Response to comments

Paper #: *bg-2017-291*
Title: *Gross changes in forest area shape the future carbon balance of tropical forests*
Journal: *Biogeosciences*

Reviewer #1:

General Comments:

Comment #1

This is an interesting study, pointing out the importance of using gross instead of net land use transitions, distinguish between clearing of primary vs. secondary forest and to define a specific and reasonable time horizon when making land-based mitigation policies. Three main steps were taken: 1) the comparison between different response curves, 2) calculating different theoretical scenarios with a bookkeeping model to show the importance of considering gross forest area change and finding critical and 3) applying the ratio to real net land cover transitions from satellite data. Thereby, step 2 clearly takes the highest priority and consideration.

Response #1

We thank the reviewer for the comments and suggestions. Please see the detailed point-by-point responses below.

Comment #2

Still, some revision is needed: the abstract is very long which makes it partly difficult to get the main message of the study. Also, the gap in current research is not carved out very well (page 2, ln 16 ff, says that other models have already implemented gross transitions) and the objectives should become clearer. In the introduction a two-fold purpose of the study is mentioned, what about the 3rd step? What was its objective? The 3rd point cannot be found in the method section, it is just roughly described in the results. Thereby some steps remain unclear: e.g. the model considers LC transition to take place at time = t0, but the satellite covers a time series of 12 years. Are all the transitions during these years threatened as if they took place at one time t=0 and then the results for the different time horizons of 20, 50 and 100 years are calculated based on that? Or is the exact time of each transition considered and the time horizons starts to be calculated after the last transition took place? Or do the gross transitions in this case refer not to time (i.e. shift of one LC to another LC and back) but instead refer to transitions within the calculated gridcells of 0.5◦ resolution, as the satellite data was mentioned to have a 30 m resolution?

Response #2

We will shorten the abstract in the revised manuscript (reproduced in **Response #4**).

We will add sentences on **P2L21** to make the research gap and objectives more clear: "However, uncertainties in the simulated E_{LULCC} by grid-based DGVMs arise from the translation of the original LULCC datasets into plant functional type (PFT) maps and different processes comprised in different models (Arneth et al., 2017; Li et al., 2017). Although DGVMs are spatially and temporally explicit and include detailed physiological processes, the simulations using these models are time consuming and require long spin-up simulations, small time step calculations of biophysical effects and carbon fluxes, including processes less relevant to E_{LULCC}. Thus, DGVMs are not appropriate to perform, for instance, sensitivity tests for the assessment of LULCC carbon fluxes."

As suggested in **Comment #3**, we will include the 3rd step in the objectives in Introduction and also mention it in the Methods.

We will add sentences in the Methods to explain how we processed the 30 m forest cover data from Hansen et al. (*2013*): "Forest cover data from Hansen et al. (2013) comprise three layers at 30 m resolution: tree cover fraction (0-100% in each pixel) in year 2000, forest area loss (each pixel labeled with a loss year) during 2000-2012, and forest gain during 2000-2012 (not specifying the gain year). Attributing the forest gain to a specific year is challenging because of the difficulty in detecting young forests from satellite reflectance measurements (Hansen et al., 2013). In this study, we used the forest loss and forest gain layers to calculate the ratios of gross-to-net area changes ($\gamma_{\mathrm{Anet}}^{\mathrm{Agross}}$) at a 0.5 ° × 0.5 ° resolution, and the average values of $\gamma_{\mathrm{Anet}}^{\mathrm{Agross}}$ from the dataset of Hansen et al. (2013) during 2000-2012 rather than for a single year since the year of forest gain is not reported. The gross changes at the 0.5 ° level were calculated by summing the absolute areas of forest loss and gain at the 30 m level during 2000-2012 in each 0.5 ° grid cell, while the net changes were the sum of gross forest loss (negative) and gross forest gain (positive)."

Comment #3

One possibility to handle the dominance of point 2 would be to make it to the only objective, and shift point 1 to the method section – the comparison seems to be anyhow just a plot of the different curves that justifies the usage of response curves based on Poorter instead of those from Houghton and Hansis. Another possibility would be to include 3 in the method section and give point 1 and 3 more weight - e.g. by calculating the critical gross to net ratios based on the Houghton and Hansis functions, applying it to the same grid cells and comparing it then with the results based on the Poorter function. This would be interesting outcome and extend the first objective of comparing the different response curves to more than just a simple plot of the different curves in the same graph. Further, it would be very interesting to not only know whether each gridcell was a sink or source but also to quantify the ELUC and sum it to total number – one if everything was primary forest at the first transition, and one as if all was secondary, and the same if the other response curves were used.

Response #3

We will include the 3rd step in the method section as suggested.

We calculated the critical ratios based on the exponential response curves from Hansis et al. (*2015*) (see **Figure R1** below) and compared the number of grid cells above the critical ratios with that using curves from Poorter et al. (*2016*) (see **Table R1** below). We didn't show the results from Houghton (*1999*) because the parameters of the exponential functions from Hansis et al. (*2015*) were already calibrated from the linear function of Houghton (*1999*).

As show in **Figure 1**, the equilibrium of secondary forest vegetation density with the recovery curve of Hansis et al. (*2015*) is higher than with Poorter et al. (*2016*) and we assumed that the same density of primary forest for both, and thus $L_{\mathrm{Hansis,primary}}(t) = L_{\mathrm{Poorter,primary}}(t)$, $L_{\mathrm{Hansis,secondary}}(t) > L_{\mathrm{Poorter,secondary}}(t)$ and $G_{\mathrm{Hansis}}(\infty) > G_{\mathrm{Poorter}}(\infty)$. Note that a positive value of carbon flux indicates carbon emission to the atmosphere. Combined with **Eq (7)** in the manuscript, $\gamma_{Anet}^{Agross} = \frac{L(t)-G(t)}{L(t)+G(t)}$, the different equilibrium states of secondary forest vegetation can explain the differences of critical ratios over time between Hansis et al. (*2015*) and Poorter et al. (*2016*) in **Figure R1**. Accordingly, a higher critical ratio leads to smaller number of 0.5 °× 0.5 °grid cells with $\gamma_{\mathrm{Anet}}^{\mathrm{Agross}}$ beyond the critical ratio (**Table R1**).

Figure R1 The critical value of γ_{Anet}^{Agross} at which $\Sigma E_{LULCC,gross}$ is zero, going from a net source to a net sink with different time horizons, using the biomass recovery response curves from Poorter et al. (*2016*) (solid, same as **Figure 4c**) and from Hansis et al. (*2015*) (dashed). Values larger than this critical value indicate that the initial forest area change has the net cumulative effect to emit CO_2 at a given time-horizon on the x-axis. Note the different y-axis scale. The lower critical ratio values in the case of primary forest initial loss is because primary forests have a larger biomass, so that a small gross-to-net initial change in forest area will legate a source at a given horizon than if secondary forests are initially lost.

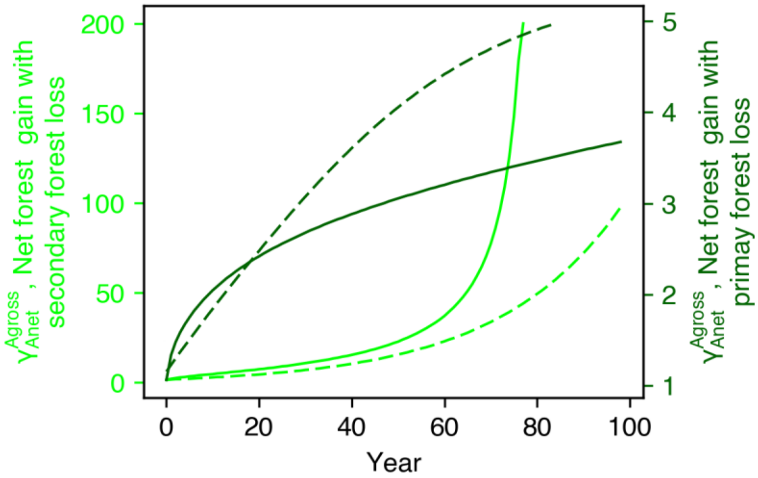

Table R1 Number of 0.5 °× 0.5 °grid cells with γ_{Anet}^{Agross} above the critical ratio for which the system is a net cumulative source of CO_2 to the atmosphere, for different time horizons. The calculation was done using the biomass recovery response curves from Hansis et al. (*2015*) and Poorter et al. (*2016*) in Latin America. The values of γ_{Anet}^{Agross} were calculated based on high-resolution net and gross forest area change data from Hansen et al. (*2013*) during 2000-2012. Secondary-to-secondary represents a net forest gain with gross secondary forest loss by assuming that all lost forests were secondary, and secondary-to-primary represents a net forest gain with gross primary forest loss by assuming that all lost forests were primary.

		20 yr		50 yr		100 yr	
		Critical ratio	Grid cell number	Critical ratio	Grid cell number	Critical ratio	Grid cell number
secondary-to-secondary	Poorter et al.	7.2	102	22.5	42	-	-
	Hansis et al.	4.2	143	15.3	57	97.4	9
secondary-to-primary	Poorter et al.	2.4	199	3.1	175	3.7	155
	Hansis et al.	2.5	198	4.1	147	5.0	126

As suggested, we also calculated the total amount of ΣE_{LULCC} of the grid cells beyond the critical ratios with different time horizons in **Figure 5**. The numbers are given in the **Table R2** below and we will incorporate it in the revised manuscript.

Taking C1 secondary-to-secondary at 20 yr horizon for example, using net transitions results in a carbon sink of 12 Tg C but using gross transitions results in a carbon emission of 21 Tg C in the grid cells with $\gamma_{Anet}^{Agross} > 7.2$ (**Figure 5**).

Table R2 Cumulative carbon flux (Tg C) using gross transitions ($\Sigma E_{LULCC,gross}$) and net transitions ($\Sigma E_{LULCC,net}$) in the grid cells with γ_{Anet}^{Agross} beyond the critical ratios at different time horizons. The gross and net forest area changes are based on the data from Hansen et al. (*2013*). Positive value of carbon flux indicates carbon emission to the atmosphere. Secondary-to-secondary represents a net forest gain with gross secondary forest loss (C1) by assuming that all lost forests were secondary, and secondary-to-primary represents a net forest gain with gross primary forest loss (C2) by assuming that all lost forests were primary.

Tg C	C1: secondary-to-secondary			C2: secondary-to-primary		
Time horizon	Critical ratio	$\Sigma E_{LULCC,gross}$	$\Sigma E_{LULCC,net}$	Critical ratio	$\Sigma E_{LULCC,gross}$	$\Sigma E_{LULCC,net}$
20 yr	7.2	21	-12	2.4	162	-38
50 yr	22.5	3	-2	3.1	125	-39
100 yr	-	-	-	3.7	99	-36

We will add these new analyses suggested by the reviewer in the revised manuscript.

Specific Comments:

Comment #4

Abstract: The abstract should be shortened to better focus on the findings, which would make it easier to read and understand. E.g. is the 3rd sentence really relevant for the findings of this study? Especially also from line 19 to 27 there might be possibilities to shorten, summarize and simplify. Where shapes of the three different curves relevant for the finding? The finding here is difficult to understand, the sentences a bit complicated and several sentences basically say the same: You found and show critical values of gross to net forest area change above which ELUC of a net a net forest area gain switches from CO_2 sink to source.

Response #4

As suggested, we will shorten the Abstract (160 words less) as follows: "

Bookkeeping models are used to estimate land-use and land-cover change (LULCC) carbon fluxes (E_{LULCC}). The uncertainty of bookkeeping models partly arises from data used to define response curves (usually from local data) and their representativeness for application to large regions. Here, we compare biomass recovery curves derived from a recent synthesis of secondary forest plots in Latin America by Poorter et al. (2016) with the curves used previously in bookkeeping models from Houghton (1999) and Hansis et al. (2015). We find that the two latter models overestimate the long-term (100 years) biomass carbon density of secondary forest by about 25%. We also use idealized LULCC scenarios combined with these three different response curves to demonstrate the importance of considering gross forest area changes instead of net forest area changes for estimating regional E_{LULCC}. In the illustrative case of a net gain in forest area composed of a large gross loss and a large gross gain occurring during a single year, the initial gross loss has an important legacy effect on E_{LULCC} so that the system can be a net source of CO_2 to the atmosphere long after the initial forest area change. We show the existence of critical values of the ratio of gross area change over net area change (γ^{Agross}_{Anet}) above which cumulative E_{LULCC} is a net CO_2 source rather than a sink for a given time horizon after the initial perturbation. These theoretical critical ratio values derived from simulations of a bookkeeping model are compared with real-world observations from the 30 m resolution Landsat TM data of gross and net forest area change in the Amazon. This allows us to diagnose areas where current forest gains with a large land turnover will still legate LULCC carbon emissions in 20, 50 and 100 years.

"

Comment #5

Introduction: Page 2, ln 8: that is for DGVMs the sub-grid transitions that sum up to net changes, here a reference to e.g. Bayer et al. 2017: doi:10.5194/esd-8-91-2017 could be nice, who focused on the problematic of sub-grid transitions.

Response #5

We will add this reference in the revised manuscript.

Comment #6

3.4 Page 7, ln 14: "we pose the question whether such ratios can be observed in the real world" – but this is not what you are answering with your approach. As far as I understood you just calculate using your rates, whether the regions are a sink or a source.

Response #6

This sentence on **P7L14** will be revised as: "…we further combined such ratios with the land use and land cover change datasets to determine whether a region is a carbon sink or source at a given time horizon."

Comment #7

Page 9, ln 22: "With a too high rotation rate of forests, i.e. a large gross to net area change ratio, a net forest gain could still legate a net carbon source over a long period in the future." I don't agree, as I think long rotation secondary forests should have other response curves than short rotation forest, as short rotation forest don't store as much carbon that can be lost afterwards.

Response #7

This sentence on **P9L22** will be revised as: "With a large gross to net area change ratio, a net forest gain could still legate a net carbon source over a long period in the future."

Comment #8

4. Discussion: You state that the response curves used in bookkeeping models from Houghton (1999) and Hansis et al. (2015) overestimate carbon density – that implies that Porters values are true, while Houghton and Hansis are wrong. But also Houghton and Hansis are based on measurements, right? Maybe just not in the right region? It would be helpful to mention in the discussion where the measurements for Houghton and Hansis models were located.

Response #8

We showed the differences in biomass recovery curves between Poorter et al. (*2016*) and Houghton (*1999*) and Hansis et al. (*2015*), but we didn't say that it implies "*Porters values are true, while Houghton and Hansis are wrong.*". We only argued that it may bias in this particular region where Poorter et al.'s field survey covers. The reasons for these differences could be the assumptions made for secondary forest by Houghton et al. (1983), the number of field sites and the different locations where field measurements were conducted, as the reviewer said.

We will add some sentences on **P8L9** to clarify it: "The biomass recovery curves of Neotropical secondary forests from Poorter et al. (2016) are lower 20 years after the initial perturbation than those used in the bookkeeping models of Houghton (1999) and Hansis et al. (2015), implying that these models simulate different LULCC carbon fluxes in Latin America from those using the recovery curves of Poorter et al. (2016). The carbon density in undisturbed forests in the bookkeeping models of Houghton (1999) and Hansis et al. (2015) were essentially based on Whittaker and Likens (1973), multiplied by a factor of 0.75 to approximate the lower carbon density of secondary forests (Houghton et al., 1983). The carbon density data from Whittaker and Likens (1973) are subject to two sources of uncertainty. First, these values represent biomass in the 1950s (Woodwell et al., 1978) rather than present days, and second, they were compiled from very limited field measurements for tropical forests. In fact, Whittaker and Likens (1973) claimed in their study that data "for tropical communities are very meager" and the mean biomass density is "a subjectively chosen intermediate value based on very few measurements" to avoid extreme values."

Reference

Houghton, R. A., Hobbie, J. E., Melillo, J. M., Moore, B., Peterson, B. J., Shaver, G. R. and Woodwell, G. M.: Changes in the Carbon Content of Terrestrial Biota and Soils between 1860 and 1980: A Net Release of CO" 2 to the Atmosphere, Ecol. Monogr., 53(3), 235–262, doi:10.2307/1942531, 1983.

Whittaker, R. H. and Likens, G. E.: Carbon in the biota., in Brookhaven symposia in biology, pp. 281–302., 1973.

Woodwell, G. M., Whittaker, R. H., Reiners, W. a, Likens, G. E., Delwiche, C. C. and Botkin, D. B.: The biota and the world carbon budget, Science, 199(4325), 141–146, doi:10.1126/science.199.4325.141, 1978.

Comment #9

Is the extent to which gross versus net transitions affect ELUC comparable what other studies investigating gross versus net transitions studied? You mention several studies about this issue which were performed with carbon models – they should also appear in the discussion, showing how your results compare with what they found.

Response #9

We will add some discussion about the impacts of gross and net transitions on E_{LULCC} on **P8L13**: "Some DGVMs (Shevliakova et al., 2009; Stocker et al., 2014; Wilkenskjeld et al., 2014; Yue et al., 2017; Bayer et al., 2017) as well as a bookkeeping model (Hansis et al., 2015) have implemented gross land use and land cover transitions, and thus simulated a higher E_{LULCC} than using net transitions. Arneth et al. (2017) reviewed the "missing processes" in LULCC modeling by DGVMs and found that ignoring gross LULCC could underestimate the global cumulative E_{LULCC} by 36 Pg C on average over the historical period (1901-2014).". However, the E_{LULCC} from land carbon models cannot be directly compared with E_{LULCC} from bookkeeping models, because of the different processes in models and the different definitions of E_{LULCC}. In addition, our study focused on the ratios of gross-to-net changes rather than the estimates of E_{LULCC}, and thus it is difficult and not necessary to compare with E_{LULCC} from land carbon models.

Comment #10

Technical corrections

General: In all figures and the text, it might be useful to replace the term "biomass carbon density" by "vegetation carbon density", as biomass is less well defined and includes in some disciplines also dead biomass and soil microbial biomass which would count here to the soil pool.

Response #10

We will revise it accordingly.

Comment #11

Page 1, ln 26: "critical value" should be plural

Response #11

We will revise it accordingly.

Comment #12

Page 2, Ln 10: "Gross LUC occurs in tropical regions with shifting cultivation (Hurtt et al., 2011) but also everywhere forests are cut and new plantations created at the same time" Is here a "where" after "everywhere" missing?

Response #12

This sentence on **P2L10** will be revised as: "Gross LULCC occurs in tropical regions with shifting cultivation (Hurtt et al., 2011) and also in other regions where forests are cut and new plantations created at the same time."

Comment #13

Table 1: The table caption uses gamma gross to net but in the table heading and the text gamma Agross to Anet is used.

Response #13

We will revise it accordingly.

Comment #14

Fig 1: biomass from primary forest: reference missing; Legend for a) and b) shows biomass, which can only be found in plot c) that has an own legend.

Response #14

We will add the reference in the legend and remove biomass from the legend in (a) and (b).

Fig 3: include dashed and solid line in legend. In figure description logarithmic asymptotic should be removed or referred to both – solid and dashed, so it becomes more clear that there is no difference in the response curve between solid and dashed, but just which systems are transformed.

Response #15

We will add it in the legend and revise the caption.

Comment #15

Fig 4 is a bit difficult to understand. The difference between plot a) and b) is hidden in the middle of the figure description in the end of a sentence. Would be better to have it in the description directly following a) resp. b), whereas "net forest gain at t=0" which is true for both plots should either be in the end or before the separation in a) and b). Or/additionally it could be mentioned as title in each plot whether it is primary to secondary or secondary to secondary. The axis title is only in plot a) but not in b) whereas the legend can be found in both plots. Please add the axis title to b) or remove the legend from a) or do both and set the legend a bit aside, which would also help the reader to not confuse it with a second y-axis title at a first glance.

Please extend "Exponential carbon loss curve from (Hansis et al., 2015) and logarithmic gain curve from (Poorter et al., 2016) are used in this example" to something like "Exponential curve from Hansis et al., (2015) for carbon loss in all pools and gain in soil pool and logarithmic curve from Poorter et al., (2016) for gain in biomass pool are used in this example, which corresponds to the combinations C1 and C2 from Table 2 for a) and b) respectively."

Response #16

As suggested, we will revise the caption and re-plot the figure (reproduced below).

Figure 4 Time evolution of cumulative carbon flux ($\Sigma E_{LULCC,gross}$) after an initial forest area change involving gross forest area changes followed by no forest area change. The three panels show results of our bookkeeping model for three case studies (a) a net forest gain at t = 0 with initial secondary forest loss followed by secondary forest regrowth (secondary-to-secondary, C1 in Table 2), (b) the same net area gain at t = 0 with initial primary forest loss followed by secondary forest regrowth (primary-to-secondary C2 in Table 2), and (c) the critical value of γ_{Anet}^{Agross} at which $\Sigma E_{LULCC,gross}$ is zero, going from a net source to a net sink for different time horizon in the x-axis. The colored curves in (a) and (b) have the same net area change (A_{net} = +1 ha) at t = 0 but variable values of the initial gross-to-net area change ratios (γ_{Anet}^{Agross}). The red line in (a) and (b) is the zero line, defining the time after initial forest area change at which the system reaches a neutral carbon balance. The light and dark green lines in (c) represent the critical ratios for a net initial forest gain scenario with secondary-to-secondary (a) and primary-to-secondary (b) gross forest area change, respectively. Values larger than this critical value indicate that the initial forest area change has the net effect to emit CO_2 for a given time horizon in the x-axis. Exponential curve from Hansis et al. (2015) for carbon loss in all pools and gain in soil pool and logarithmic curve from Poorter et al. (2016) for gain in biomass pool are used in this example.