysis in response to these concerns. In the revised manuscript, we compare performance to each rule to each reference map as opposed to the average. We also include a treatment of uncertainty in the reference maps. In the end we now show its difficult to differentiate between Rules 1-3 and recommend Rule 1 for both its relatively good performance and underlying prior recommendation from the HYDE.

Reviewer 3: General. Please check the whole manuscript for missing whitespaces in front of references and within references.

Response: Changes made.

Reviewer 3: P1 L15 'accurately' does not seem to be an appropriate wording given the large uncertainties both in climate and land-use modeling. Please remove.

Response: We have rephased this sentence to remove the word 'accurately'.

Reviewer 3: P1 L16 I would suggest to use 'land-cover change time series' only, i.e. remove the 'land-cover'.

Response: We have rephased it as "*climate models need consistent land-cover change time-series at a global scale*".

Reviewer 3: P1 L18-21 Please include that GLM2 was used for the simulations already here.

Response: They are changed to "*Building upon the latest Land Use Harmonization dataset (LUH2), land-cover dynamics, particularly in forest cover and carbon stock, were simulated based on each rule from 850 to 2015 globally by Global Land use Model 2 (GLM2) at quarter degree spatial resolution.*".

Reviewer 3: P1 L23-25 I think 'optimal transition rule' is not the correct wording. This sentence is also quite complicated. I would suggest to rephrase, emphasizing that within GLM2 the mentioned rule turned out to perform best. The wording here indicates that this rule is ‘optimal’ irrespective of the model used, which is not supported (and probably also not intended) by the results of the manuscript.

Response: We have reorganized this sentence as “*Examinations at global, country, and grid scales indicate that the recommended translation rule for CMIP6 models is 1) completely clear vegetation in land-use …”.*

Reviewer 3: P1 L26-28 I am wondering if mentioning the detailed forest area is required, while not referring to the carbon density and LUC emissions at all?

Response: We have added results for carbon density there as “*According to this rule, contemporary global forest area is estimated to be 37.42 10^6 km^2, 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*”.

Reviewer 3: P2 L5-7 I think it is not correct to present this statement as a fact. The numbers are based on a historical LU reconstruction, i.e. model results. Please rephrase to, e.g., ‘Model results show […]’ or ‘It has been estimated, […]’.

Response: We have rephased it as “*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 disturbance*s”.

Reviewer 3: P2 L7 Include ‘amongst others’ as there are many more impacts of LUC and land management on the carbon cycle than deforestation, afforestation, and wood harvest.

Response: P2 L8-10 has modified as “*Impacts on the carbon cycle result from several processes among others: deforestation removes natural forest and …*”

Reviewer 3: P2 L12-13 Same as above. Please highlight that this is also an (uncertain) model result, e.g. by including the uncertainty ranges.

Response: We have rephased this as “*Cumulatively, models estimate that land-use land land-use change have contributed to a net flux 190±75 Pg C to the atmosphere during 1870-2017 (Le Quéré et al., 2018)”.*

Reviewer 3: P2 L13-14 What are 'these emissions'? Please rephrase in a way that the reference to land-use emissions becomes clear.

Response: We have rephased it as "*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*"

Reviewer 3: P2 L13-15 The numbers presented here are probably all derived by using LUH(2) as land-use forcing. Thus, I think it would perfectly fit the storyline to add a sentence that explains that exactly due to these uncertainties a 'better' translation between land use and land cover is required. Otherwise, one may ask, why we would need all these transition rules, if we already know about historical land-use impact.

Response: We have added uncertain range at the end of 1st paragraph of introduction and pointed out at the next paragraph that a globally consistent translation rule is required for ESMs and DGVMs.

Reviewer 3: P2 L18-22 What about just saying LULCC reconstructions enter Earth System Models (ESMs) (e.g., Lawrence et al., 2016), Dynamic Global Vegetation Models (DGVMs) (e.g., Le Quéré et al., 2018), and bookkeeping models (Hansis et al., 2015; Houghton and Nassikas, 2017) to quantify biogeochemical and biophysical impacts of historical land-use change.' I don't think the details about models and MIPs is required here.

Response: We have changed these lines as "*LULCC reconstructions enter Earth System Models (ESMs) (Lawrence et al., 2016), Dynamic Global Vegetation Models (DGVMs) (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 specific simulations (LUMIP), and biodiversity studies (IPBES)*".

Reviewer 3: P2 L18-22 Remove '(e.g., HYDE, SAGE)'. Replace 'Goldewijk et al., 2017' by 'Klein Goldewijk et al., 2017'. Add Ramankutty and Foley, 1999 and Pongratz et al., 2008.'

Ramankutty, N. and Foley, J. A.: Estimating historical changes in global land cover: Croplands from 1700 to 1992, Global Biogeochem. Cycles, 13(4), 997–1027, doi:10.1029/1999GB900046, 1999.

Pongratz, J., Reick, C., Raddatz, T. and Claussen, M.: A reconstruction of global agricultural areas and land cover for the last millennium, Global Biogeochem. Cycles, 22(3), GB3018, doi:10.1029/2007GB003153, 2008.

Response: These lines are changed to "*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 …*".

Reviewer 3: P2 L24-26 The manuscript is about historical land use, i.e. the harmonization with future LULCC seems to be an irrelevant information here.

Response: The lines are changed to "*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*"

Reviewer 3: P2 L28-33 Remove the reference 'Shevliakova et al., 2013' between the sentences and only put it in the end of the paragraph.

Response: We have moved the citation to the end of the paragraph.

Reviewer 3: P3 L1-3 I would not agree that there is 'a lack of explicit global rules'. As the authors show later on, it is relatively easy to come up with some. I would rather argue that there is no consistency/agreement on which rule to apply. Apart from that, in this context it is also worth to mention that such 'global transition rules' probably do not exist at all [see, e.g., Prestele et al. 2017].

Prestele, R., Arneth, A., Bondeau, A., de Noblet-Ducoudré, N., Pugh, T. A. M., Sitch, S., Stehfest, E. and Verburg, P. H.: Current challenges of implementing anthropogenic land-use and landcover change in models contributing to climate change assessments, Earth Syst. Dyn., 8(2), 369–386, doi:10.5194/esd-8-369-2017, 2017.

Response: We agree that there is no agreement on which rule should be used, thus we have changed 'a lack of explicit global rules' to "a globally consistent rule".

Reviewer 3: P3 L5 … 'and the location where a land-use change happens'.

Response: It has been changed as "*the degree of land-cover alteration varies with the types of land-use changes and the location where a land-use change happens*".

Reviewer 3: P3 L5-7 While this statement sounds very intuitive, I wonder if there is any literature supporting these tendencies?

Response: We agree that the potential activity is intuitive, but are also not aware of specific literature on it.

Reviewer 3: P3 L11-15 Complicated sentence. Please shorten. In my opinion, everything after '…not yet provided' is not necessarily required. What about joining with the following sentence instead? Isn't it exactly what the authors are aiming at: providing recommendations how to treat these 'new land-use types' in the translation?

Suggestion: 'However, explicit suggestions for land-cover and 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 translation will potentially produce very different land-cover dynamics, which will impact the land surface biophysical and biochemical processes.'

Response: Great suggestions. these lines are changed as "*However, explicit suggestions for land-cover and 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.*"

Reviewer 3: P3 L18 I would not agree that the approach presented here will reduce any uncertainty. It rather can provide recommendations for consistent treatment across models, if the 'optimal' rule is adapted by the CMIP6 models. But this does not allow any conclusions how uncertainty will be affected.

Response: these lines have been revised as "*To recommend a global translation rule for translating historical land-use changes for CMIP6 models, this study investigates the impacts of land-use change on land-cover by proposing several alternative sets of translation rules, which ae then integrated into the Global Land use Model 2 (GLM2) model (Hurtt et al., 2017, 2019) to simulate …*"

Reviewer 3: P3 L22 Remove 'other' in front of 'independent'.

Response: change made.

Reviewer 3: P3 L22-25 Here, too, I recommend not using the term 'optimal'.

Response: We have changed 'optimal' to 'recommended'.

Reviewer 3: P4 L1-5 Is there a specific reason not to include the ESA CCI land cover for comparison? Remove the details about the comparison dataset here. They are all mentioned in section 2.5

Response: the ESA CCI land cover dataset has different land-cover classification schemes with the six satellite-based datasets, and therefore the legend translation (Table S1 from Song et al 2014) may be not applicable for ESA CCI. We have re-organized P4 L1-L5.

Reviewer 3: P4 L7-28 As the method section is already quite long, I would suggest to shorten here. I do not think there is a lot of added value to describe LUH2 in this detail for the purpose of the paper. I guess there will be an associated LUH2 publication soon, so it is probably enough here to just describe the key features that are relevant for the analysis in this manuscript.

Response: section 2.1 has been shortened.

Reviewer 3: P4 L11-13 This sentence doesn't seem to fit in the context here.

Response: It has been removed.

Reviewer 3: P4 L17 While 'data-driven' is probably not wrong, I think it is misleading as it implies that the constraints used in LUH2 are based on observations. However, to my knowledge most of the constraints are model outputs in some way (be it the HYDE reconstruction or models derived from remote sensing images, etc.). Therefore, I would recommend not to use 'data-driven' here.

Response: We have removed 'data-driven' and this revised sentence is "*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), …*".

Reviewer 3: P4 L28 Where do the 2 kg C/m^2 come from? How do they relate to other forest definitions? Are there any references that could support this threshold? Some more information would be valuable for the reader.

Response: It is difficult to link biomass density to tree density as their relationship may strongly vary with tree species and also locations, and there are many different definitions of forest in the literature. The threshold value of 2 kg C/m_2 potential biomass was used for consistency with prior studies and GLM2/LUH2 (see references below).

Hurtt GC, Pacala SW, Moorcroft PR, Caspersen J, Shevliakova E, Houghton R, Moore B (2002) Projecting the Future of the US Carbon Sink. Proceedings of the National Academy of Sciences of the United States (PNAS)/ 99(3): 1389-1394.

Hurtt GC, Frolking S, Fearon MG, Moore B, Shevliakova E, Malyshev S, Pacala SW, Houghton RA (2006), The underpinnings of land-use history: three centuries of global gridded land-use transitions, wood harvest activity, and resulting secondary lands. Global Change Biol 12:1208–1229

G. C. Hurtt, L. P. Chini, S. Frolking, R. A. Betts, J. Feddema, G. Fischer, J. P. Fisk, K. Hibbard, R. A. Houghton, A. Janetos, C. D. Jones, G. Kindermann, T. Kinoshita, Kees Klein Goldewijk, K. Riahi, E. Shevliakova, S. Smith, E. Stehfest, A. Thomson, P. Thornton, D. P. van Vuuren, Y. P. Wang (2011) Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. Climatic Change 109:117–161

Reviewer 3: P5 L1 What are the 'analytical purposes' of rules 5-9? For the rest of the manuscript they are mostly used to state that the results with these results are 'way off', but this is not very surprising given their idealized/unrealistic character. I would therefore recommend to leave them out, as they rather add confusion.

Response: Rules 5-9 are included for model experimental design completeness and for reference to the other cases. In the text, we clearly differentiate them as such.

Reviewer 3: P5 L8-12 I agree that the effect of spatial and temporal varying rules is beyond the scope of this study. However, these are very strong simplifications and it would be useful to get an indication of how including this variation would affect the results. Maybe the authors could look a bit more detailed into the country-level and gridded results for the different rules and diagnostics. Can there be seen any patterns, if one of the rules is 'more likely' in certain regions than in others? If this is not feasible, the authors should include more detailed elaboration how the results may be affected in the discussion section.

Response: We have added regional comparison of Rules 1-3 estimates of carbon density at Figure S5.

Reviewer 3: P5 L18-19 It sounds a bit 'circular' that the output of GLM2 (i.e., LUH2) is used as input into GLM2 for the analysis in this manuscript. Could the authors provide more explanation how this was implemented? Are these independent model runs?

Response: To better explain the model runs, we have rephased these lines as "*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 0.25° spatial resolution*"

Reviewer 3: P5 L23-24 More detail required regarding the model run (time period, etc.).

Response: We have updated the model info such as inputs, time period, environmental factors not considered at the first paragraph of section 2.3.

Reviewer 3: P5 L23-29 These are effectively 'results'. I would recommend to move to section 3.1.

Response: They have been moved to section 3.1.

Reviewer 3: P5 L31 ff. I do not know about the specifications of GLM2/LUH2, but in LUH1 [Hurtt et al. 2011], choices had to be made about starting date, priority for land-use transitions, wood harvest inclusion, etc. If this still exists for GLM2/LUH2, it would be useful to indicate here, which configuration of GLM2 was used to derive LUH2 to allow the reader to understand how the historical transition rates have been derived. In the discussion, a short evaluation of how changing these assumptions would change the results of the analysis, would help.

Hurtt, G. C., Chini, L. P., Frolking, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D. P. and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500-2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, Clim. Change, 109(1), 117–161, doi:10.1007/s10584-011-0153-2, 2011.

Response: For the LUH1 dataset we performed a large sensitivity analysis in which we systematically varied model inputs and decisions. However, owing to the complexity and increased detail of LUH2 we have not performed a similar sensitivity study for this dataset. As such, there are now choices to be made by the user regarding the specifications of the dataset. Of course, this does not imply that there is no uncertainty in the various model factors and changing the inputs and model decisions would ultimately change the carbon accumulated in the land surface, but would not necessarily change the overall recommendation of which translation rule to use.

Reviewer 3: P7 L26 Not an expert in carbon impacts of land management. However, I am wondering if management of land necessarily means that there is no further accumulation of biomass in the remaining 'natural' vegetation?

Response: When natural vegetation remains on managed land there are a range of possibilities – the accumulation of carbon could decrease over time (if for example that vegetation is grazed), it could remain constant (if it is explicitly managed and with the intent to keep it), or it could grow with time (if it is allowed to expand spatially). In the absence of any other information we have chosen a simple, middle-of-the-road, assumption that the carbon in remaining vegetation is explicitly managed and remains constant. Furthermore, we have acknowledged the possible impact of the assumption at the results section that consistent underestimation of carbon stocks in Rules 1-3 may be related to this assumption.

Reviewer 3: P9 L20 Instead of only using an average 'smallest difference' for the gridded results, looking more into the spatial patterns would maybe help to derive stronger justification for recommending one of the suggested rules.

Response: We have added difference maps of forest cover and carbon density (Figure 2, S2 and S3), and zoom in some regions for detailed comparison (Figure S5).

Reviewer 3: P9 L29 'Higher forest cover' compared to what? The average reference map? Unclear. In addition, rather than presenting the three forest cover maps in Fig. 2, it would be more useful to show difference maps (rule 1-3 minus reference; rule 4 minus reference). This would facilitate the identification of differences between the maps.

Response: "higher" has been changed to "high", we just want to claim Rules 1-4 could reproduce the general pattern of forest cover such as where has more forest than other places. Furthermore, we have added the difference maps in Figure 2 for better comparison.

Reviewer 3: P10 L9-11 Here, the authors emphasize the uncertainty in the definition of 'forest', which cannot easily be resolved. Which definition used in one of the reference maps is closest to the forest definition used in GLM2 (> 2 kg C/m²). Using the 'closest' map to compare the GLM2 results to would probably give a better indication than having a huge range of 'reference' maps (where the range partly originates 'only' in definition issues).

Response: It is good to evaluate rules with multiple independent satellite dataset to reduce uncertainties originating from particular methods or sensors, but also difficult to visualize the comparison between reference maps and model estimates. Here, we still prefer to keep these six satellite datasets, but extend Figure 4 by including comparisons to all rule to each of the six datasets rather than the averaged dataset. The extended analysis still supports our conclusions that Rules 1, 2, 3 outperform Rule 4 in terms of gridded forest cover.

Reviewer 3: P10 L12-15 Rule 7 is within the range according to Fig. 3.

Response: These lines haven been updated to "*The forest cover based 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.*"

Reviewer 3: P10 L16-17 Rule 5 and 7, too (see Fig. 3).

Response: These lines have been modified to "*In contrast, Rules1-4, 5 and 7 produced estimates of global forest area within the range of diagnostics*."

Reviewer 3: P10 L19-20 The statement is not wrong, but also the analytical rules 'locate' around 75% of global forest land in these eight countries. This cannot be used as a characteristic of distinction between the rules.

Response: The sentence "*Rules 1-4 also produce the same pattern of locating most forest land within these eight countries (Table 4).*" has been removed.

Reviewer 3: P10 L27-28 I am not sure, if the mean average delta compared to an average global forest map is a good metric here. The average reference map is a rather 'artificial' map, and not necessarily the most plausible one. Does the assessment of 'smallest' difference change, if compared to the reference maps individually? Rather than using averages, I think the authors should aim at identifying a reference map that corresponds most with the forest definition within GLM2 and compare to this map. Additionally, showing a map of the differences would also allow to identify if certain rules match the current situation better in particular regions. As several rules are within the range of published forest cover areas, this would allow a better justification for one certain rule and/or regional diversification.

Response: Good suggestion to determine a reference map for evaluation. However, it is difficult to find such one which correspond most with GLM definition, as GLM does not has forest cover map before applying the rules of the paper. Instead, we have extended the Figure 4 by comparing rule estimates to each of six satellite-based forest cover maps as well as to the averaged map. We also added difference maps in Figure 2 for better justification.

Reviewer 3: P10 L10-12 What happened to rule 4? From Table 5 it can be seen that it reduces the pasture anomaly, too. Why does it not appear any more in the text and Figs. 5/6?

Response: Emissions of Rule 4 have been added to Figure 5 and 6.

Reviewer 3: P10 L13 Is the difference of 1 Pg C really a 'significant' difference?

Response: We have rephased this sentence as "*Rule 2 reduces more anomalous emissions than Rule 1 (reduced 6 Pg C in Rule 1 and 7 Pg C in Rule 2),…*"

Reviewer 3: P11 L16-20 The differences in the average difference between model and reference are rather small across all rules (except for some of the analytical). Again, are the authors sure that this average difference is a suitable indicator (see also comment above reg. forest area)?

Response: The "small" difference across rules is what we anticipated for two reasons. First, Rules 1-3 have same treatment of land-use changes to cropland, but different treatment for those from non-forested land (primary and secondary) to managed pasture or rangeland. Second, the carbon density of non-forested land is also relatively small (usually below 2 kg C/m2 in GLM2). Therefore, the small difference in carbon density and emission estimates are expected. For better readability of Figure 8, we rescaled the y-axis, we can see Rules 1-3 outperforms Rule 4. And also, we have also calculated the averaged difference over different regions (i.e. four latitudinal bands in Figure S4) instead of averaging over globe.

Reviewer 3: P11 L22-25 In Fig. 9 hardly any difference can be seen for the three rules. How large are the differences between the individual rules and the reference? How do the authors conclude from this Fig. that rule 1 and 2 are closer than rule 3? What happened to rule 4?

Response: We have modified Figure 9 by calculating the relative difference in carbon stock comparing to two carbon density maps. Rule 4 is excluded as it shows large bias in forest cover in Brazil and also larger averaged difference in carbon density (Figure 3), Figure 9 compares carbon stock of Rules 1-3 and then determine which should be recommended.

Reviewer 3: P11 L28-30 Please see major comment 'Conclusions.'

Response: Please see the response to comment 'Conclusions' at P11.

Reviewer 3: P12 L1-5 These statements are not wrong, but only repeat parts of the results. Please remove.

Response: We have reorganized the discussion section, and these lines also have been removed.

Reviewer 3: P12 L7-8 How do the authors think that the results presented here can facilitate the reconstruction of historical land-cover change? Please elaborate.

Response: We think by combining the LUH2 land-*use* transitions with the suggested rules for land-*cover* changes that could occur during those land-use transitions, it would enable the reconstruction of land-cover changes over the entire historical period. We have re-organized the whole discussion.

Reviewer 3: P12 L10 ff. It is still not clear at this point why rule 1/2 are 'better' than rule 3/4. Additionally, I wonder what is the added value of the study, if one of the main conclusions is that rule 1 is 'better' than rule 2 due to assumptions taken in HYDE.

Response: Our analysis takes the suggested rule from the HYDE3.2 paper, and subjects that rule to a series of tests designed to determine if that rule is consistent with multiple datasets and assumptions. This analysis goes beyond that which is presented in the HYDE paper. Furthermore, this analysis is performed within a consistent modeling frame-work, and in particular, with a different underlying map of land-cover/biomass.

Reviewer 3: P12 L24-30 While not wrong, I think irrelevant here as it (1) mainly repeats what has been written in the methods section and (2) does not provide justification for one of the rules presented. The authors should aim at emphasizing the reasons why they recommend rule 1 to CMIP6 models.

Response: We have re-organized the discussion section and also explained why rule is recommended.

Reviewer 3: P13 L6 Not clear why the authors introduce a new model here.

Response: we have removed it.

Reviewer 3: P13 L14 I do not agree with this statement/conclusion. Several rules presented here lead to similar results (within the range of reference maps) and justification is missing, why one of the rule is better than another. The claim that an 'optimal' rule has been determined by the analysis is not supported by the results.

Response: We have changed 'optimal' as 'recommended' and added extra figures and explanation at results section to support the justification of rule recommendation.

Reviewer 3: Figure 1 Isn't Fig. 1(b) a binary map (forest/no-forest)? In this case the legend doesn't make sense.

Response: No, it is the forest cover map of which most of grid-cells have fractions close to 100% at year of 850.

Reviewer 3: Figure 2 Please add difference maps to facilitate the identification of differences between the maps. Only 4 rules (instead of 9 as mentioned in the caption) are shown.

Response: Caption is corrected, and also the difference maps are included.

Reviewer 3: Table 1 Are the 'analytical rules' required for the purpose of the manuscript?

Response: Inclusion of Rules 5-9 could be used to interpret individual impacts of cropland, managed pasture and rangeland expansion, also give baseline estimates of resulting forest cover and vegetation for ESMs/DGVMs if similar rules are implemented.

Reviewer 3: Figure 3 For the analytical rules the x-axis labels are not centered any more.

Response: Figure 3 recreated to address this concern.

Reviewer 3: Figures 5-6 Why is rule 4 omitted from these Figs.?

Response: Rule 4 is included in the recreated Figures 5 and 6.

Reviewer 3: Figure 7 Also here difference maps would help to guide the reader.

Response: The difference maps have been added in Figure S2

Reviewer 3: Figure 8 Switch Rule 1 – Rule 2 (x-axis).

Response: Figure 8 recreated.

Reviewer 3: Figure 9 Differences between the rules hardly can be seen. Maybe zooming in for different percentages would improve the readability?

Response: We have modified Figure 9 by adding two zooming-in subplots.

Global ~~Transition~~ ~~Translation~~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 ~~accurately~~ quantify the magnitude of these impacts, climate models need consistent ~~land-cover and~~ 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 ~~transition~~ translation rules are evaluated based on assumptions about the way land-use change could potentially impact land-cover. ~~Building upon the~~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 ~~particularly in forest cover and carbon stock,~~ were simulated based on ~~each rule~~multiple alternative translation rules from 850 to 2015 globally~~ by Global Land use Model 2 (GLM2), at quarter degree spatial resolution~~. For each rule, t~~T~~he resulting forest cover, carbon density, and carbon emissions ~~for each rule~~ were compared with independent estimates ~~those~~ from remote sensing observations, U.N. Food and Agricultural Organization reports, and other studies. Examinations ~~with GLM2 model~~ at global, country, and grid scales indicate that the ~~optimal~~ recommended ~~transition~~ 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 ~~forested land (including both primary and secondary)~~ to rangeland; 3) ~~remain~~keep vegetation in land-use changes from primary non-forest and/or secondary non-forest~~forested land (including both primary and secondary)~~ to rangeland. ~~for vegetation growing in primary and secondary land (including both~~

forest and non-forest) to be completely cleared during the expansion of cropland, urban land, and managed pasture, and to remain during rangeland expansion only if the land was originally non-forested. This confirms the translationition rules suggested earlier in the HYDE dataset underlying LUH2. According to this rule, contemporary global forest area is estimated as to be 37.42 10^6 km^2, and forest area estimates at global and country scales both stay within the range derived from remote sensing products. Likewise, the eEstimated carbon stock is in high close agreement with reference biomass datasets, particularly over regions with 50% forest cover, and global and pantropical averaged absolution difference in carbon density between estimate and reference maps is under 2.5 kg C/m^2. . This rule also mitigates the anomalously high carbon emissions from land-use change observed in previous studies in the 1950s.

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)(Betts, 2001;Bonan, 2008;Feddema et al., 2005;Guo and Gifford, 2002;Post and Kwon, 2000;Pongratz et al., 2010;Brovkin et al., 2006;Claussen et al., 2001). It has been estimated that, dDuring 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) (Hurtt et al., 2006b). 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)(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)(Smith and Torn, 2013)(Smith and Torn, 2013)has a lower maximum potential biomass than primary forest (Nilsson and Schopfhauser, 1995). 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) (Dewar, 1991;Nave et al., 2010;Hurtt et al., 2011). Cumulatively, models estimate that land-use activitiesland-use and land-use change during 1870-2017 havehave contributed to a net flux of 190±75190 Pg C Pg C carbon to the atmosphere during 1870-2017 (Le Quéré et al., 2018)(Le Quéré et al., 2018)(Houghton and Nassikas, 2017). While these 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)(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) (e.g., see (Lawrence et al., 2016)(Lawrence et al., 2016), for land-use specific model simulations in the Coupled Model Intercomparison Project 6 (CMIP6), and (Brovkin et al., 2013) for CMIP5), Dynamic Global Vegetation Models (DGVMs) (e.g., see (Le Quéré et al., 2018)(Le Quéré et al., 2018) for simulations with 16 DGVMs for the annual carbon budget estimates), and bookkeeping models (Hansis et al., 2015)(see (Le Quéré et al., 2018) for usage of the bookkeeping models by (Hansis et al., 2015) and (Houghton and Nassikas, 2017) 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 specific simulations (LUMIP), and biodiversity studies (IPBES)the net land-use change carbon flux). 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)(Klein Goldewijk et al., 2017;Ramankutty and Foley, 1999;Pongratz et al., 2008;Kaplan et al., 2009) (e.g. HYDE, SAGE) {Goldewijk, 2017, Anthropogenic land use estimates for the Holocene–HYDE 3.2;Kaplan, 2009, The prehistoric and preindustrial deforestation of Europe;Ramankutty, 1999, Estimating historical changes in global land cover: Croplands from 1700 to 1992} and land-use transitions (Houghton, 1999; Hurtt et al., 2006, 2011)(Hurtt et al., 2006b;Hurtt et al., 2011;Houghton, 1999). In particular, the recent Land-Use Harmonization 2 (LUH2) dataset (Hurtt et al., 2017)(Hurtt et al., 2017b) harmonizes the most up-to-date historical data with 6 different future scenarios andhas been developed to provides 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 many of the above LULCC products (Chini et al., 2012; Houghton et al., 2012; Pongratz et al., 2014)(Houghton et al., 2012;Chini et al., 2012;Pongratz et al., 2014). For example, the Global Carbon Budget reports the spread of cumulative LULCC carbon emission during 1870-2017 estimated by DGVMs is as large as 75 Pg C though all models are forced by the LUH2 (Le Quéré et al., 2018)(Le Quéré et al., 2018). LULCC carbon emissions in CMIP5 have an anomalous spike during the years 1950-1960(Shevliakova et al., 2013). These anomalous emission estimates by ESMs (hereinafter referred to as the "pasture anomaly") are caused by an implausible high conversion rate of natural and secondary vegetation to pasture, with the 1950s having double the conversion rate of the 40's or 60's (Shevliakova et al., 2013). 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)(Shevliakova et al., 2013).

One reason for the above uncertainties is the lack of a explicit globally consistent rules that translate land-use change estimates into 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)(Di Vittorio et al., 2014;Di Vittorio et al., 2018;Brovkin et al., 2013;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 uere.1 in (Pongratz et al., 2018)(Pongratz et al., 2018)(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 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)(Klein Goldewijk et al., 2017). However, explicit suggestions for land-cover and 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 DGVMsand the current split is based on an aridity index and population density (Klein Goldewijk et al., 2017) rather than actual information on underlying natural vegetation being transformed in their land-cover (e.g., clearing of forest for pasture) vs keeping their land-cover while being put under a different use (e.g., shrubland being grazed without a transformation to a grassland). 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..

To recommend a global translation rule for translating historical land-use changes for CMIP6 models, To reduce the uncertainties in estimating land-cover dynamics, thisthis study investigates the impacts of land-use change on land-cover. by proposing sSeveral alternative sets of transitiontranslation rules, which ae then are proposed and integrated ed into the Global Land use Model 2 (GLM2) model (Hurtt et al., 2017, 2019)(Hurtt et al., 2019, 2017b;Hurtt et al., 2017a) 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 other independent estimates. The goal is to propose an optimal transition rule for converting historical land-use changes (from LUH2) to land-cover changes for use in ESMs and DGVMs. This optimal recommended rule combined with LUH2 could improve estimates of forest area and carbon stock 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 transitiontranslation rules. The historical land-use change information is specified by the LUH2 dataset (v2h, available at http://doi.org/10.22033/ESGF/input4MIPs.1127http://luh.umd.edu/) which serves as the forcing data for a new generation of advanced ESMs as part of CMIP6. Section 2.1 describes the details of land-use change characterization, and section 2.2 defines each transitiontranslation 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 with multiple published datasets of land-cover , , including Global Land Cover Characterization (GLCC)(Loveland et al., 2000), Global Land Cover (GLC2000)(Bartholomé and Belward, 2005), GlobCover(Bicheron et al., 2008), the MODIS Land Cover Product(Friedl et al., 2010), forest cover products(DeFries et al., 2000;Hansen et al., 2010;FAO, 2015) carbon stock, (Ruesch and Gibbs, 2008;Baccini et al., 2012), and estimates of land-use change emission (see details in section 2.5)(Pongratz et al., 2009;Houghton, 2010;Le Quéré et al., 2018;Stocker et al., 2011;Reick et al., 2010;Shevliakova et al., 2013;Houghton and Nassikas, 2017).

2.1 Land-use change characterization

LUH2 (version v2h) provides global, annual, gridded land-use states and transitions for the historical period 850-2015, and connects continuously to 6 different future scenarios from Integrated Assessment Models for the years 2015-2100 (Hurtt et al., 2017b). LUH2 accounts for diverse human-induced land-use activities including agricultural management, deforestation, and urbanization. LUH2 also includes bi-directional changes between natural forest and managed land (pasture and cropland) within a grid cell, including the effects of wood harvest and shifting cultivation. Since the rate of carbon loss due to deforestation is much faster than the carbon accumulation rate in the recovery process, using these gross land-use transitions helps to correct the underestimation of LULCC carbon emissions based only on the net transitions (Arneth et al., 2017). The LUH2 dataset was generated with the GLM2- (Hurtt et al., 2017, 2019)(Hurtt et al., 2017b;Hurtt et al., 2017a;Hurtt et al., 2019), which, like its predecessors , GLM(Hurtt et al., 2006, 2011)(Hurtt et al., 2006a;Hurtt et al., 2011), estimates annual sub-grid-cell land-use states and transitions using an accounting-based method.by including This model determines the fraction of every grid cell transitioning between each land-use type (e.g. primary land, cropland, urban) at each time step using multiple multiple data-driven constraints such as including gridded patterns of historical land-use from the HYDE database (Goldewijk et al., 2017)(Goldewijk et al., 2017), historical national wood harvest reconstructions, and potential biomass and recovery rates (Hurtt et al., 2006, Hurtt et al, 2011), and others. (Hurtt et al., 2006a;Hurtt et al., 2011). Building upon previous work from CMIP5, for which the original LUH1 dataset was used, LUH2 has updated inputs from HYDE for historical agricultural patterns (Klein Goldewijk et al., 2017), a new historical wood harvest reconstruction, new maps and rates of shifting cultivation, extendeds the timespan to 850-2100 and increased spatial resolution toat 0.25×0.25˚., and constrains the forest cover gross transitions using remote sensing observations (Hansen et al., 2010). 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 ~~Transition~~Translation rules

Nine ~~transition~~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~~ 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 ~~2~~ 3 differ in treatment of vegetation in non-forested land when converted to ~~managed pasture~~rangeland, and the resulting difference between their ~~forest and~~ carbon stocks indicate the impact of ~~managed pasture~~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)~~(Klein 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 ~~transition~~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 ~~transition~~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 ~~some r~~Rules 5-9 ~~(labelled as analytical rules)~~ 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 ~~analytical rule~~ Rule 6 could suggest individual impact of cropland expansion.

2.3 Simulation of land-cover change

In this study, land-cover change is simulated ~~within~~ by performing a modified~~the~~ GLM2 simulation in which the computed ~~by combining~~ land-use transition rates (using the same methodology as~~from~~ LUH2) are supplemented with a set of ~~-with each transition~~translation rules (Table 1) to track forest cover change and carbon dynamics at 0.25º spatial resolution. GLM2 uses a statistical model to estimate ~~, a global extension of the Miami ecosystem model(Lieth, 1975) is used to estimate the historical potential distribution of vegetation carbon stocks and carbon recovery rates of primary natural vegetation.~~ ecosystem stocks and fluxes with temperature and precipitation as inputs (see (Hurtt et al., 2002)(Hurtt et al., 2002)~~(Hurtt et al., 2002)~~ for details). Climatological temperature and precipitation during 1901-2000 were produced from the MSTMIP (Wei et al., 2014) and used to spin up the 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.

The Miami model was run globally at 0.25×0.25° resolution using MSTMIP climatology(Wei et al., 2014), environmental factors were not taken into consideration such as CO_2 fertilization or nitrogen limitation. It resulted in an estimated global vegetation carbon stock (including above- and belowground) of 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 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., 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).

When land is converted to cropland, managed pasture, and/or rangeland, each transitiontranslation 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 transition rate from forest to pasture, if the applied transitiontranslation 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-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:

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

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, rangeland, urban) at time t, $f^{gained}(i,t)$ and $f^{lost}(i,t)$ are the vegetation fractions gained or lost to/from land-use type i, and they could be calculated: $f^{gained}(i,t)$ 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.

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

$$f^{lost}(i,t) = \frac{f(i,t)}{l(i,t)} \sum_{k=1,k\neq i}^{8} a_{ki}\ , (i = 5,6,7,8; k = 1,23,4,\cdots,8)\ , \quad (3)$$

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 ~~transition~~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~~ Rules 1 and 2, but 0 for the same type of change in ~~rules~~ Rules 8 and 9. This translator factor is 1 for all types of land-use change in ~~rule~~ Rule 3 since all vegetation is cleared during all land-use changes. $l(i,t)$ is the land-use fraction estimate by LUH2 for ~~of land-use~~ 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~~remain or be lost ~~or remained~~ in land-use ~~changes~~changes to cropland, pasture or rangeland depending on ~~transition~~translation rules. According to the definition of primary land in the LUH2, ~~that the land previously undisturbed by human activities,~~ 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 ~~vegetation cover~~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. ~~recovered through the process of abandonment of these non-primary and non-secondary land-use.~~ 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:

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

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

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

~~=, , (5)~~

~~=, , (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.

~~Therefore, the resulting forest cover at time *t* in from these nine rulestranslation rules includes the vegetation originally growing in on primary and secondary forested land, vegetation recovered from abandoned cropland, managed pasture and rangeland, and vegetation remaining in cropland, managed pasture, rangeland and urban which is not cleared during land-use change.~~

2.4 Simulation of vegetation carbon dynamics

~~Forest~~ 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. ~~(Erb et al., 2018) noted that c~~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)~~(Erb et al., 2018)~~.

Similar to land-cover change simulation in section 2.3, if ~~transition~~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 ~~mean~~ age is set as zero. If vegetation is not cleared based on ~~transition~~translation rules, the biomass remains but ceases to increase, and the ~~mean~~ age of this vegetation also remains unaffected, because the ~~mean~~ 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 calculated over all vegetation with different ages, -then the mean age increases year by year and ~~the~~ biomass regrows towards equilibrium~~, and the mean age of vegetation increases year by year~~. Thus, the biomass density in secondary vegetation at time t is calculated for each grid cell using its ~~stand~~ mean age, potential biomass, and potential NPP:

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

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 Miami GLM2 model and varied by grid location (shown in Figure.1a), 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 constant over simulation period from 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 land-cover transitiontranslation rules, as well as lands that convert from human management back to natural lands. Thus, the total carbon stocks in this study should are expected to be lower than other estimates (Houghton, 2003; Saatchi et al., 2011)(Houghton, 2003)(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 transitiontranslation rules

To evaluate which transitiontranslation 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 transitiontranslation 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.

To produce a reference map of contemporary forest coverDiagnostics 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)(Loveland et al., 2000;Bartholomé and Belward, 2005;Bicheron et al., 2008;Friedl et al., 2010;DeFries et al., 2000;Hansen et al., 2010) (see Table 2) are collected as well asand the Global Forest Resources Assessment (FRA) 2015 (FAO, 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)(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)(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 ~~transition~~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 ~~transition~~translation rules. Two datasets were employed: the IPCC Tier-1 biomass carbon map for the year 2000 (Ruesch and Gibbs, 2008)(Ruesch and Gibbs, 2008)~~(Ruesch and Gibbs, 2008)~~ and a pantropical biomass map (hereinafter referred to as the Baccini's product~~-~~ (Baccini et al., 2012)~~(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 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.

In addition, the ability of the ~~transition~~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)~~(Reick et al., 2010;Stocker et al., 2011;Houghton, 2010;Houghton and Nassikas, 2017;Shevliakova et al., 2009;Pongratz et al., 2009;Le Quéré et al., 2018)~~. 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 treatment of environmental change, for example, (Pongratz et al., 2009; Reick et al., 2010; Shevliakova et al., 2009; Stocker et al., 2011) ~~(Reick et al., 2010;Stocker et al., 2011;Shevliakova et al., 2009;Pongratz et al., 2009)~~ include effects of evolving climate or atmospheric CO_2 concentration on LULCC emissions, which is not accounted for in bookkeeping mode based studies (Houghton, 2010; Houghton and Nassikas, 2017)~~(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 ~~transition~~translation rules. We posit that the ~~optimal~~ recommended ~~transition~~translation rule should not produce anomalous carbon emissions that are outside the compiled range.

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 ~~transition~~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 ~~determined optimal~~recommended ~~transition~~translation rules should produce: 1) the ~~most accurate~~ forest cover ~~that has~~with the smallest difference with diagnostic maps at global, country and grid scale, ~~and~~ the total forest cover at global and country level should be ~~within~~ 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 ~~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 rangeland has handled in HYDE (Goldewijk et al., 2017)~~(Klein Goldewijk et al., 2017)~~ will also be taken into account in identifying the ~~optimal~~ recommended rule.

3 Results

3.1 Potential forest cover and biomass carbon

The ~~Miami~~GLM2 ~~It resulted in an estimated~~estimates -global vegetation carbon stock (including above- and belowground) in 850 ~~of~~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 Pg C in~~-~~ (Kucharik et al., 2000)~~(Kucharik et al., 2000)~~, 772 Pg C in (Pan et al., 2013)~~(Pan et al., 2013)~~ and 923 Pg C in~~-~~ (Sitch et al., 2003)~~(Sitch et al., 2003)~~. Forested land in GLM2 is defined as land which has aboveground potential biomass of at least 2 ~~K~~kg C/m^{2} (Hurtt et al., 2006, 2011)~~(Hurtt et al., 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)~~(Pongratz et al., 2008)~~, and potential forests and woodlands area was 55.3 million km^2 in~~-~~ (Ramankutty and Foley, 1999)~~(Ramankutty and Foley, 1999)~~.

3.~~1~~ 2 Forest cover evaluation

The global gridded forest cover maps resulting from ~~rules~~ Rules 1-4 in 2000 are generally consistent in forest extent with satellite-based observations (shown in Figure 2). For example, they all estimate ~~higher~~ high forest cover in tropical rainforests and northern boreal forests but low~~er~~ cover in ~~western~~ Western USA, ~~eastern Australia,~~ Eastern Europe and Central Asia. As ~~rules~~ 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 from ~~rules~~ Rules 1, 2, and 3 are the same. All rules of 1-4 consistently estimate higher forest cover than the averaged satellite-based forest cover in W~~w~~est Siberia and South~~southern~~ China, and lower forest cover in African savannas and East Siberia, Western Mexico and Argentina. Separately, Rule 4 shows larger forest cover than Rules 1-3 in S~~s~~outh and S~~s~~outheast 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.

The total area of global forest in 850 amounts to 47.82 million km^2 according to the ~~Miami~~ 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 ~~transition~~translation rules produce a wide range of global forest cover in 2000 from 37.42 to 45.89 million km^2. In ~~rules~~ Rules 1, 2, and 3, the 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 R~~r~~ule 4 forest remains during ~~conversion to~~ 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 ~~Analytical~~ 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 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.~~79~~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)~~(Sexton et al., 2016)~~. The global forest area in the year 2000 resulting from ~~our~~ the ~~transition~~translation rules are compared to the range of seven diagnostic estimates (Figure 3b). The forest cover based on ~~analytical Analytical~~~~rules~~ Rules ~~7~~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, ~~rules1~~Rules 1-4, ~~Analy~~5 and 7 produced estimates of global forest area within the range of diagnostics.

The forest cover estimation from ~~transition~~translation rules are further compared with diagnostic datasets at the country level. 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. ~~Rules 1-4 also produce the same pattern of locating most forest land within these eight countries (Table 4).~~ The forest cover estimates from ~~rules~~ Rules 1-4 are generally well within the range of diagnostics for most of the eight countries (e.g. Brazil, Indonesia, and United States of America) in terms of forest area and slightly overestimated in the Russian Federation and Canada, where the estimates of ~~rules~~ Rules 1-3 are closer to the upper bound of the diagnostics than ~~rule~~ Rule 4. China and Brazil are the two countries where Rules 1-4 shows relatively larger difference in forest area and the difference are 1.17 million and 1.08 million respectively. ~~Analytical~~ Rule 5 and 7 overestimated forest area of China, Russian Federation and Canada though their global forest areas are within the range of diagnostic.

These comparisons evaluate the ~~accuracy~~ resulting gross forest cover of the ~~transition~~translation rules ~~in translating land-use change to land-cover change in terms of gross forest cover~~ 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 ~~was~~ were used to calculate the average of absolute difference across global grids (Figure 4) respectively. Rule~~s~~ 1, 2, and 3 consistently produce the smallest overall difference than Rule 4 and other rules ~~(i.e. below 90 km^2) with the averaged satellite-based forest cover map~~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. Regional comparison of average of absolute difference (Figure S1) suggests Rule 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.

3.~~2~~ 3 Evaluation of carbon dynamics

The net carbon emissions of the nine ~~transition~~translation rules ~~was~~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 ~~rules~~ 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, R~~r~~ule 3 produced the largest emissions as the carbon in both forested and non-forested land is released for all land-use changes, and ~~rule~~ 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, R~~r~~ule~~s~~ 1, 2, 3 and 4 estimated comparable emissions with other studies, while the emissions of the ~~analytical~~ R~~r~~ules 6-9 are out of range (Table 5).

Carbon emissions from pasture expansion were calculated for LUH1 (Hurtt et al., 2011)~~(Hurtt et al., 2011)~~ and this is used as a baseline to assess the improvement of ~~transition~~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. In LUH1, the anomalous emissions spike during 1950-1960 mainly arises from overestimating the emissions from pasture expansion, especially in ~~four~~ three regions ~~and countries~~ (i.e. ~~west and central~~ Africa, ~~China~~East, South and Central Asia, ~~former~~ and North ~~USSR~~ America~~and South America excluding Brazil~~). The carbon flux from expansion of managed pasture and rangeland in LUH2 was ~~significantly~~ reduced at global (Figure 5) and regional (Figure 6) scales in simulations based on ~~rules~~ 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 ~~the~~ anomalous emissions ~~more significantly~~ than ~~rule~~ Rule 1 (reduced 6 Pg C in ~~rule~~ Rule 1 and 7 Pg C in ~~rule~~ Rule 2), because ~~rule~~ Rule 1 completely clears vegetation when transitioning to managed pasture, whereas ~~rule~~ 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 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 Rules 1 and 2 -3 still best capture the carbon density heterogeneity (Figure 8)with the bias less than 2.2 Kg kg C/m^2 at global comparison and produce bias less than 2 Kg kg C/m^2 for aboveground biomass at pantropical comparison. Regional comparison of the IPCC Tier-1 biomass map and rule estimates indicate Rules 1-4 have comparable AAD of carbon density 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 if Rules 1 and 2 significantly outperform Rule 3 or if Rule 2 significantly outperforms Rules 1 and 3, because bias in of the IPCC Tier-1 biomass very likely shift the zero line of Figure S5b either toward peak of Rule 3 or Rules 1 and 2. Three bias levels of IPCC Tier-1 biomass map (i.e. ±10%, ±20% and ±30%) were discussed considered and resulting shift range of zero line is shown as grey shaded box (in Figure S5b). It could be seen that the peaks of Rules 1-3 fall into the shifting range, meaning none of Rules 1-3 robustly produced better carbon estimates than other two rules at three bias levelsAt these levels of uncertainty in the reference, Rules 1-3 could not be distinguished in performance. Finally,

the carbon stock comparison between Rules 1-3 (Figure 9) similarly comparesshows tThe total carbon stock, grouped by forest cover using the averaged satellite-based forest cover map, from rules 1, 2, and 3in comparison with are compared with IPCC Tier1 and the Baccini product (Figure 9). these three rules showhaveunderestimate carbon stock at low forest fraction, but and give better agreement with diagnostics as forest fraction increases. Rssomewhatagreement of The locations where rules 1-3 produce different estimates in carbon density are shown in Figure S3a. Rule 3 underestimate the carbon density of most of the location (shown in Figure S3b), the difference histograms of rules 1 and 2 are closers to zero, suggesting the improvement in carbon density estimates. The improvement could be found in Ukraine and eastern Russia, China and US.

Rules 1 and 2 still produce the closet carbon stock compared to the two diagnostic datasets, especially for grids with higher forest fraction (e.g. >50%), and slightly underestimate for grids with higher fraction of non-forest land-use which may result from zero biomass assigned to these lands after land-use change.

4 Discussion and Conclusions

/*main results*/ This study discussed quantified the result of multiple alternative translation rules for estimating the potential effects of land-use change on landcover possible alterations of land-cover as a result of prescribed land-use change and simulated the resulting forest cover and carbon dynamics through GLM2 modelutilizing the LUH2 data-set, and the underlying land model embedded in it (GLM2). -The evaluations of forest cover and carbon on forest area at both global, and country and grid level , and forest cover difference at grid level jointly indicate that rRules 1-3 outperform s other rules and are able produce the closest estimates of estimatescontemporary forest cover an carbon to global diagnostics. from the LUH2 toin comparison with the satellite-based forest cover datasets from the LUH2. Rule 4 and analytical rule 5 have relatively larger error in grid level estimates though their global forest areas are within the range of satellite-based estimates. Moreover, the evaluation of carbon stock and LULCC emissions similarly indicate similar results that rules 1-3 estimateoutperform other rule with reasonable historical LULCC emissions, reduced emissions from pasture in 1950s and the smallest error in carbon density in comparison with diagnostics. Rule 4 and analytical 5 produce LULCC emissions with range of diagnostics and even smaller 1950s pasture emissions than rules 1-3, however, these two rules show larger error in carbon density at grid level than rules 1-3 (Figure 8).Differentiation between Rules 1-3 depends largely on estimates of forest carbon because these rules produce equivalent estimates of forest cover. Comparisons of carbon stock and gridded difference in carbon density have shown that R rules 1 and 2 produce less underestimationbetter estimates of carbon density than Rrule 3 relative to references. Factoring in the uncertainty in the carbon density reference 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.

Further examination of the Therefore, rule 3-5 are excluded from recommendation by jointly considering all evaluations of forest cover and vegetation carbon.

cfrom these were compared to

/*importance land cover recon, uncertainty in carbon*/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, and the resulting contemporary forest cover and carbon density are comparable to independent estimates. Furthermore, this study also provides insights into the uncertainty attribution of LULCC emissions estimates from ESMs and DGVMs. 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)(Jones et al., 2013). 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 Rrules 1-4 and it could be larger when other rules are implemented.

/*dependencies and caveats*/When considering translation rules, Rules 1-3 have comparable error

The comparisons on forest cover, carbon stock and LULCC emissions ultimately indicates that both rules 1 and 2 could accurately translate land-use change to land-cover change and reproduce the majority of current forest cover and plant carbon stock. Specifically, these rules state that the vegetation growing in primary and secondary land (both forested and non-forested) is completely cleared and all carbon released during the expansion of cropland and urban land, but vegetation remains only during rangeland expansion on non-forested land (rule 1) or remains during managed pasture and rangeland expansion if the land is non-forested originally (rule 2). The vegetation remaining in managed pasture and rangeland is cleared when the land is subsequently converted to non-primary and non-secondary land (i.e. cropland, urban, managed pasture and rangeland). As a result, based on rule 1 (2), forest area decreased to 37.42 million km^2 in 2000, LULCC results in 70 (72) Pg C carbon emissions during 850-1850 and 170 (175) Pg C during 1850-2000, further reducing pasture anomaly emissions by 6 (7) Pg C in 1950-1960s.

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. The information from this study could facilitate reconstruction of historical land-cover change; building upon LUH2, the suggested transition rules could reproduce the smallest difference in contemporary forest cover and carbon stock with independent estimates from remote sensing. Currently, rule 1 is recommended by LUH2 to translate the land-use change transitions into land-cover transitions in ESMs or DGVMs. While transition rule 2 generates a global forested area which is closer to the averaged remote sensing-based estimates, the difference in the forested area simulated by rules 1 and 2 is within the margin of uncertainty for remote sensing-based products, and is therefore scientifically insignificant. Therefore, recommendation of rule 1 over rule 2 is based on an assumption about the way in which rangeland versus managed pasture is established and managed, which is also consistent with the recommendation in HYDE 3.2 dataset(Klein Goldewijk et al., 2017) that removes all vegetation when establishing cropland, urban land, or managed pasture, and leaves all vegetation when establishing rangeland, regardless of the underlying vegetation type.

More rigorous evaluation of the land-cover dynamics resulting from various transition rules from 850 to present is difficult because the available diagnostic datasets only document the land-cover and carbon stock in recent decades. For example, most global satellite-based observations only estimate land-cover after 1980 (DeFries et al., 2000;Loveland et al., 2000;Bartholomé and Belward, 2005;Bicheron et al., 2008;Friedl et al., 2010;Hansen et al., 2010). Alternatively, contemporary measurements were used as diagnostics to assess the translation accuracy of each transition rule. This is because, in principle, the effects of prior land-use change activities before 2000 are manifested in the current state of land-cover (e.g. forest cover and carbon stock). As the current land-cover state is the cumulative sum of natural state and alterations from previous land-use change, the error of incorrect translation of land-use change to alterations on land-cover will also be accumulated throughout and eventually result in a biased estimation when compared to diagnostics. Therefore, the optimal transition rule should reproduce the current land-cover state. In addition, multiple estimates of land-cover and carbon density from independent studies were employed to reduce the inherent uncertainties of diagnostics. Six widely used global land-cover datasets were integrated into an average map aiming to reduce the uncertainties that stem from a particular model or sensor observation. Similarly, for assessing carbon stock, two different and independent datasets were collected.

iIt is important to note that the determined transitionthe results of this study may depend rules strongly depend on the land-use change dataset being used, the andland-cover properties being evaluated, reference datasets, and the modelsand the diagnostics used for evaluation. This study used the LUH2 dataset because of its required used in CMIP6 and widespread used in other studies. With GLM2, rRule 1 and rule 2 could provide forest cover, carbon density and historical LULCC emissions matched with the independent estimates from remote sensing and other studies, and this rule only serve to translate the changes for the LUH2 dataset to corresponding land-cover change. . These two rules provide the best match of forest cover and terrestrial carbon stock from LUH2. The land cover propertiesis evaluation was addressed here include only based on two critical properties of land-covervariables (i.e. forest cover and carbon stock) due to their significance in the exchange of water, mass, and energy between atmosphere and land surfacebiophysical and biogeochemical significance. MBesides, multiple sources of diagnosticsdatasets based on remote sensing and other sources were selected for evaluation with the intention to provide a reduce the inherent uncertainties stemming from a particular model or sensor observationrobust reference. The use of GLM2 model was selected to provide the most internally consistent treatment of these issues given its role in producing the LUH2 dataset. Given these considerations, its is possible that different results could be obtained for different systems.Recommendation of different rules is expected when different land-cover properties are evaluated against other or improved diagnostic datasets or simulate by other models.

Uncertainties of the recommended rule could result from many reasons including uncertainties from diagnostics, rule design, and forest and carbon dynamic modelling. 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. Combined uncertainties from forest cover and vegetation carbon diagnostics may limit the evaluation of translation rules, especially in locations where forest cover or vegetation carbon is low. Moreover, this study does not consider regionally/gridded varying rules and also assumes hard-clearing in land-cover changes, meaning the vegetation would be totally removed or left totally intact. However, region/grid-specific rules or soft-clearing may be more realistic in which part of the vegetation (quantified as the clearance ratio) is cleared. For example, the evaluation in Figure S5C indicates rule 3 produce less bias in carbon density estimate at Kazakhstan and Mongolia if assume the uncertainty of IPCC Tier-1 biomass map is very small. However, region/grid-specific rules or soft-clearing may add complexity for the implementation in ESMs/DGVMs or even uncertain with the given uncertainties of diagnostics of forest cover and vegetation carbon. Furthermore, In addition to carbon stock, the dynamics of forest cover and vegetation carbon from past to present highly interact with climate change and increasing atmospheric CO_2, which is are not considered in this study. Finally, In addition, the forest area and the LULCC carbon emissions and carbon density as resulting from LUH2 and the transition rules in this study are based on a simple global terrestrial model (i.e. Miami-LU model) and its uncertainties. Although the Miami-LU model includes the spatial heterogeneity in vegetation regrowth rate and tracks subgrid-scale heterogeneity of carbon density in a manner similar to the more advanced Ecosystem Demography (ED) model (Hurtt et al., 1998;Moorcroft et al., 2001;Hurtt et al., 2002a), the carbon emission estimates using the same transitiontranslation rules and land-use change dataset would bemay be different if using other carbon models/DGVMs or carbon accounting models were used. For example, the emissions from other studies in Table 3 may include emissions from soil pool decomposition, which is not accounted for in our model. Besides, the potential forest cover and carbon stock of GLM2 may also vary largely across other ESMs/DGVMs, thus the difference may be propagated to resulting contemporary forest cover and vegetation carbon.In addition, rules other than 1 and 2 may produce better regional land-cover dynamics; new studies aimed at determining continental-, country- or grid-specific transition rules are needed. Finally, the transition rules are defined as hard-clearing, meaning the vegetation would be totally removed or left totally intact. However, soft-clearing may be more realistic, in which part of the vegetation (quantified as the clearance ratio) is cleared. Future studies could focus on optimizing the clearance ratio using multiple land-cover type datasets.

/*conclusion*/ Future researchThis study determines an optimalrecommendeds a global transition rule that matched forest cover and carbon stock estimates from multiple vetted sources. However, more research is needed to investigate both the robustness of these findings, and potentially identify even more optimal better implementations. The CMIP6 LUMIP study is designed to quantify some of these effects (Lawrence et al., 2016)(Lawrence et al., 2016)(Lawrence et al 2016) through model inter-comparison. Additional work on translation rules should include possible spatial/temporal variiying tulesrules, partial land clearing, and more land cover variables (e.g. forest age, height, soil carbon, energy balance).
the improvement of this rule on LULCC carbon emission estimates such as if the rule could mitigate anomalous emissions from pasture/rangeland expansion during 1950s in CMIP6. To further reduce uncertainties in estimating land-cover dynamics, research could be expanded with emphasis on spatially and temporally varying rules. In addition to forest cover and carbon, more land-cover characteristics (e.g. forest age and tree height) are encouraged to be integrated to determine and constrain the optimal transition rules.

Code and data availability. The source code of the modified GLM2, source and citation of inputs, results of all translation rules and scripts for producing figures and tables are~~is~~ ~~available~~ archived at~~-~~ https://doi.org/10.5281/zenodo.3533792 ~~http://luh.umd.edu/code.shtml~~, LUH2 dataset is available at http://doi.org/10.22033/ESGF/input4MIPs.1127~~http://luh.umd.edu/data.shtml~~. IPCC Tier-1 ~~-~~biomass is available at https://cdiac.ess-dive.lbl.gov/epubs/ndp/global_carbon/carbon_documentation.html, Baccini's aboveground biomass is available at https://doi.org/10.3334/ORNLDAAC/1337~~https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1337~~. TCCF, MODIS LC, GLCC, GFC, GLC2000 and GlobCover can be obtained from http://www.landcover.org/data/treecover/, https://doi.org/10.5067/MODIS/MCD12Q1.006, https://doi.org/10.5066/F7GB230D, https://earthenginepartners.appspot.com/science-2013-global-forest~~http://www.landcover.org/data/treecover/ , http://www.landcover.org/data/lc/ , https://edcftp.cr.usgs.gov/project/glcc/globdoc2_0.html , https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.6.html , https://forobs.jrc.ec.europa.eu/products/glc2000/data_access.php, http://due.esrin.esa.int/page_globcover.php ,~~ https://forobs.jrc.ec.europa.eu/products/glc2000/glc2000.php, http://due.esrin.esa.int/page_globcover.php respectively. ~~All other data are available from authors upon reasonable request.~~

Author contributions. LM, GH, LC and RS designed this study. LM conducted the simulations and wrote the main body of the paper. All authors discussed the results and commented on the paper at all stages.

Competing interests. The authors declare that they have no conflict of interest.

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Figures & Tables

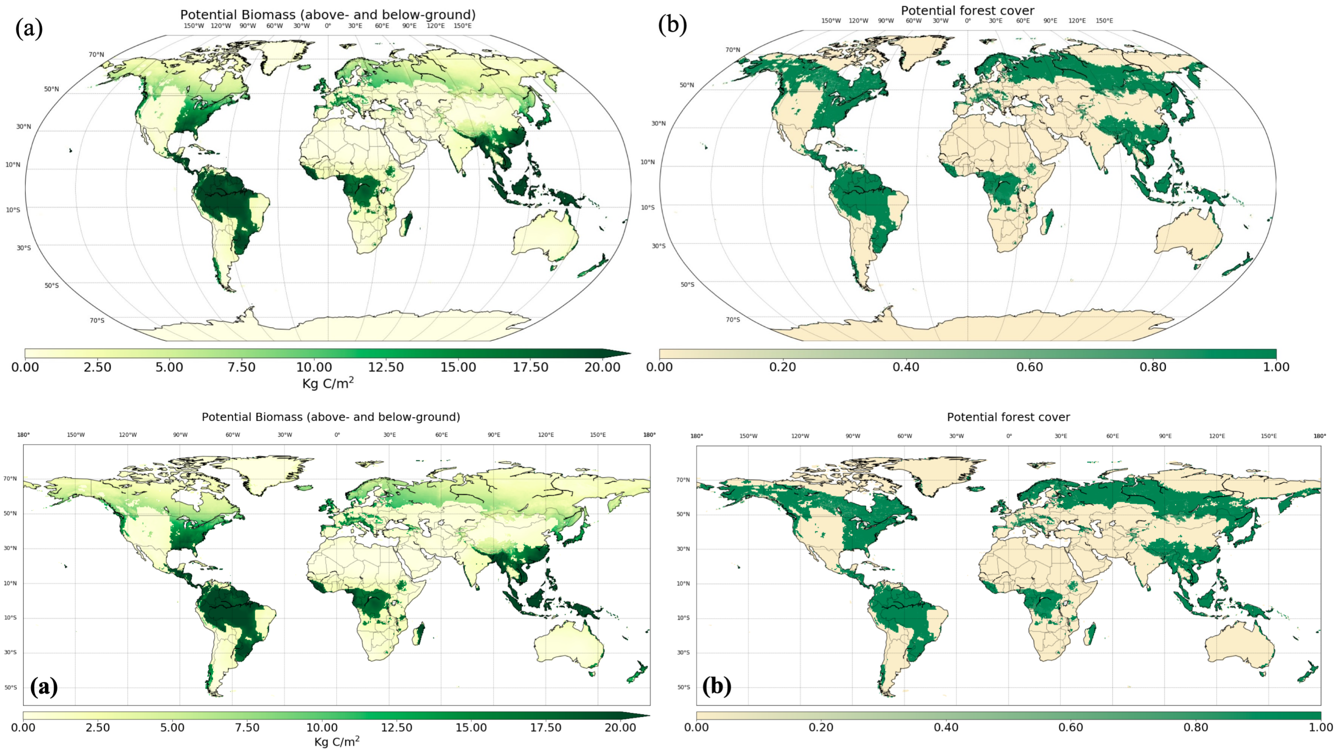
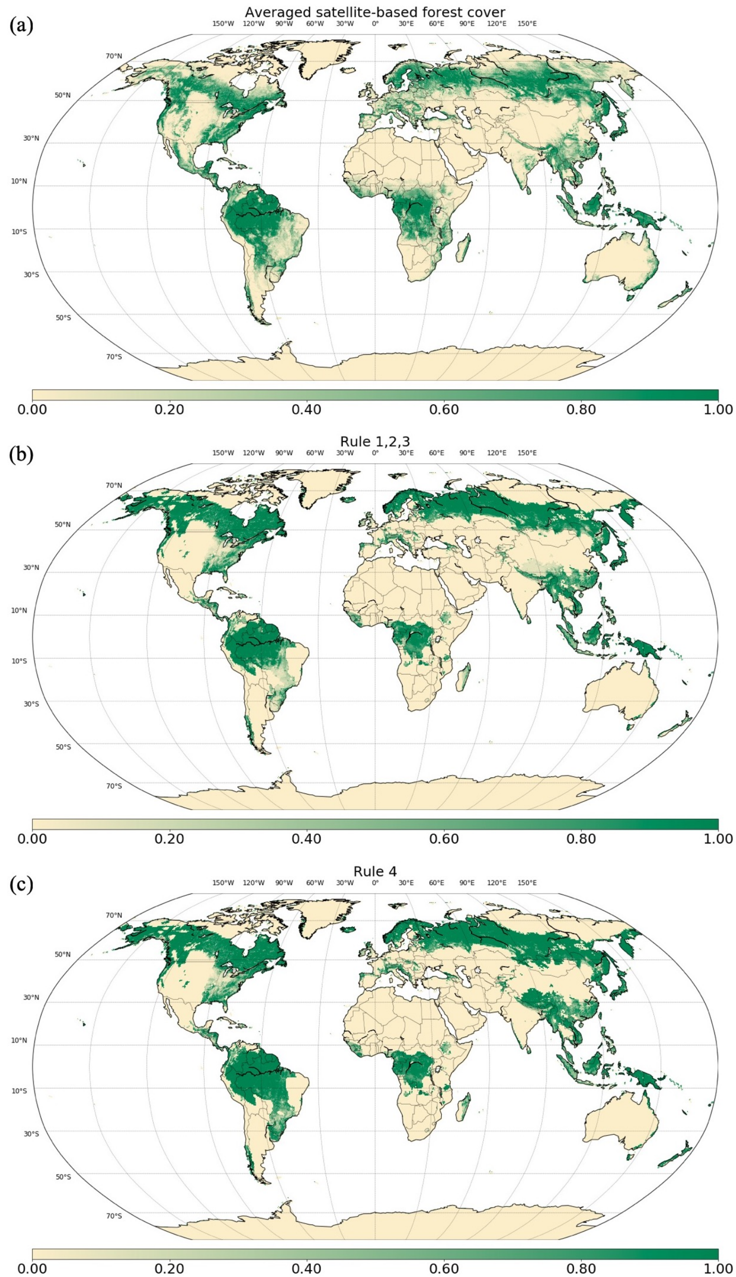


Figure 1. Potential biomass density (a) and potential forest cover (b) in 850 estimated by ~~Miami~~ GLM2 model.


(a)
Averaged satellite-based forest cover
0.00
0.20
0.40
0.60
0.80
1.00
(b)
Rule 1,2,3
0.00
0.20
0.40
0.60
0.80
1.00
(c)
Rule 4
0.00
0.20
0.40
0.60
0.80
1.00

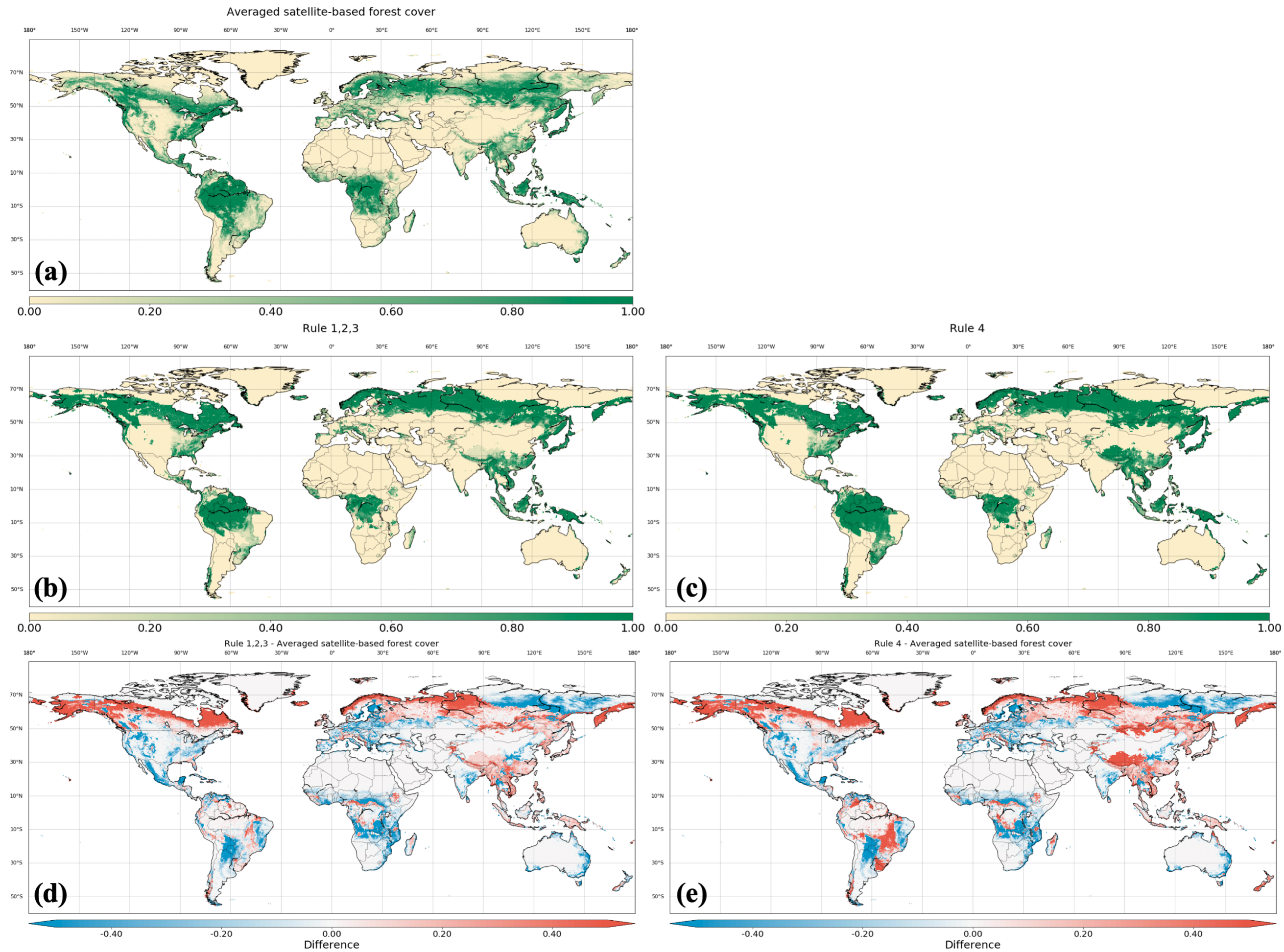


Figure 2. Forest cover in 2000 from the ~~Global forest cover in 2000 estimated by the 9 transition rules and the~~ A~~a~~veraged satellite-based forest cover in (a), ~~map~~ Rule 1, 2, 3 in (b) and Rule 4 in (c). (d) and (e) are maps of forest cover difference between (b) and (a), and (c) and (a) respectively.~~. (a) Averaged satellite-based forest cover map; (b) Rule 1, 2, 3; (c) Rule 4.~~

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 ~~forest~~.

Transition Rule	Rule 1	Rule 2	Rule 3	Rule 4	~~Analytical rule~~Rule 5	~~Analytical rule~~Rule 6	~~Analytical rule~~Rule 7	~~Analytical rule~~Rule 8	~~Analytical rule~~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.

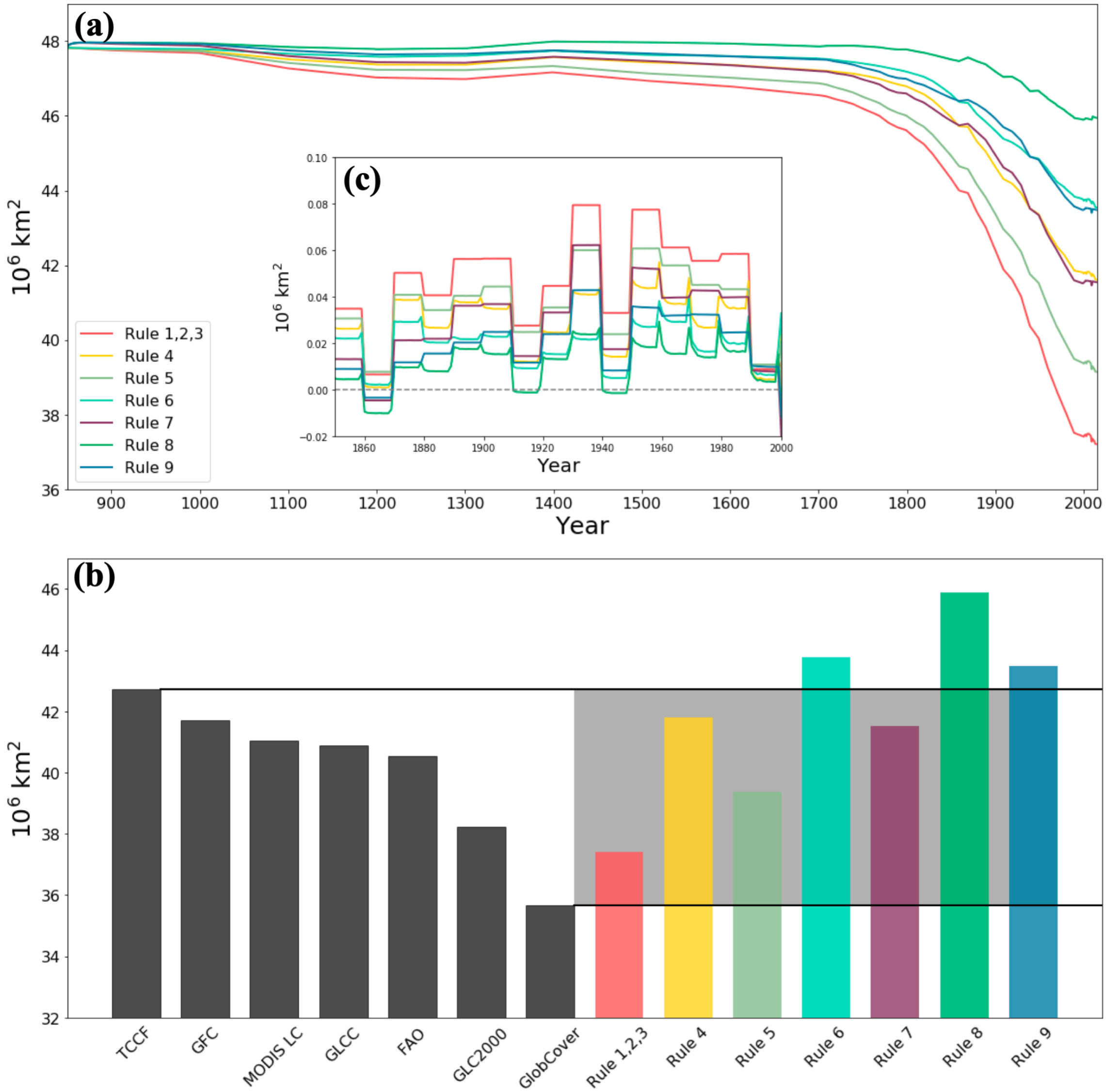
Product	Global Forest Area (10^6 km^2)	Time	Publication	Data Type/Classification Scheme
GLCC	40.89	1992-1993	Loveland et al. 2000	Land Cover (IGBP)
GLC2000	35.79	1999-2000	Bartholome et al. 2005	Land Cover (GLC 2000)
GlobCover	37.38	2004-2006	Bicheron et al. 2008	Land Cover (GlobCover)
MODIS LC	38.60	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)	41.93	2000	Hansen et al. 2010	Tree Percentage
FAO	40.55	2000	FRA 2015	National Censuses

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


(a)
(b)
(c)
10⁶ km²
Year
Rule 1,2,3
Rule 4
Rule 5
Rule 6
Rule 7
Rule 8
Rule 9
TCCF
GFC
MODIS LC
GLCC
FAO
GLC2000
GlobCover

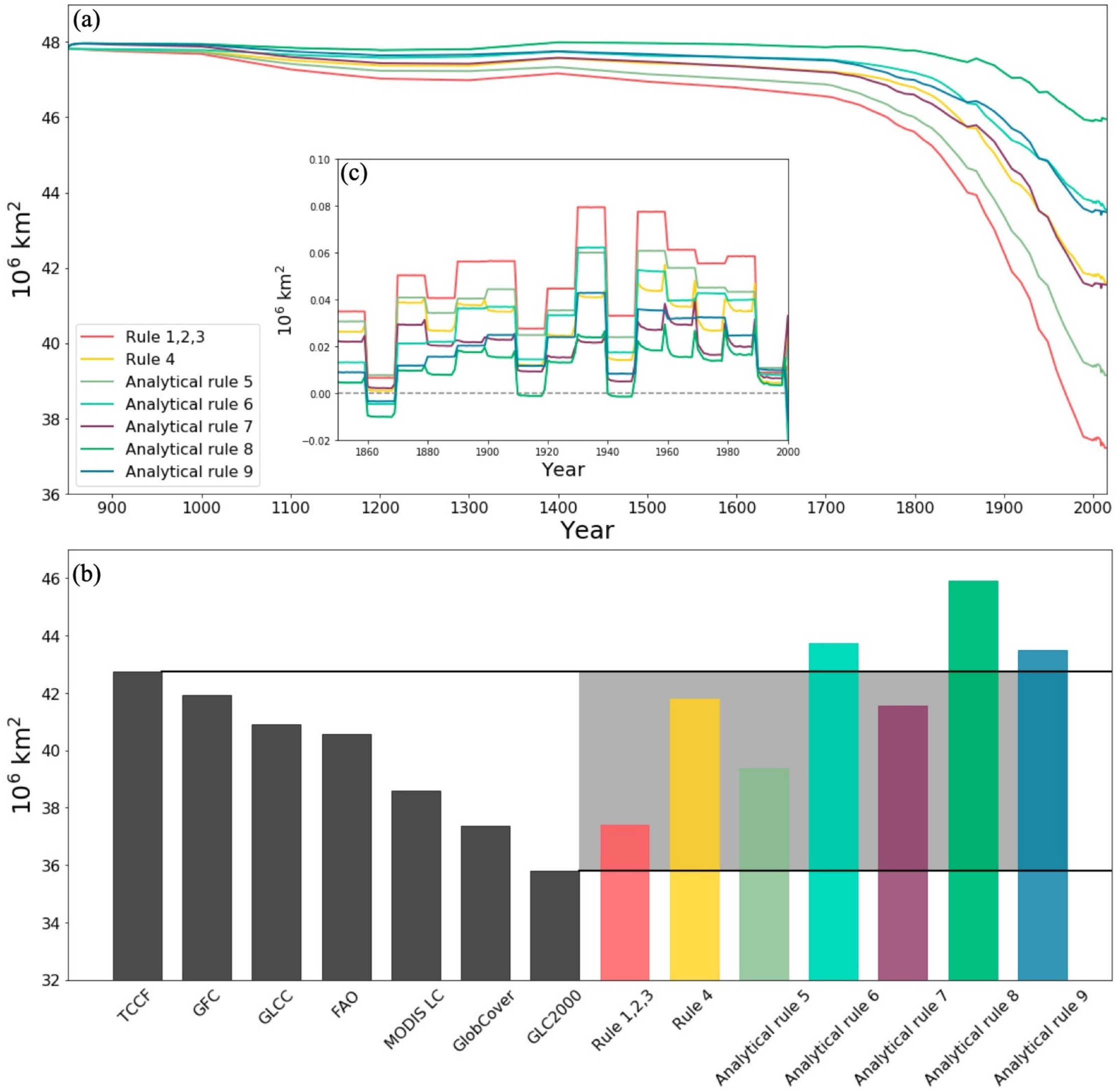


Figure 3. (a) Global forest area resulting from ~~transition~~translation rules from 850 to 2015; (b) Comparison of global forest area in 2000 between remote sensing and FAO (shown as black bars) and results of ~~transition~~translation rules (colored bars); (c) Annual change rate from 1850 to 2000. Positive value indicates the forest loss.

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 transitiontranslation 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**	**Analytical ruleRule 5**	**Analytical ruleRule 6**	**Analytical ruleRule 7**	**Analytical ruleRule 8**	**Analytical ruleRule 9**	
Russian Federation	8.7672	9.1815	8.8480	9.2723	9.0501	9.4844	9.1310	6.4165-8.4462
Brazil	4.6361	5.7069	4.9089	5.968	5.0705	6.1412	5.3433	4.2119-5.925
Canada	5.6259	5.637	5.6359	5.647	5.7680	5.814	5.7780	3.27.41-4.3641
United States of America	2.813	2.9496	3.068	3.2119	3.6562	3.7876	3.9087	2.5365-3.1936
China	2.045	3.2223	2.445	3.612	2.456	3.634	2.856	1.4334-2.0147
Democratic Republic of the Congo	1.57	1.61	1.60	1.64	1.63	1.67	1.66	1.57-2.112
Indonesia	1.302	1.334	1.367	1.3840	1.6058	1.602	1.645	0.99-1.6470
Peru	0.76	0.78	0.78	0.80	0.77	0.79	0.79	0.7069-0.7980
Others	10.029.88	11.4733	10.8672	12.3117	11.4639	1213.0893	12.4833	11.12.2143-16.17.0875
World	**37.4242**	**41.8080**	**39.3838**	**43.7676**	**41.5252**	**45.8989**	**43.4848**	**35.797966-42.7474**

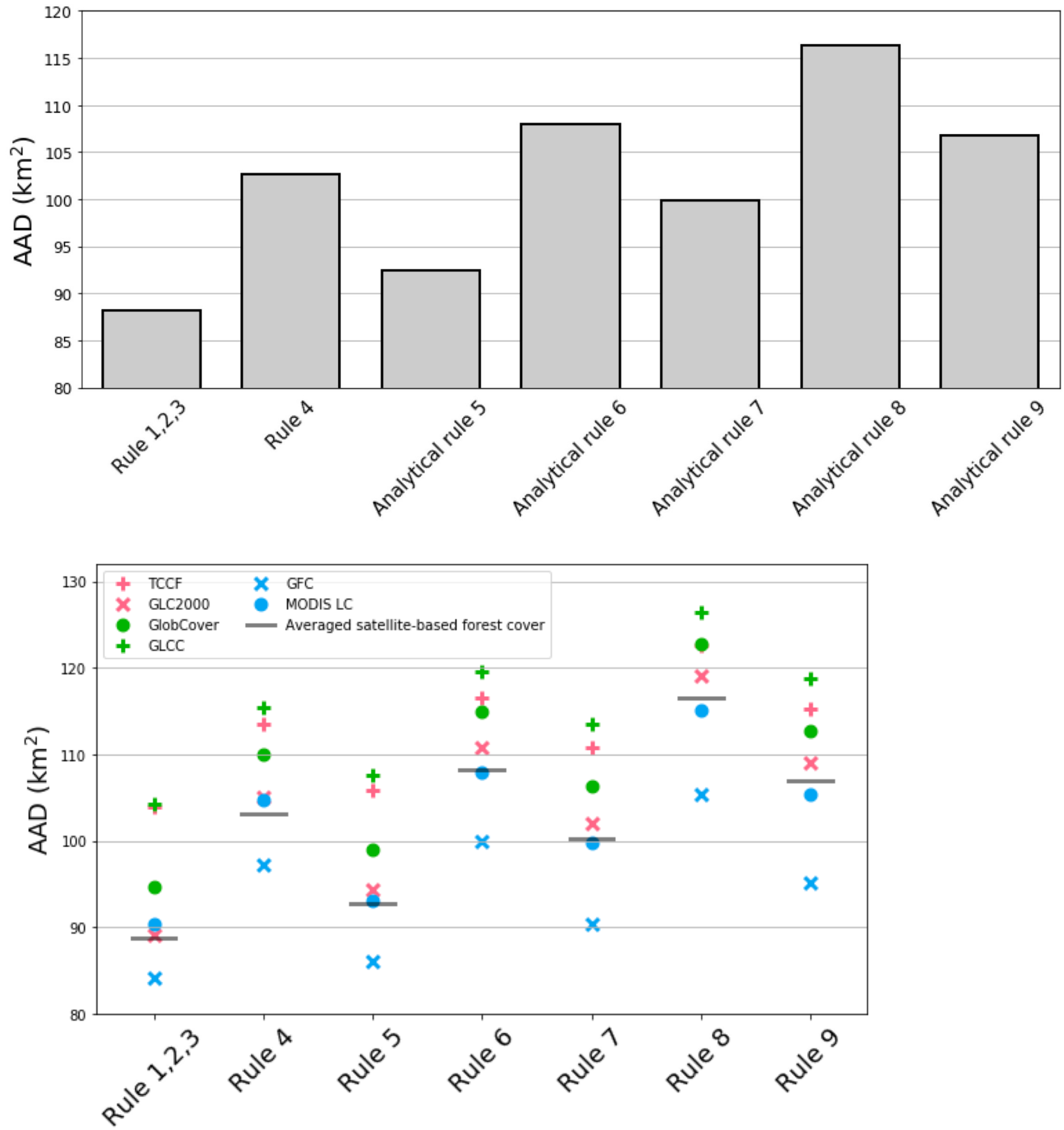


Figure 4. Global a~~A~~verage of absolute difference in ~~global~~ forest area between maps estimated by ~~transition~~translation rules, and ~~the averaged satellite-based forest cover map~~ each of the six satellite-based forest cover maps as well as the averaged satellite-based forest cover map.~~.~~

Table 5. Summary of LULCC carbon emissions estimated by the 9 ~~transition~~translation rules and those from other studies in Table ~~4~~3

~~Transition~~Translation Rule	Carbon Emissions Estimation (Pg C)			Emission Range from Table ~~4~~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			
~~Analytical rule~~ Rule 5	63	146	17			
~~Analytical rue~~ Rue 6	41	104	11	47-80	108-195	26
~~Analytical rule~~ Rule 7	28	107	13			
~~Analytical rule~~ Rule 8	5	65	7			
~~Analytical rule~~ Rule 9	13	67	7			

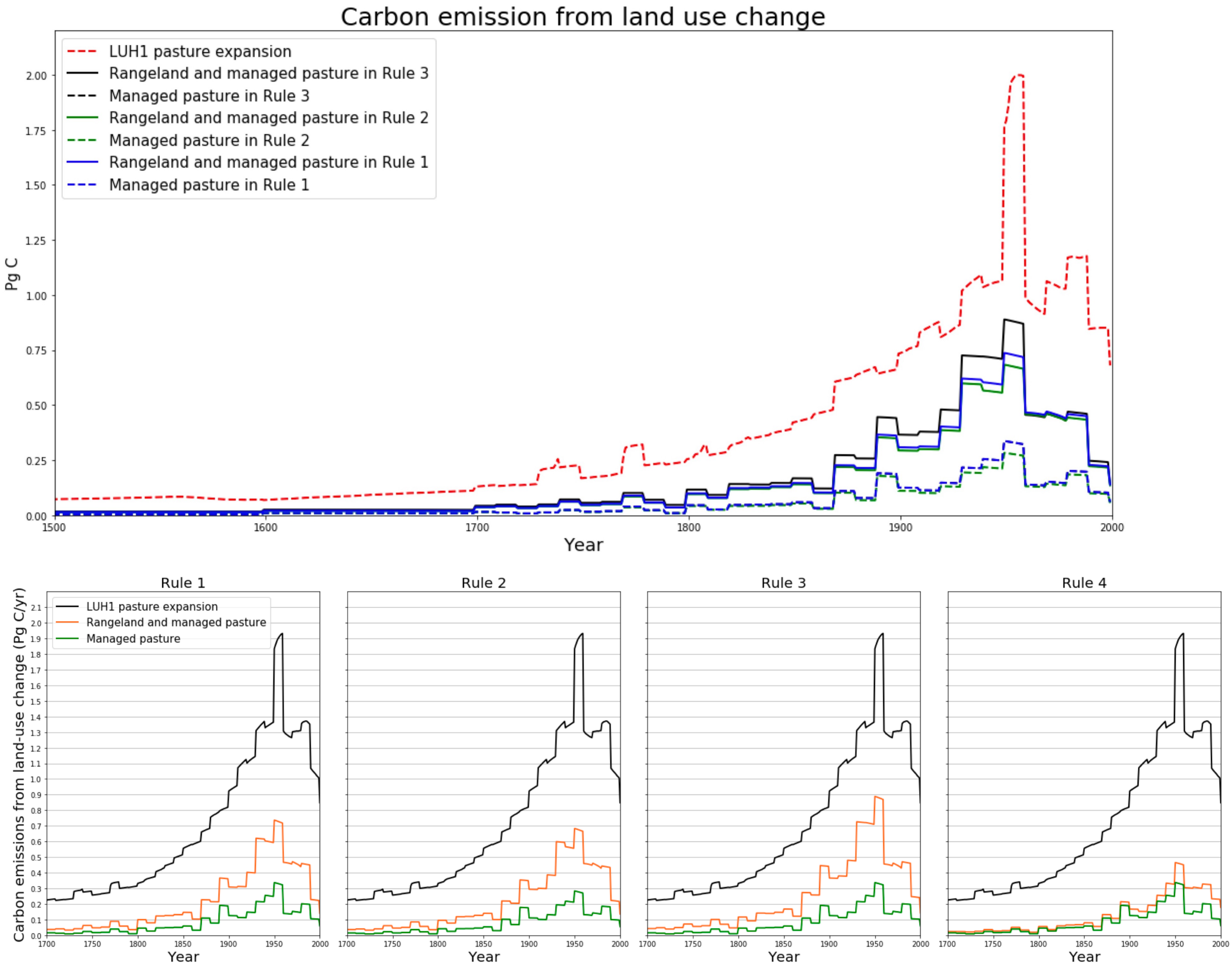
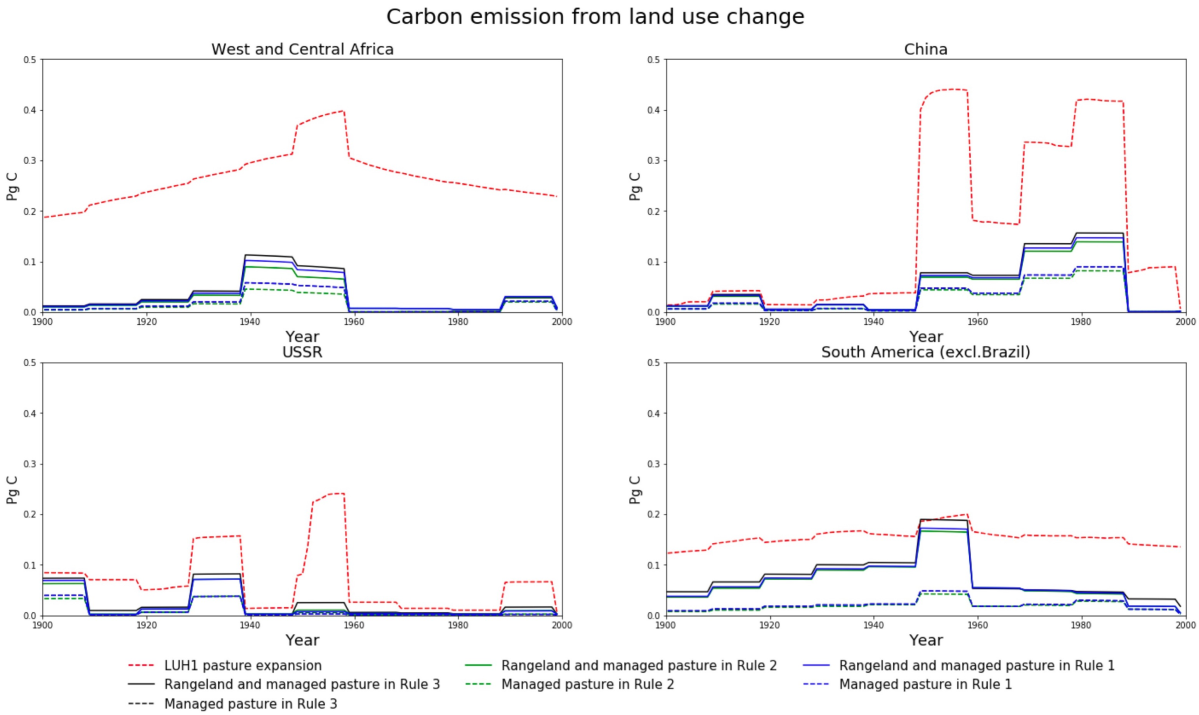


Figure 5. Carbon emission due to vegetation (forests and non-forests) removal in expansion of managed pasture and rangeland. ~~Red~~ Black ~~dash~~ line represents emissions from pasture expansion in LUH1. ~~Blue,~~Orange and green ~~and black solid~~ lines represent emissions from expansion of managed pasture and rangeland and from expansion of just managed pasture respectively in LUH2. ~~estimated by rule1, 2 and 3 respectively, and blue, green and black dash lines are emission from managed pasture expansion only by rule1, 2 and 3 respectively.~~ Note that the pasture category in LUH1 corresponds to managed pasture and rangeland together in LUH2.

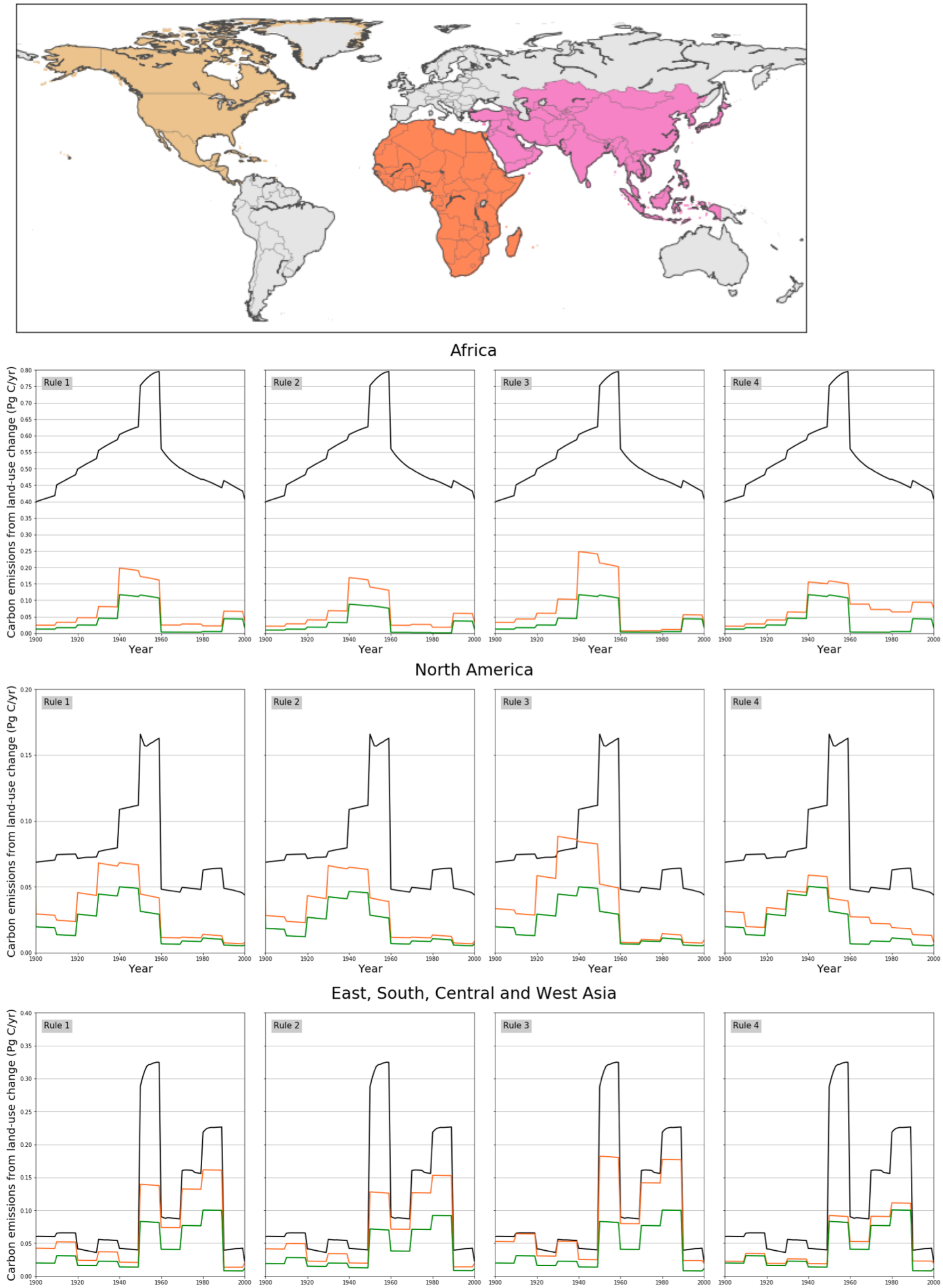

Carbon emission from land use change
West and Central Africa
China
USSR
South America (excl.Brazil)
Pg C
Year
LUH1 pasture expansion
Rangeland and managed pasture in Rule 3
Managed pasture in Rule 3
Rangeland and managed pasture in Rule 2
Managed pasture in Rule 2
Rangeland and managed pasture in Rule 1
Managed pasture in Rule 1

(a)

(b)

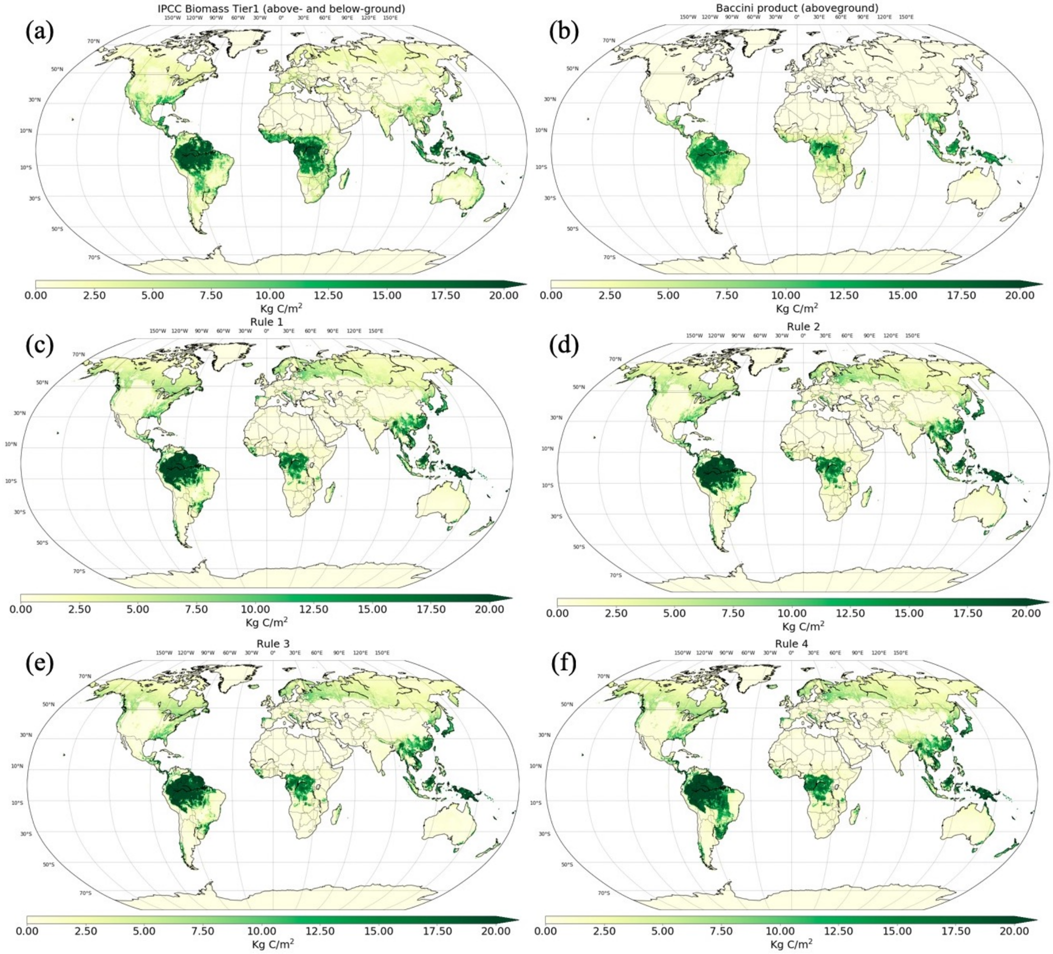
(c)

(d)



Africa
North America
East, South, Central and West Asia
Rule 1
Rule 2
Rule 3
Rule 4
Carbon emissions from land-use change (Pg C/yr)
Year

Figure 6. As in Figure 5 but ~~four~~ three regions~~ and countries~~: (~~a~~b) ~~West and central~~ Africa; (~~b~~c) ~~China~~East, South, Central and West Asia; (~~c~~d) [redacted]North America~~;~~. (a) illustrates the defined boundaries of (b) - (d).~~ (d) South America.~~


(a)
IPCC Biomass Tier1 (above- and below-ground)
(b)
Baccini product (aboveground)
(c)
Rule 1
(d)
Rule 2
(e)
Rule 3
(f)
Rule 4
0.00 2.50 5.00 7.50 10.00 12.50 15.00 17.50 20.00
Kg C/m2

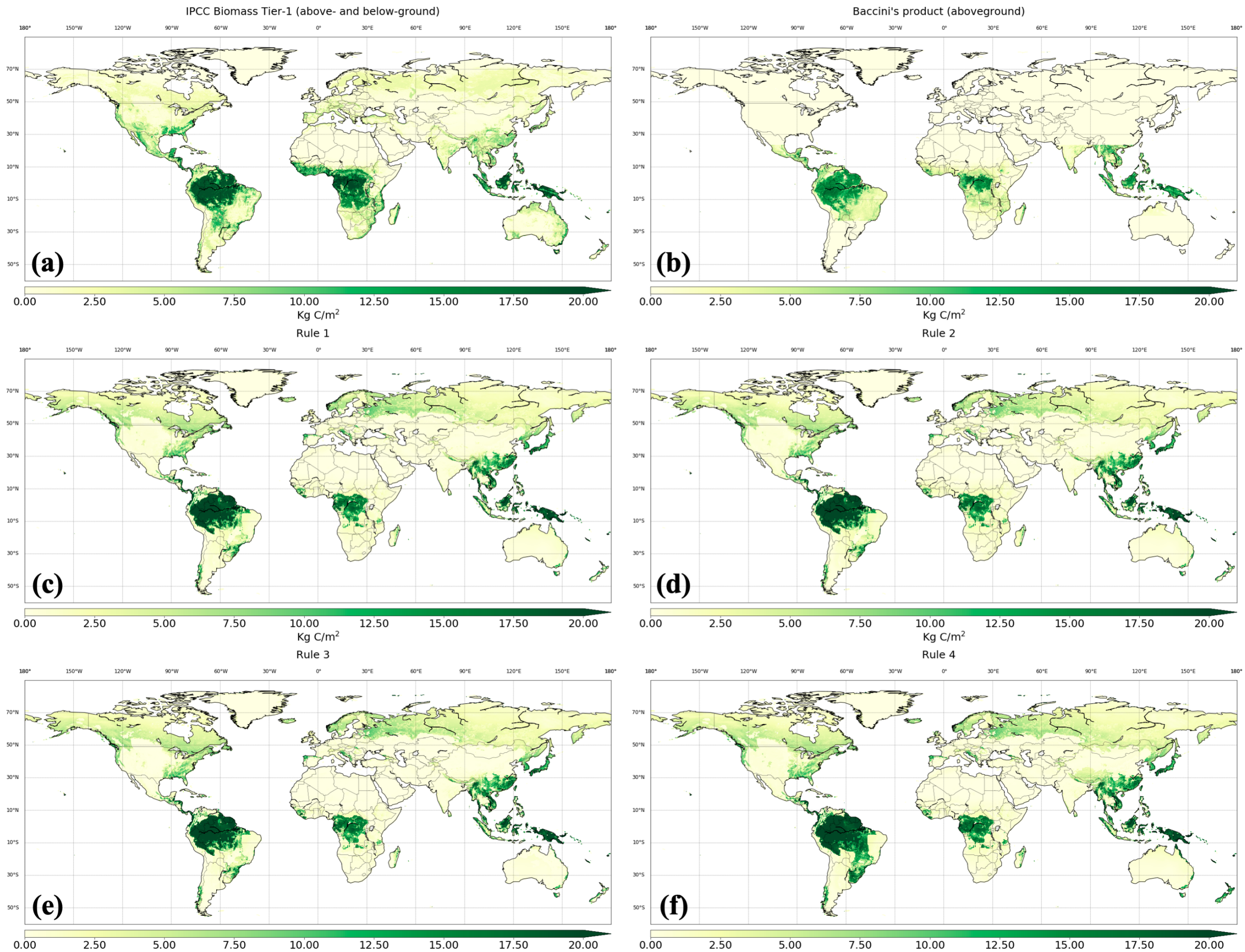
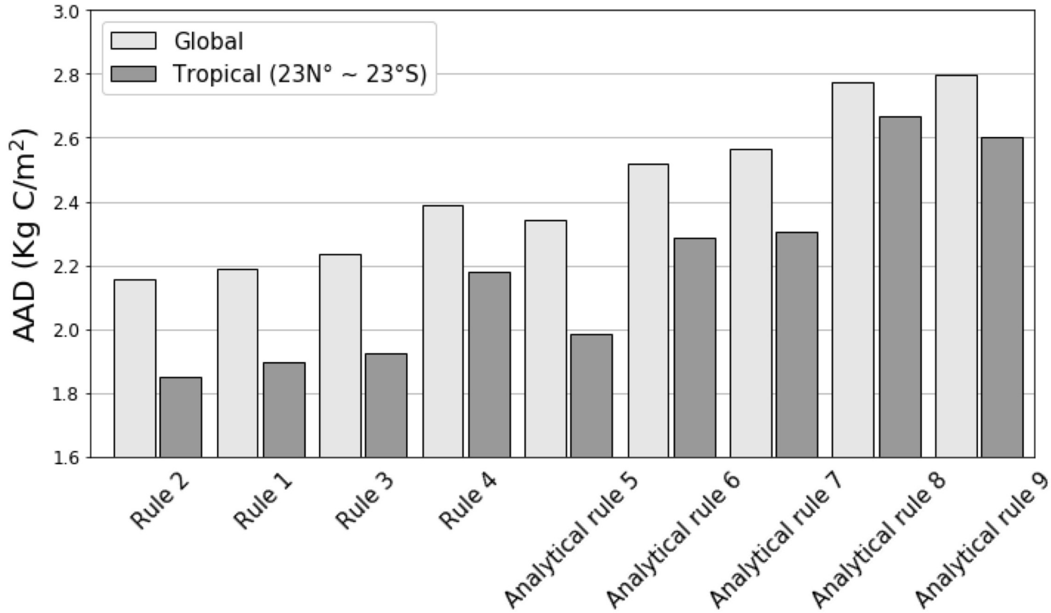


Figure 7. (a) IPCC Biomass Tier-1 density; (b) Baccini's product (only aboveground) at pantropical; global carbon density (above- and below-ground) maps estimated by ~~rule~~ Rules 1-4 from (c) to (f).



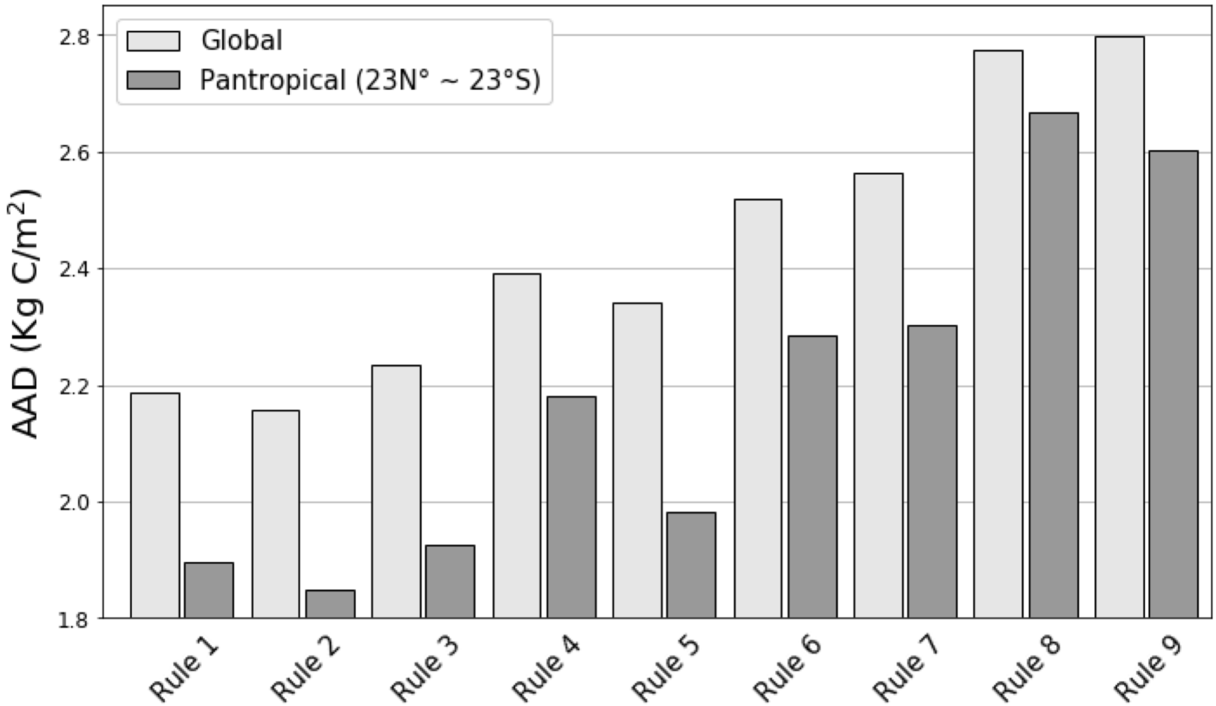
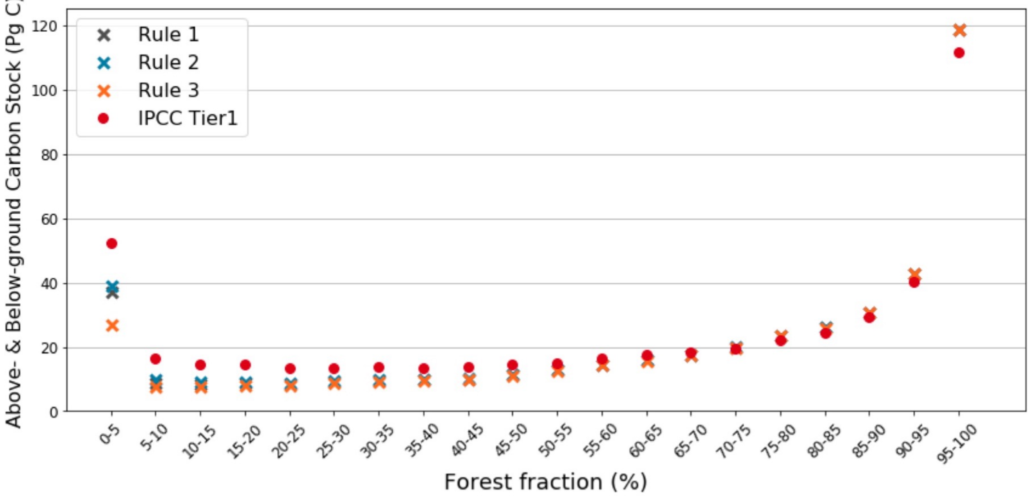


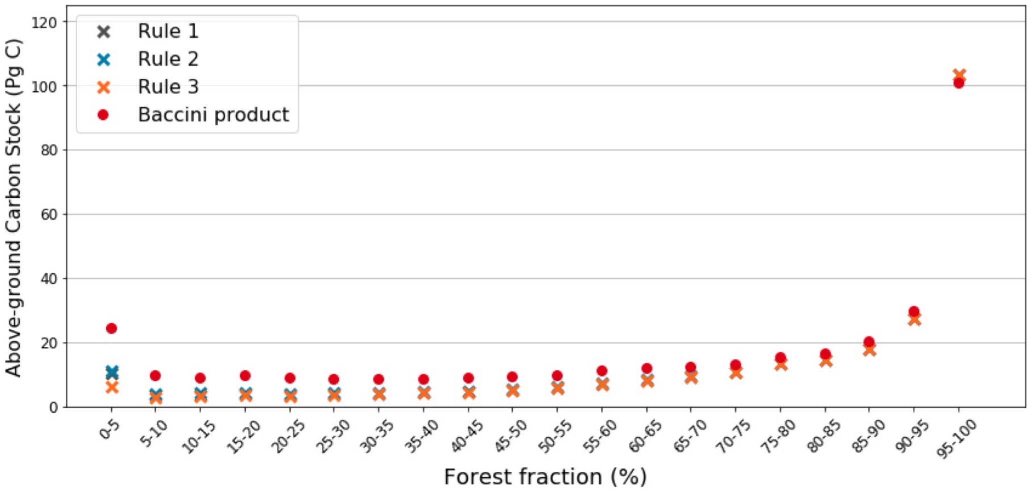
Figure 8. Average of absolute difference in carbon density between estimations of the 9 ~~transition~~translation rules and two diagnostic maps: global comparison with IPCC Tier-1 biomass density map (incl. above- and below-ground); tropical comparison with Baccini's carbon density map (only aboveground)~~.~~.

(a)



Rule 1
Rule 2
Rule 3
IPCC Tier1
Above- & Below-ground Carbon Stock (Pg C)
Forest fraction (%)
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-55
55-60
60-65
65-70
70-75
75-80
80-85
85-90
90-95
95-100
0
20
40
60
80
100
120

(b)



Rule 1
Rule 2
Rule 3
Baccini product
Above-ground Carbon Stock (Pg C)
Forest fraction (%)
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-55
55-60
60-65
65-70
70-75
75-80
80-85
85-90
90-95
95-100
0
20
40
60
80
100
120

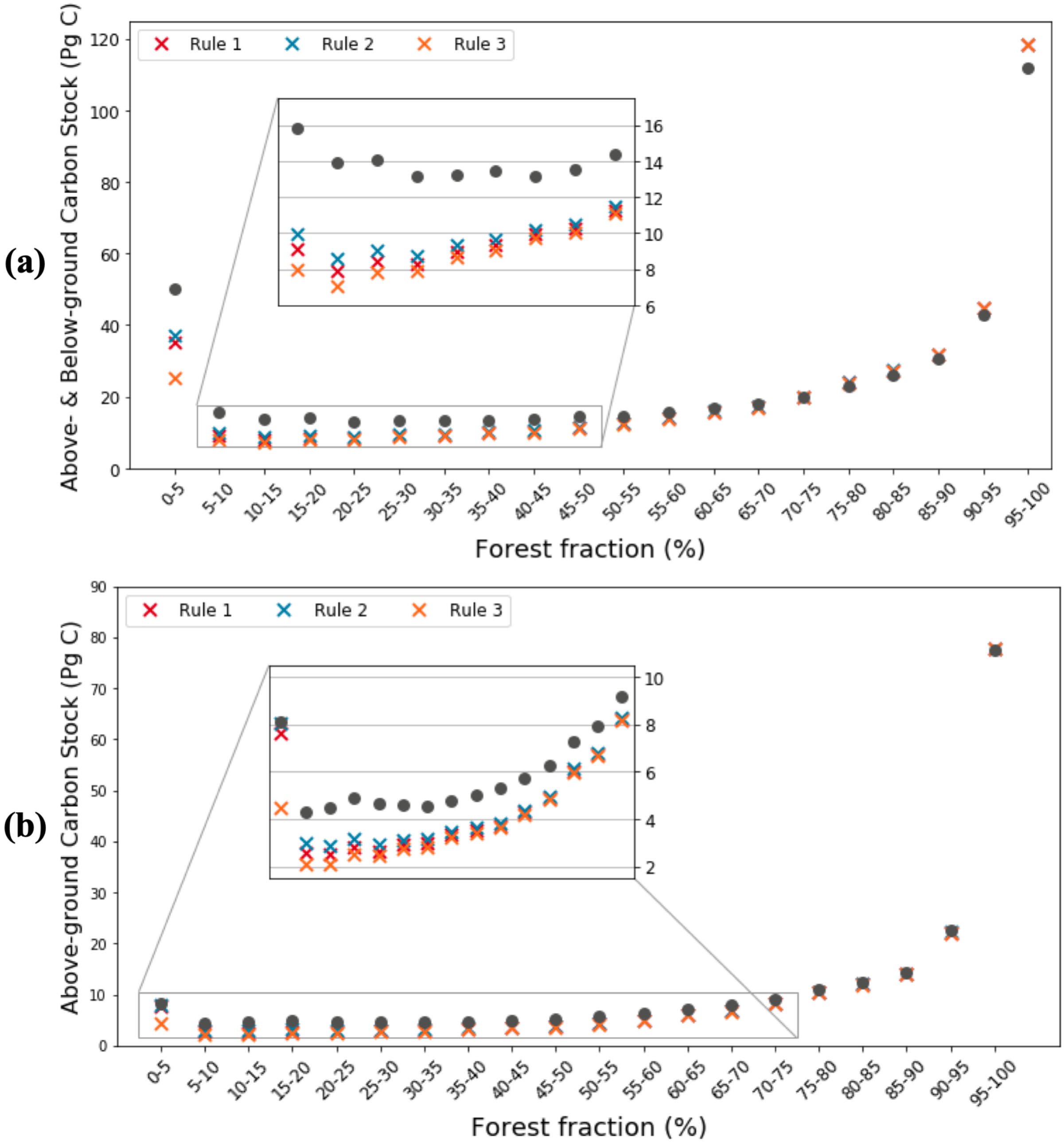


Figure 9. Total carbon stock grouped by forest fraction from the averaged satellite-based forest cover map. (a) global (above- and below-ground); (b) pantropical (aboveground).~~Total carbon stock grouped by forest fraction from averaged satellite-based forest cover map. (a) global; (b) pantropical.~~

Supplementary

Table. S1. Legend translation to produce a common forest canopy cover for various land cover datasets based on (Song et al., 2014). For references see Table. 2.

Products	Land cover class	Fraction
GLCC, MODIS LC	Forest (evergreen needleleaf; deciduous needleleaf; evergreen broadleaf; evergreen needleleaf; mixed)	0.80
	Woody savannas	0.45
	Cropland/Natural Vegetation Mosaic	0.25
	Savannas	0.20
	Open shrublands; closed shrublands; grasslands; croplands; urban and build-up; snow and ice; water bodies; permanent wetlands; barren or sparsely vegetated	0
GLC2000	Tree cover (evergreen broadleaved, closed deciduous broadleaved)	0.70
	Tree cover (evergreen needleleaf; deciduous needleleaf; mixed leaf type; regularly flooded fresh or saline)	0.575
	Mosaic: Tree cover/other natural vegetation	0.50
	Tree cover (open deciduous broadleaved)	0.275
	Mosaic: cropland/tree cover/ other natural vegetation	0.25
	Tree cover burnt; shrub cover (evergreen, deciduous); herbaceous cover; sparse herbaceous or sparse shrub cover; regularly flooded shrub and/or herbaceous cover; cultivated and managed areas; mosaic: cropland / Shrub and/or grass cover; bare areas; water bodies; snow and ice; artificial surfaces and associated areas	0
GlobCover	Closed forest (broadleaved deciduous; needle leaved evergreen)	0.70
	Closed to open forest (broadleaved evergreen or semi-deciduous, mixed broadleaved and needle leaved, broadleaved forest regularly flooded)	0.575
	Open broadleaved deciduous forest/woodland; open needle leaved deciduous or evergreen forest;	0.30
	Mosaic vegetation (grassland/shrubland/forest) / cropland; mosaic forest or shrubland / grassland	0.20
	Mosaic grassland / forest or shrubland	0.175
	Mosaic cropland / vegetation (grassland/shrubland/forest)	0.117
	Post-flooding or irrigated croplands (or aquatic); rainfed croplands; closed to open (broadleaved or needle leaved, evergreen or deciduous); closed to open herbaceous vegetation (grassland, savannas or lichens/mosses); sparse vegetation; closed broadleaved forest or shrubland permanently flooded; closed to open grassland or woody vegetation on regularly flooded or waterlogged soil; artificial surfaces and associated areas; bare areas; water bodies; permanent snow and ice	0

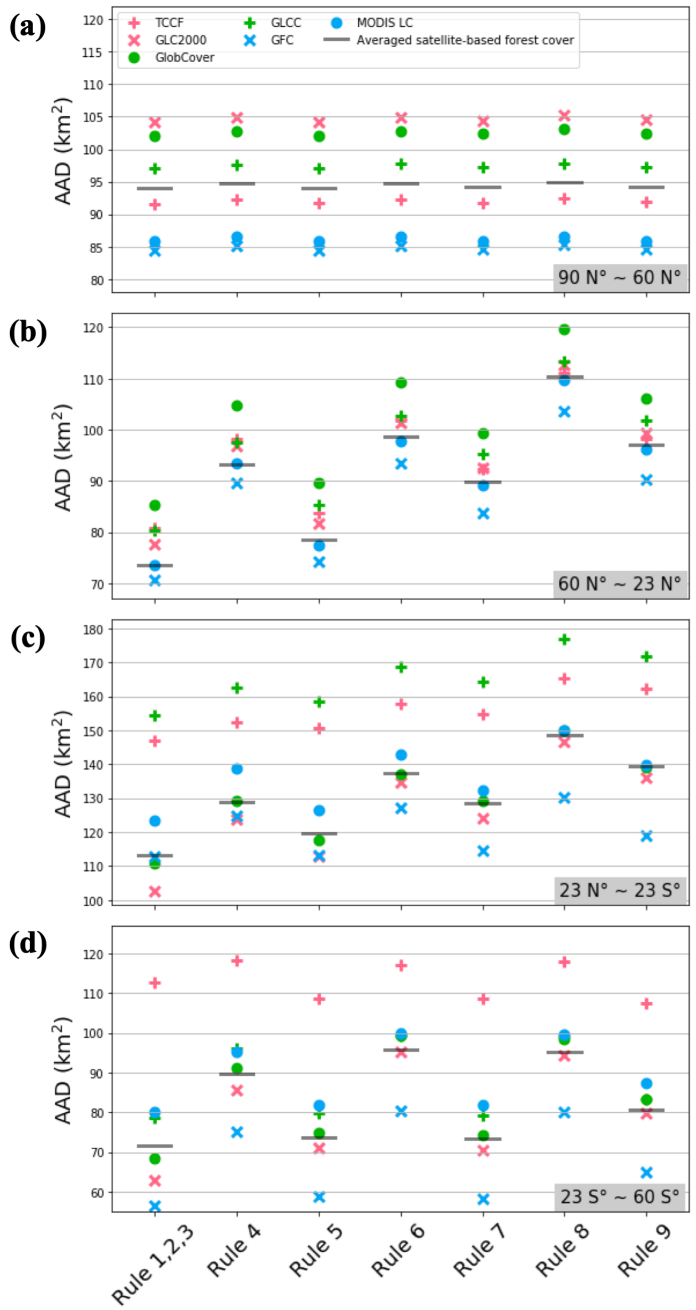


Figure S1. Regional average of absolute difference in ~~global~~ forest area between maps estimated by ~~transition~~translation rules, and six satellite-based forest cover maps and the averaged satellite-based forest cover map. ~~'AR' represents analytical rule.~~

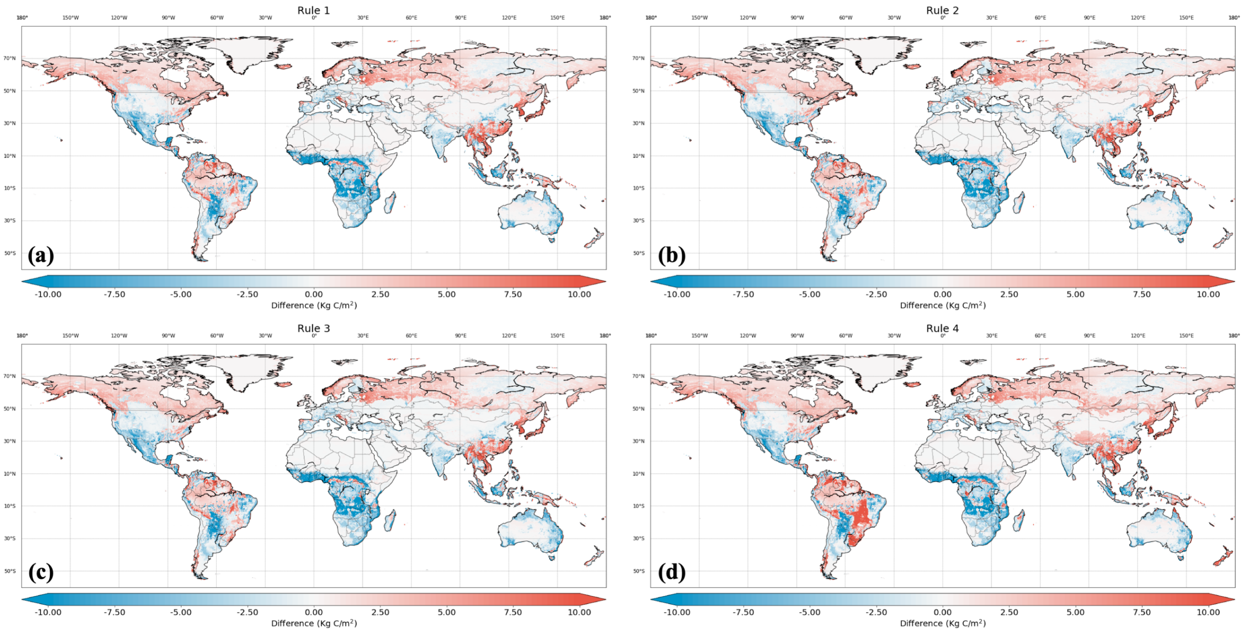


Figure S2. Global carbon density difference between IPCC biomass Tier-1 (Figure 7a) density map and estimates of ~~rule~~ Rules 1-4 from (a) to (d).

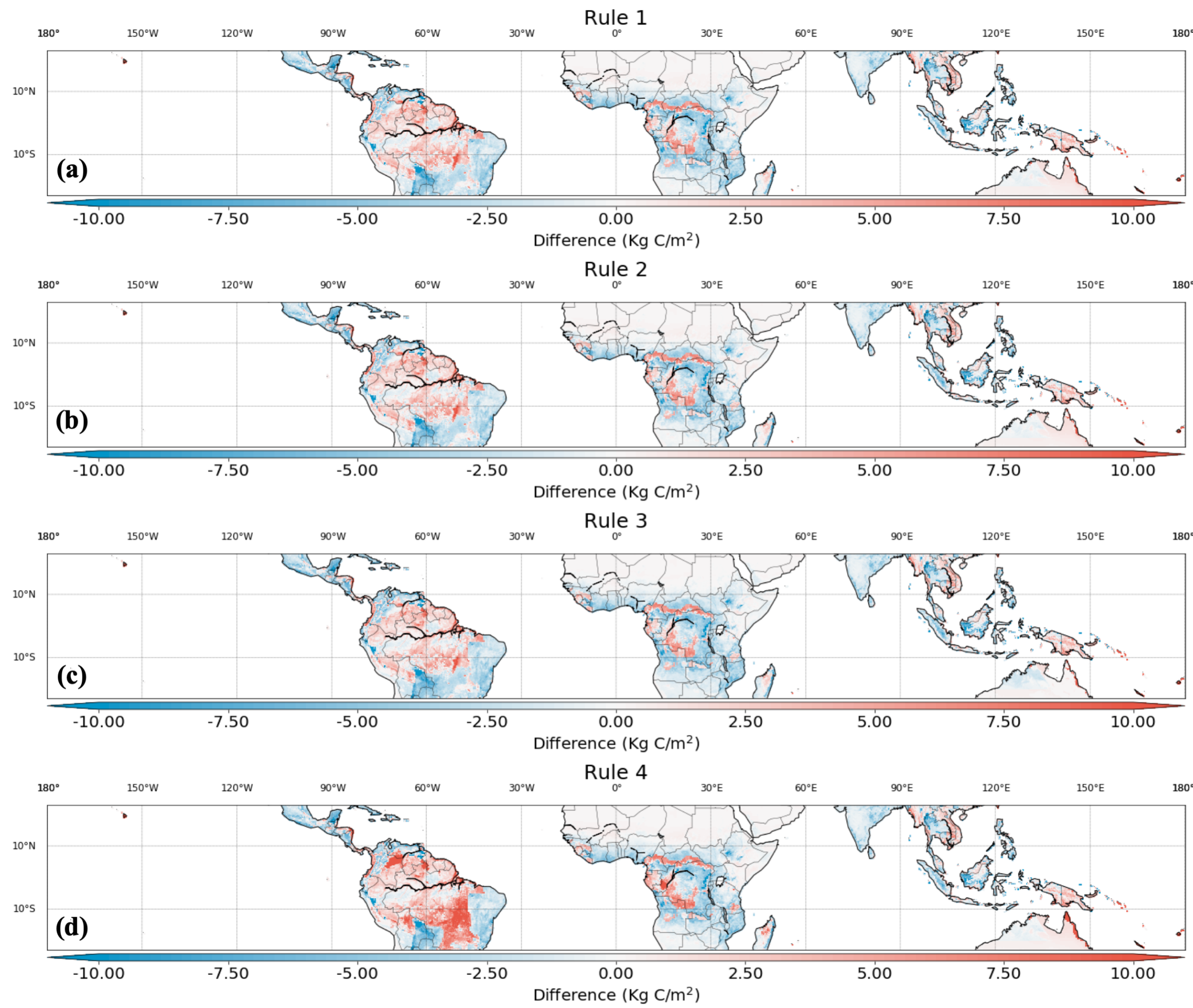


Figure S3. Global carbon density difference between the Baccini's product (Figure 7b) and estimates of ~~rule~~ Rules 1-4 from (a) to (d).

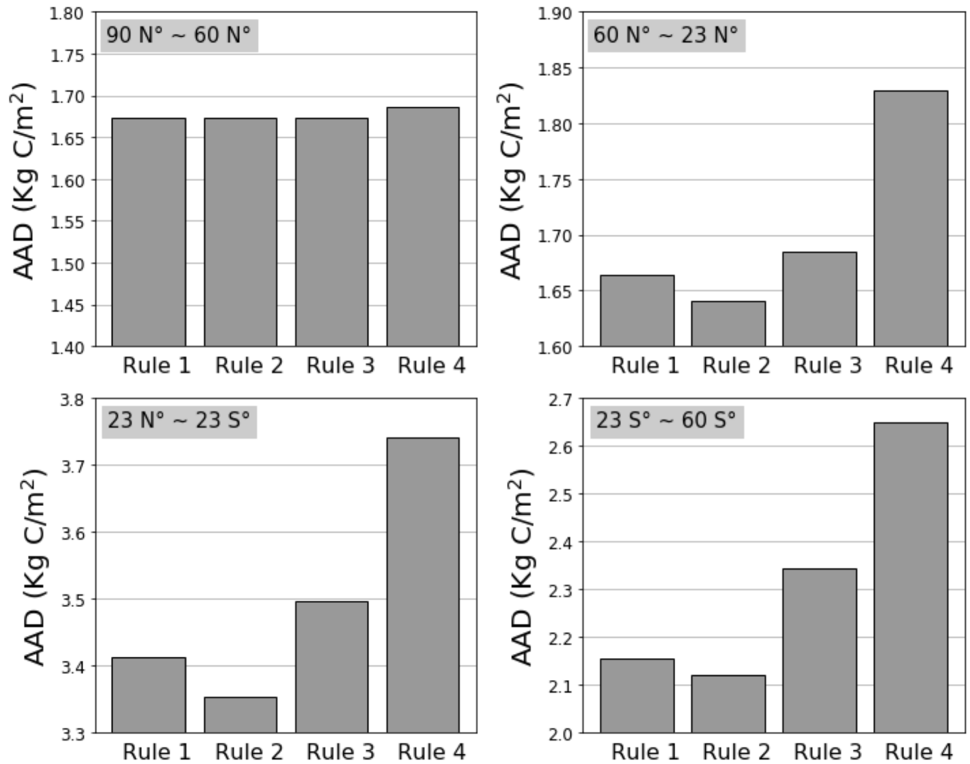


Figure S4. Average of absolute difference in carbon density between estimations of the ~~rule~~ Rules 1-4 and the IPCC Tier-1 biomass density map at different latitudinal band zones. 'AR' represents analytical rule.

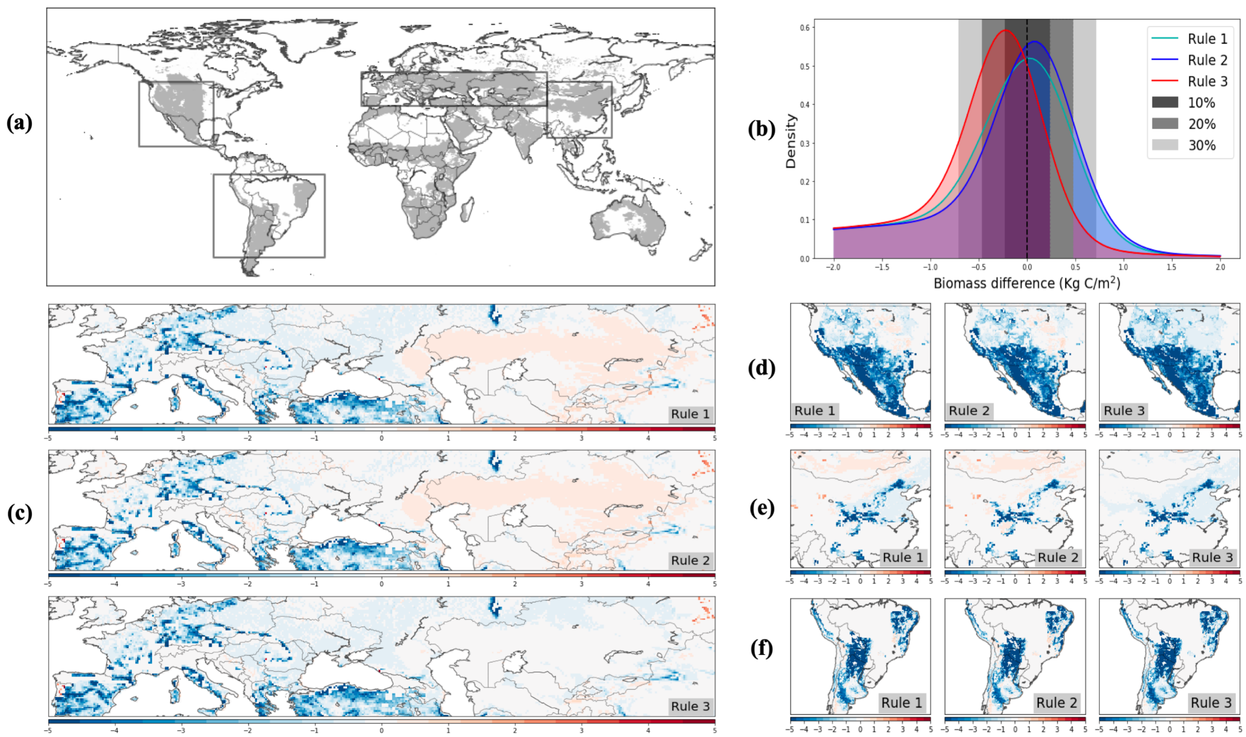


Figure S5. Carbon density difference comparison between the IPCC Tier-1 biomass density map and estimation of ~~rules~~ Rules 1-3. (a) Shaded regions represent where ~~rules~~ Rules 1-3 differ in estimates of carbon density; (b) Histogram of carbon density difference of shaded regions in (a), shared bounds present shift range of zero line under three assumed bias levels of the IPCC Tier-1 biomass. ~~1~~ (c) – (f) are regional comparison of carbon density difference of ~~rules~~ Rules 1-3, regions where ~~rule~~ Rules 1-3 have the same estimate of carbon density are not shown.