Dear Editor and Referees:

Thank you for your valuable comments, which greatly helped us to specify weakness and unclarity in the manuscript.

First of all, importantly, I re-conducted all experiments and re-calculated carbon flows by the VISIT model and improved accuracy of the mass balance of carbon budget, using the input data same to the first manuscript. Also, 146 parameter ensemble simulations (i.e. increased from 128 of the first submission) were conducted again. Additionally, consideration of leap years was revised to remove small but noisy 4-year-cycle fluctuations in the time-series of carbon stocks. As a result, all figures and tables were updated, and results became more convincing.

Both referees were interested in uncertainties in the present simulation-based estimates of minor carbon flows and carbon budget. In the previous manuscript, the simulated results were compared with a few datasets and values in the literature. As recommended by the referees, I compared the simulated results with a larger number of data in a more comprehensive manner. For example, biomass and soil carbon stocks were compared with observational data (Fig. S8) and MCFs estimated in this study were compared with previous studies as summarized in new Table 2.

The manuscript was revised on the basis of your comments. Otherwise, I tried to justify my research strategy in the light of present data availability and time limitation. My point-by-point reply to your comments is presented below, and the annotated manuscript shows how the manuscript was modified from the previous version.
I hope this revision is satisfactory for being accepted for publication.

Original comments in bold italic. *Sentences in the revised manuscript in blue italic.*

Anonymous Referee #1

[Comment 1-1] ***General comments: Ito presents an interesting and comprehensive study on the net effects of Minor Carbon Flows (MCFs) on the regional and global carbon (C) balances. Although this study is highly important for research on the global carbon (C) cycle and climate change, many uncertainties remain unaddressed. Uncertainties play an important role in this study because the individual effects of the MCFs are much smaller***

compared to the GPP and respiration fluxes. I believe that sensitivity and ensemble simulations are not enough to address the various large uncertainties related to the methods and models that quantify the MCFs. I would urge for a more detailed comparison of the results to existing observations and to other studies that have addressed certain MCFs in more detail in the past.

[Reply 1-1]

Thank you for this comment. I agree to include a more comprehensive comparison with existing observations and other studies on MCFs. The revised manuscript has an additional table (seen as new Table 2, below) for this purpose; more estimates and remarks will be included.

Table 2. Summary of previous estimates of minor carbon flows (MCFs).

MCF	Reference	($Pg\ C\ yr^{-1}$)
F_{LUC}	Houghton et al. (2003): bookkeeping	2.1 ± 0.8
	Le Quéré et al. (2018): GCP 2018 models	1.5 ± 0.6
	Le Quéré et al. (2018): GCP 2018 bookkeeping	1.4 ± 0.7
	This study (EX_{ALL}, 1980–1989 mean ± SD)	0.99 ± 0.02
	(EX_{ALL}, 1990–2015 mean ± SD)	0.60 ± 0.16
F_{BB}	Wiedinmyer et al. (2011): FINN	2.18
	van der Werf et al. (2017): GFED4s	2.2
	van Marle et al. (2017): BB4CMIP6	1.90
	This study (EX_{ALL}, 1990–2015 mean ± SD)	1.69 ± 0.21
F_{BVOC}	Guenther et al. (2012): MEGAN model	0.96
	Sindelarova et al. (2014): MEGAN model	0.76
	This study (EX_{ALL}, 1990–2015 mean ± SD)	0.75 ± 0.036
F_{CH4}	Fung et al. (1991)	0.14
	Saunois et al. (2016): GCP synthesis	0.135
	This study (EX_{ALL}, 1990–2015 mean ± SD)	0.12 ± 0.006
F_{AP}	Bondeau et al. (2007): LPJmL model	2.2
	Ciais et al. (2007)	1.29
	Wolf et al. (2015): FAOSTAT-base	2.05 ± 0.05
	This study (EX_{ALL}, 1990–2015 mean ± SD)	1.45 ± 0.073
F_{WH}	Winjum et al. (1998)	0.98
	Pan et al. (2011): inventory analysis	0.189
	This study (EX_{ALL}, 1990–2015 mean ± SD)	1.03 ± 0.082
F_{DOC}	Meybeck (1993)	0.20
	Dai et al. (2012)	0.17
	This study (EX_{ALL}, 1990–2015 mean ± SD)	0.14 ± 0.004
F_{POC}	van Oost et al. (2007): agricultural soils	0.25
	Regnier et al. (2013)	0.1 ± >0.05
	Galy et al. (2015)	0.157 (0.107–0.231)

Chappell et al. (2016): displacement by erosion	0.3–1.0
Naipal et al. (2018): ORCHIDEE + RUSLE	0.16 ± 0.06
This study (EX_{ALL}, 1990–2015 mean ± SD): riverine export to the ocean, 20% of soil displacement	0.19 ± 0.011

Major comments:

[Comment 1-2] ***1) As indicated in this study, many uncertainties remain in the simulation of MCFs. There have been several studies in the past that have focused on individual MCFs in great detail and tried to address these uncertainties. This study, however, simulates the MCFs in a much simpler way. Although this is understandable, the question that remains is: Does the combination of MCFs in a single framework lead to new insights in the global C cycle, or does it pose more uncertainties and might even lead to the misinterpretation of their net effect? I feel that this issue has not been fully addressed by Ito.***

[Reply 1-2] This is a great comment. I'm convinced that this is one of the early attempts to include MCFs into a single consistent model framework, and in this sense, that this study carries novel implications such as interactions between MCFs and effects on net ecosystem production. On the other hand, I agree that these points were not adequately declared in the previous manuscript. The sparse observational data and simple parameterization of MCFs can bring additional uncertainties, which need to be recognized, into our global carbon accounting. However, I believe such attempts would lead to deeper understanding and more accurate evaluation of carbon budget. The revised manuscript includes these statements.

(Sect. 4.5 of the revised manuscript)

"*This study is an early attempt to evaluate the effects of various MCFs. The results have convinced me that changes in MCFs will have considerable influences on the global carbon budget (e.g., Piao et al., 2018; Lal et al., 2019; Pugh et al., 2019), and more such attempts are required to improve our understanding of the global carbon cycle, which plays a critical role in future climate projections. However, given the imperfect state of knowledge about these MCFs, their inclusion can introduce other errors and biases. I took the estimation uncertainty into account by perturbing representative parameters, but this study did not examine other sources of uncertainties such as differences among ecosystem models and forcing data. Indeed, many ecosystem models have been developed with different degrees of complexity (e.g., dynamic global vegetation models), and intercomparison studies have shown that existing ecosystem models differ widely in their environmental responsiveness to changes in major carbon flows* *(e.g., Friend et al., 2014; Huntzinger et al., 2017). For example, the models differ in global GPP by more than 30%, even though the processes contributing to primary production are well understood and increasingly constrained by observations (Anav et al., 2015). This single-model study was necessarily limited in searching the full range of estimation uncertainty, and further studies using multiple MCF-implemented models are highly desirable.*"

[Comment 1-3] ***2) Secondly, it remains unclear to me if including the MCFs leads to a better or worse representation of net C fluxes between land and atmosphere and the C stored in biomass and soil. This study indicated that the VISIT model has been validated with various datasets at field, regional and global scales on ecosystem CO2 exchange. I am curious how the inclusion of MCFs changes the performance of the model. For example, do we see a better spatial variability in biomass and soil C stocks after including MCFs?***

[Reply 1-3] Thank you for this comment. In the light of uncertainties, it may be too early to conclude that including MCFs surely improves quantitative accuracy of terrestrial carbon cycle models. At least several aspects, the model encapsulating MCFs performed better than the old, no MCF one. For example, the net biome production in 1990–2009 (1.13 Pg C yr^{-1} of EXALL vs 2.78 Pg C yr^{-1} of EX0) was estimated more closely to the GCP 2018 one (1.22 Pg C yr^{-1}). It is an excellent idea to compare the spatial distribution of biomass and soil carbon stocks with observation-based data. The revised manuscript includes the comparison of vegetation and soil carbon stocks (Fig. S8).

(Sect. 4.1 of the revised manuscript)

"EX_{ALL} successfully captured the large aboveground vegetation biomass stock in the tropics and the small stock in boreal zones seen in observations (Fig. S8a). A similar comparison of soil carbon (Fig. S8b) also indicates the model's ability to capture the spatial gradient in this stock; an overestimation in the northern mid-latitudes (around 30°N) is attributable to high soil carbon accumulation in the Tibetan Plateau simulated by the model in frigid regions. It is not clear, however, whether EX_{ALL} (with MCFs) captured the global patterns with greater accuracy than EX0 (without MCFs), because observational datasets show considerable discrepancies, and the differences between the model simulations were relatively small."

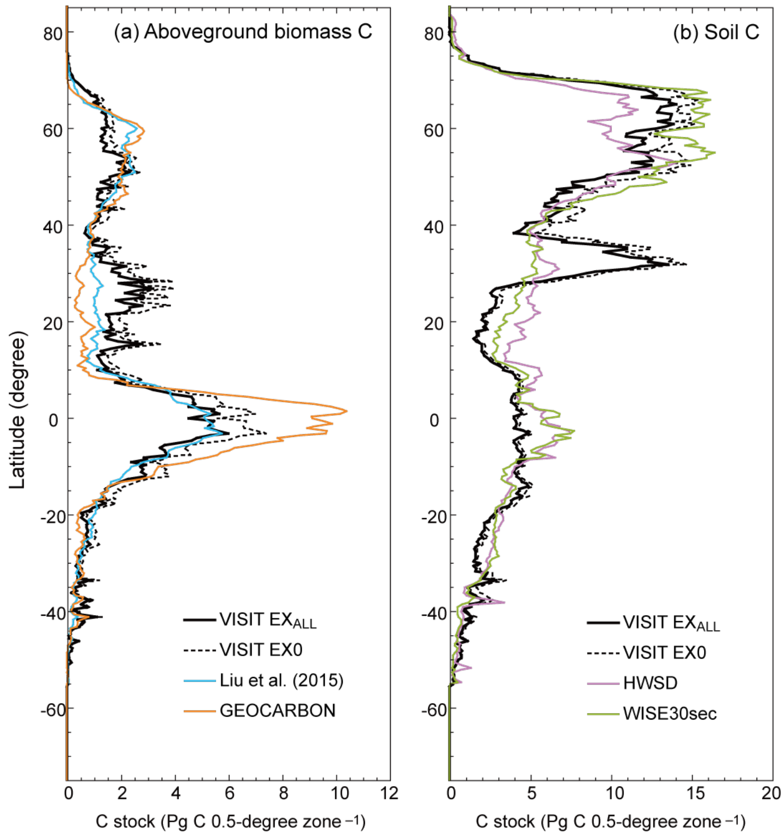

Figure S8. Latitudinal distribution of (**a**) aboveground biomass carbon and (**b**) soil organic carbon simulated by VISIT in EX0 and EX_{ALL} experiments. Also shown in (**a**) are distribution from Liu et al. (2015) and GEOCARBON (Avitabile et al., 2014). Also shown in (**b**) are distributions from the Harmonized World Soil Database (FAO/IIASA/ISRIC-CAS/JRC, 2012) and WISE30sec (Batjes, 2016).

References of Fig. S8

Avitabile, V., Herold, M., Lewis, S. L., Phillips, O. L., Aguilar-Amuchastegui, N., Asner, G. P., Brienen, R. J. W., DeVries, B., Gatti, C. R., Feldpausch, T. R., Girardin, C., de Jong, B., Kearsley, E., Klop, E., Lin, X., Lindsell, J., Lopez-Gonzalez, J., Lucas, R., Malhi, Y., Morel, A., Mitchard, E., Pandey, D., Piao, S., Ryan, C., Sales, M., Santoro, M., Vaglio Laurin, G., Valentini, R., Verbeeck, H., Wijaya, A., and Wilcock, S.: Comparative analysis andfusiuon for improved global biomass mapping, Global Vegetation Monitoring and Modeling, Avignon, France, 2014.

Batjes, N. H.: Harmonized soil property values for broad-scale modeling (WISE30sec) with estimates of global soil carbon stock, Geoderma, 269, 61–68, https://doi.org/10.1016/j.geoderma.2016.01.034, 2016.

Liu, Y. Y., van Dijk, A. I. J. M., de Jeu, R. A. M., Canadell, J. G., McCabe, M. F., Evans, J. P., and Wang, G.: Recent reversal in loss of global terrestrial biomass, Nature Clim. Change, 5, 470–474, https://doi.org/10.1038/NCLIMATE2581, 2015.

[Comment 1-4] ***3) The various uncertainties in parameter estimation of the MCFs such as for the POC and agriculture MCFs are not quantified. For example, in line 21-22 on page 7, the implications of a constant harvest index for crop yields is not quantified. In relation to this, the study of Hay (1990) shows that for Europe the harvest index increased substantially since the 1900s. Furthermore, in line 19-20 on page 8 constant factors have been used for C emissions by decomposition, sedimentation and export to rivers. These factors are very uncertain. Several previous studies (Berhe et al, 2007; Van Oost et al.,2012) show for example that colluvial and alluvial reservoirs play a crucial role in C burial and that the fraction of C emitted to the atmosphere as a result of erosion as indicated by the studies of Lal et al. might be overestimated.***

[Reply 1-4] Thank you for this insightful comment. In this study, the range of uncertainties in each MCFs was assessed by parameter-ensemble simulations. I know that other uncertainties (e.g., methodological uncertainties among different schemes) could substantially affect the results, but considering them should increase computational cost too much. Instead, in this study, I assumed a wide range of parameter uncertainties to harvest the uncertainty range as much as possible (Supplementary Figure S2). For example, transition from the low members to high members may roughly indicates the effects increased harvest index. I appreciate your suggestions on the temporal change in harvest index and reservoir effects on POC export. I found a several papers on the reservoir effect on riverine export (e.g., Mendonça et al., 2017, Nature Communication, 8, doi:10.1038/s41467-41017-01789-41466). The revised manuscript mentions about these effects and associated uncertainties. Straightforward assessments of these factors need further data collection, revised parameterization, and systematic simulations, which would be done in forthcoming studies.

(Sect. 4.4 of the revised manuscript)

"However, this study did not explicitly consider lateral displacement of carbon between adjacent grid cells and associated emissions, such as river transport and international commerce (e.g., Battin et al., 2009; Bastviken et al., 2011; Peters et al., 2012), and reservoir effects on riverine transport (e.g., Mendonça et al., 2017). In this regard, modeling of agricultural practices should be improved to obtain more reliable regional carbon budgets. It is particularly important

to evaluate efforts to increase harvest index and to raise carbon sequestration into cropland soils, as proposed by the "4 per 1000" initiative (Dignac et al., 2017; Minasney et al., 2018).
More clarity is needed in the parameterization of disturbances. This study considered the impacts of wildfires and land-use conversion, but in a conventional manner, possibly leading to biased results (see Sect. 4.5 for biomass burning). Other potentially influential disturbances, such as pest outbreaks and drought-induced dieback associated with climate extremes, were not explicitly considered, although they can perturb ecosystem carbon budgets (Reichstein et al., 2013). In the long term, ecosystem degradation induced by forest fragmentation, overgrazing, and soil loss by wind erosion can further affect carbon budgets (e.g., Paustian et al., 2016; Brinck et al., 2017). Integration of these processes awaits future studies."

[Comment 1-5] ***4) Land use change emissions are proven to be highly uncertain, while being the largest contributor to C emissions amongst the MCFs. For example, the study of Fuchs et al. (2016) shows that gross land use change leads to considerable differences in C emissions compared to net land use change. Without taking such issues into account it is difficult to assess the overall uncertainty of land use change. I think that the author should go deeper into these methodological uncertainties related to the MCFs, especially for land use change.***
[Reply 1-5] Thank you for this comment. I could not find Fuchs et al. (2016) but Fuchs et al. (2015, Global Change Biology, 21, 299–313). I completely agree with your statement that there remain tremendous uncertainties in the present estimation of C emissions (and uptakes) associated with land-use change. In this study, we used gross land-use change derived from the land-use transition matrix (Hurtt et al., 2011, Climatic Change, 109, 117–161).
As shown in Supplementary Figure S7, existing biome models and inventories differ widely in the historical land-use emissions. The range of parameter-ensemble VISIT simulations was roughly comparable with that among biome models, but still I agree that methodology-related uncertainties should be considered.
(Sect. 4.5 of the revised manuscript)
"Considering the shortcomings of broad-scale and long-term observations of MCFs, estimation uncertainties could be larger than presently thought. For example, each of the coefficient factors of the erosion scheme (Eq. 6) can be expected to have large ranges of uncertainty, and few data are available to constrain for the fate of laterally transported POC and DOC. Data related to land-use changes (e.g., gross vs. net land-use transition) and procedures to implement them in models are not standardized (e.g., Fuchs et al., 2015)."

Minor Comments:

[Comment 1-6] ***L 20, page1: The author finds that including MCFs in the global C budget reduces the land C storage due to the smaller residence time. This might be seen as contrasting to the fact that land is a net C sink, which remains unexplained for a large part. Thus, the attempt to capture all the major mechanisms of the C cycle leads to even more uncertainty. This is something that needs to be addressed in the paper.***

[Reply 1-6] Thank you this insightful comment. I agree that the shorter mean residence time (MRT) and net carbon sink seems contrasting. Clearly, the net carbon sink was not caused by elongation of MRT. The MRT of carbon stocks became longer in EX0, implying the it was not primarily related to MCFs or certain uncertainty. In Sect 2.3 of the revised manuscript, MRT (inverse of turnover rate) of vegetation and soil carbon was approximately calculated by the following, assuming a 'relaxed' steady state (cf. Carvalhais et al., 2014, Nature, 514, 213–217).

MRT (vegetation, yr) = Biomass C stock / NPP

MRT (soil, yr) = Soil C stock / heterotrophic respiration

Here, increases in NPP and heterotrophic respiration could largely account for the apparent shortening of MRT. The historical elevation of atmospheric CO_2 concentration and temperature rise resulted in enhanced NPP and heterotrophic respiration, in the model simulation. In the revised manuscript, I discuss the point with a caution to the definition of MRT.

[Comment 1-7] ***L 23, page 1: Instead of aggregating results per cropland fraction it would be more interesting to see the results per land cover type (forest, grass, crop).***

[Reply 1-8] Thank you for this comment. As you recommended, I aggregated the MCFs per land cover types (revised Figure 8a) and would be included in the revised manuscript. The new figure clarified the difference among the land cover types, which seems different from the aggregation by cropland fraction (revised Figure 8b) and precipitation (revised Figure 8c). (Sect 3.3 of the revised manuscript)

"Certain spatial tendencies become clearer in a global aggregation of the simulated results (Fig. 8) related to the dominant land-cover type in each grid cell, the cropland fraction, and aridity represented by annual precipitation. In forest-dominated grid cells (Fig. 8a), F_{BB} made the largest (>30%) contribution, followed by F_{WH}, F_{BVOC}, and F_{LUC}, and in cropland-dominated cells, about half of the influence of MCFs was due to agricultural practices (F_{AP}). Because grassland-dominated cells contain fractions of woodland and cropland, F_{AP} and F_{WH} as well as

F_{POC} made contributions in these cells. In desert-dominated cells, F_{BB} made up the majority of the contributions. In cells with small fractions of cropland including tropical forests (Fig. 8b), F_{WH}, F_{BB}, and F_{BVOC} made strong contributions, whereas in cells dominated by crops, F_{CH4} made a substantial contribution reflecting the vast area of paddy fields in Asia. F_{POC} made large contributions at all cultivation intensities, but particularly in moderately cultivated areas. An analysis based on precipitation was also informative (Fig. 8c). In arid areas (annual precipitation < 500 mm), F_{BB} had the largest impacts, as expected from the dominance of fire-prone ecosystems such as boreal forests and subtropical woodlands. In wet areas (precipitation > 1500 mm), F_{LUC} and F_{POC} made large contributions, and F_{BB} had a minor effect. The influence of F_{WH} was strongest in moderately humid to wet areas."

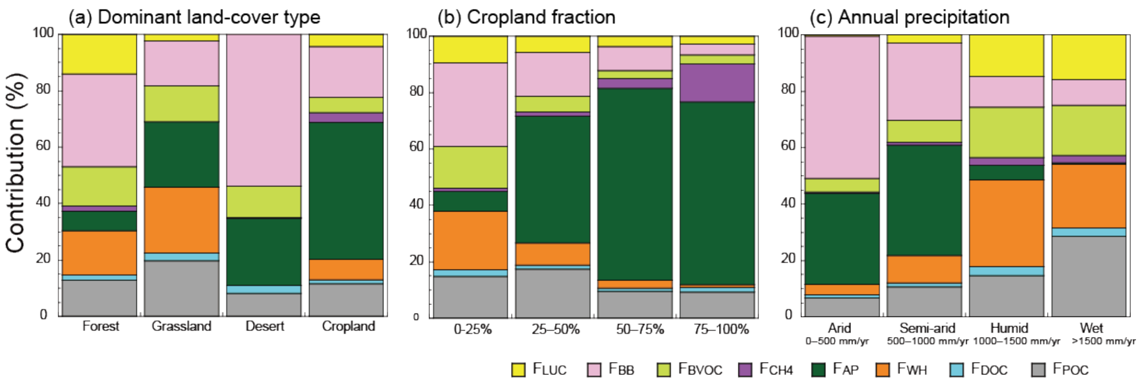

Figure 8. Relative contribution of MCFs to the terrestrial carbon budget simulated by EX_{ALL} in 2000–2009: (**a**) aggregated by dominant land cover type, (**b**) aggregated by cropland fraction within grid cells, and (**c**) aggregated by annual precipitation.

[Comment 1-8] ***Why did the author use the VISIT model? What would be the difference in results if a global land surface model would be used instead? For example, the ORCHIDEE land surface model, which simulates explicitly and in great detail the various ecosystem processes described in this study, and has the possibility to be coupled to the atmosphere and ocean models.***

[Reply 1-8] This is a good comment. In this study, I used the VISIT model, because I have developed the model from scratch and therefore know every detail. This is important to implement the MCFs into a terrestrial model in a biogeochemically consistent and practically efficient manner. Another advantage is the low computational cost of the model (less than 2 days for a whole simulation with a single CPU), allowing us to conduct >100 ensemble simulations with multi-CPU machine in a few weeks. Moreover, the VISIT model has already been coupled with an Earth System Model, which are going to make contributions to CMIP6. I acknowledge that there are many terrestrial models (e.g., ORCHIDEE, CLM, LPJmL, JULES, etc.), which have great details and sometimes their codes are available as open-source. I expect that the present study demonstrates the importance of MCFs and facilitate similar studies by other models.

(Sect 2.1 of the revised manuscript; underline added)

"In comparison to other carbon cycle models, the model has a computationally efficient structure, making it feasible to conduct large numbers of long-term simulations. The model has participated in several model intercomparison projects, making it possible to assess the limitations of a single-model study."

(Sect 4.5 of the revised manuscript; underline added)

"I took the estimation uncertainty into account by perturbing representative parameters, but this study did not examine other sources of uncertainties such as differences among ecosystem models and forcing data. Indeed, many ecosystem models have been developed with different degrees of complexity (e.g., <u>dynamic global vegetation models</u>), and intercomparison studies have shown that existing ecosystem models differ widely in their environmental responsiveness to changes in major carbon flows (e.g., Friend et al., 2014; Huntzinger et al., 2017). For example, the models differ in global GPP by more than 30%, even though the processes contributing to primary production are well understood and increasingly constrained by observations (Anav et al., 2015). This single-model study was necessarily limited in searching the full range of estimation uncertainty, and further studies using multiple MCF-implemented models are highly desirable."

[Comment 1-9] ***L 1, page 6: Why are human-prescribed fires not considered? In previous studies it is shown that population density and crop fraction are important drivers of burnt area (Lasslop and Kloster, 2017). It would be interesting to compare methane emissions from the model to observations.***

[Reply 1-9] Thank you for this comment. I checked Lasslop and Kloster (2017, Environmental Research Letters, 12, 115011) and associated papers. One possible justification is that the present model has already simulated extensive global burnt area (around 600 Mha per year) comparable with that by satellite observation including both wild and human-caused fires. However, I agree that human impacts on fire regime is significant and related to population and land-use. As demonstrated in Supplementary Figure S11, the simulated biomass burning did not capture the decreasing trend after 1998. By using an updated fire scheme (it is beyond the scope of this study), I would like to include human impacts on fire regime. Comparison with the simulated emissions with observed atmospheric concentrations of methane (and carbon monoxide, black carbon etc.) should be effective for model validation.

[Comment 1-10] ***Page 6, section 2.2.4: How is the wetland fraction determined in the model and is that comparable to observed wetland distribution globally?***

[Reply 1-10] Thank you for this comment. I am sorry about the largely simplified description of methane simulation, although it was fully described in Ito and Inatomi (2012). The wetland fraction for each grid was determined by the Global Lake and Wetland Dataset (Lehner and Döll, 2004, Journal of Hydrology, 296, 1–22). I applied this observation-based map through the simulation period. The uncertainty of wetland and inundation maps would be addressed in the wetland methane model intercomparison project (e.g., Poulter et al., 2017, Environmental Research Letters, doi: 10.1088/1748-9326/aa8391). The revised manuscript includes the description and reference of wetland map.

(Sect. 2.2.4 of the revised manuscript)

"The wetland fraction $f_{wetland}$ was derived from the Global Lake and Wetland Dataset (Lehner and Döll, 2004) was held fixed throughout the simulation period. Temporal variations of the inundation area and water table depth in the wetland fraction are key factors in estimating $F_{wetland}$. In this study, seasonal variation of the inundated area was prescribed by satellite data by microwave remote sensing (Prigent et al., 2001), and temporal variability of water table depth was determined by the water budget estimated by the VISIT model (Ito and Inatomi, 2012). Therefore, interannual variability in inundation area, such as that due to droughts and floods, could have been underrepresented in this study."

[Comment 1-11] ***How is crop harvest simulated in the tropics? And is crop irrigation included?***

[Reply 1-11] In the tropics (annual mean temperature > 20°C and lowest monthly temperature > 10°C), a generic multiple cropping system was assumed; crop harvest occurs through the year round at a constant rate. Crop irrigation was considered only in an implicit manner. Namely, water stress factor on maximum photosynthesis rate was relaxed in croplands, assuming the effect of irrigation. On the other hand, hydrological budget of irrigated water was not considered.

(Sect. 2.2.5 of the revised manuscript)

"The scheme assumes a single-cropping cultivation system in temperate regions, where the growing period is determined by a critical mean monthly temperature of 5°C. In tropical regions (annual mean temperature > 20°C), a continuous (non-seasonal) cropping system is assumed in which planting and harvesting occur at constant rates in every month. Irrigation is not explicitly included in the model; instead the water-stress factor for cropland plants is relaxed from its value for natural vegetation."

[Comment 1-12] ***In section 2.2.8, how are the individual erosion parameters calculated? Previous studies have shown that erosion rates can be highly uncertain when applying the RUSLE model on the global scale using coarse resolution input data. Including the L and P factors in the RUSLE at the global scale can also contribute to large uncertainties as they are local-scale dependent.***

[Reply 1-12] Thank you for this comment. I found several recent studies explored soil erosion at the global scale (e.g., Naipal 2018; Borrelli et al., 2018, Nature Communications, 8, doi:10.1038/s41467-017-02142-7; Xiong et al., 2019, Geoderma 343, 31–39). The RUSLE is a simple model of soil displacement by water erosion and then has been used widely. In the present study, as explained in my previous study (Ito, 2007, Geophysical Research Letters, L09403), slope factors (L and S) were calculated using a 1km-mesh topography data (GTOPO30 and HYDRO1k); rainfall factor (R) was calculated using an empirical parameterization by Renard and Freimund (1994, J. Hydrol., 157, 287– 306) every year; soil erodibility factor (K) was calculated on the basis of soil composition (organic matter, clay, silt, and sand) with a parameterization by Torri et al. (1997, Catena, 31, 1–22); vegetation coverage (C) and management protection (P) factors were derived from look-up tables for each of the land cover types from Yang et al. (2003, Hydrol. Processes, 17, 2913– 2928) and Morgan (2005, Soil Erosion and Conservation, 3rd ed). The locality effect of L could be ameliorated by using a fine-mesh topography data. On the other hand, the P factor could be heterogeneous due to farm-by-farm difference in soil management such as mulching and contour farming. It is, however, difficult to determine P value for each farm and to obtain a spatially representative value for each 0.5° grid, although ongoing development of high-resolution remote sensing and AI-based categorization would make it possible in the future. At this stage, I conventionally estimated P at each grid from the cropland fraction and whether developed or developing country. In relation to soil degradation and conservation, future studies would estimate the P factor in a more realistic manner. The revised manuscript describes how F_{POC} was estimated using the RUSLE and discusses the potential uncertainties.

(Sect. 2.2.8 of the revised manuscript)

"Export of POC is assumed to occur mainly in association with soil displacement by water erosion, which can cause soil degradation. The VISIT model incorporates the Revised Universal Soil Loss Equation (Renard et al., 1997) to estimate the rate of soil displacement by water erosion (Ito, 2007). Annual displacement of soil carbon is calculated by:

$$F_{POC} = fC \times R \times L \times S \times K \times C \times P, \quad (6)$$

where fC is soil carbon content and R, L, S, K, C, and P are coefficient factors of rainfall, slope length, slope steepness, soil erodibility, vegetation coverage, and conservation practices, respectively, as described in Ito (2007). fC is obtained from the VISIT simulation, and F_{POC} is extracted from the soil surface litter pool. Although it was developed for management of local croplands, this practical scheme and its derivatives have been used for continental-scale studies (e.g., Yang et al., 2003; Schnitzer et al., 2013; Naipal et al., 2018). Transport of terrestrial carbon to inland waters or the ocean is, however, a complicated process (Berhe et al., 2018); for example, large fractions of displaced soil are redistributed in riverbanks, lakeshores, and estuaries. The fate of eroded carbon is assumed to be 20% in CO_2 evasion by decomposition, 60% in sedimentation, and 20% in export to lakes and oceans (Lal, 2003; Kirkels et al., 2014). The export fraction is highly uncertain and is discussed further in the parameter uncertainty analysis of Sect. 4.5."

[Comment 1-13] ***L 17, page 8: "The carbon of Fpoc is extracted from the litter pool." Why is the SOC of the topsoil not taken into account? This could produce biases in C erosion rates, especially for cropland.***

[Reply 1-13] Thank you for this comment. You are right, because soil erosion can occur not only in litter but also in SOC layer in a real world. My assumption of F_{POC} extraction from litter pool is only for simplicity, because I did not have enough data on the fractional contribution of litter and SOC to eroded carbon. I will explain this in the revised manuscript and in a forthcoming study, I would like to address this issue on the basis of a synthesis of soil erosion.

(Sect. 2.2.8 of the revised manuscript)

"fC is obtained from the VISIT simulation, and F_{POC} is extracted from the soil surface litter pool. Although it was developed for management of local croplands, this practical scheme and its derivatives have been used for continental-scale studies (e.g., Yang et al., 2003; Schnitzer et al., 2013; Naipal et al., 2018)."

(Sect. 4.5 of the revised manuscript)

"For example, each of the coefficient factors of the erosion scheme (Eq. 6) can be expected to have large ranges of uncertainty, and few data are available to constrain for the fate of laterally transported POC and DOC."

[Comment 1-14] ***L 25, page 8: How would neglecting riverine lateral fluxes (POC and DOC) contribute to the uncertainty of MCFs?***

[Reply 1-14] Thank you for this comment. The present model does not explicitly simulate lateral carbon exchange between grids such as POC and DOC transport by rivers. As a result, carbon export in one upstream grid and deposition in another downstream grid were not considered. I do not think the magnitude of the effect exceed 1 Pg C per year, but at least in certain areas, this process would affect net carbon budget.

[Comment 1-15] ***L 21, page 9: Why is Fpoc classified as biogeochemical flow and not anthropogenic? Fpoc is the result of human-induced erosion, as far as I understand.***

[Reply 1-15] Thank you for this comment. As you pointed out, soil erosion (F_{POC}) has been largely enhanced by human activities, and in my model simulation, the flow was separately evaluated for croplands and natural ecosystem. The term, 'biogeochemical' flow, is a conventional one and does not indicate a 'natural' flow. Indeed, other 'biogeochemical' flows such as F_{CH4} (including paddy emission) were more or less affected by human activities, but in more indirect manners than anthropogenic flows such as land-use and harvests. The revised manuscript explains the definition of 'biogeochemcial' flow in a clearer manner.

(Sect. 2.3.1 of the revised manuscript)

"• EX_{BGC}: biogeochemical flows (F_{BVOC}, F_{CH4}, F_{DOC}, and F_{POC}) were added to EX0.

• EX_{ATP}: anthropogenic (human-dominated) flows (F_{LUC}, F_{BB}, F_{AP}, and F_{HW}) were added to EX0.

The (last) two simulations (EX_{BGC} and EX_{ATP}) sought to evaluate the relative contributions of what are conventionally considered biogeochemical and human-affected processes."

[Comment 1-16] **L 5, page 10: Why is only the erodibility perturbed randomly and not the**

other RUSLE factors that maybe be more sensitive such as erosivity?

[Reply 1-16] Thank you for this comment. Other factors such as precipitation, slope and its length, vegetation cover, and management are influential to F_{POC} and should have their own uncertainties, and I agree that it is desirable to assess them in a systematic manner. In this study, I chose the erodibility as a representative one for simplicity, with a sufficient width of perturbation. As shown in the result of ensemble simulation (Supplementary Figure S2), the simulated F_{POC} ranged widely from 0.1 to 1.4 Pg C yr^{-1}. Elsewhere, I would like to assess the effect of erosion-related factors using multiple input data.

(Sect. 4.5 of the revised manuscript)

"For example, each of the coefficient factors of the erosion scheme (Eq. 6) can be expected to have large ranges of uncertainty, and few data are available to constrain for the fate of laterally transported POC and DOC."

[Comment 1-17] ***L 7-15, page 11: It would be useful to compare these results to the findings of other studies that quantified one or more of the individual MCFs at the global scale.***

[Reply 1-17] I agree to compare the results with other global-scale model studies that quantified one or more MCFs. The results will be summarized into a new table (cf. Table 2 of the revised manuscript, also shown above in this reply).

[Comment 1-18] ***L 15, page 11: I find it surprising that the DOC export has a larger effect on SOC stocks in comparison to POC export. What could be the possible cause of this?***

[Reply 1-18] Thank you for this comment. One reason for the stronger impact of DOC export is that a large part of POC export occurred in croplands and ecosystems on steep slopes. In contrast, DOC export occurred in a vast extent of ecosystems especially in humid tropical area (Figures 6h and 6i of the REVISED paper). The impacts of DOC and POC exports were much smaller than those by land-use change and biomass burning, and the difference of the impacts (about 2 Pg C) could be, at least partly, caused by such spatial patterns.

[Comment 1-19] ***L 8, page 36: Soil erosion rates have been compared to the findings of Chappell et al. (2016) only, however, Chappell et al. did not calibrate their erosion model for other land cover types than cropland. It would be useful to compare the results also to the study of Naipal et al. (2018), who estimated gross SOC erosion for the period 1850-2005.***

[Reply 1-19] Thank you for this comment. In the revised manuscript, the result would be compared with that in Naipal et al. (2018) (see Table 2 of the revised manuscript).

[Comment 1-20] ***Page 37, figure 6: Why is Fap negative in some regions?***

[Reply 1-20] Thank you for this comment. The negative F_{AP} in the previous manuscript was due to an inaccurate mass balance calculation in croplands, and it was corrected in the second version. As a result, all croplands take positive (i.e. net carbon export) F_{AP} values (see Figure 6e and 6f of the revised manuscript).

Anonymous Referee #2

Main comments:

[Comment 2-1] ***This study estimated the influences of eight minor disturbances (MCFs) on global land carbon budget over the historical period 1901-2016 using a process-based terrestrial ecosystem model VISIT. Carbon contributions from minor disturbances like CH4, BVOC, and carbon loss by water (or river) erosion were often ignored in the past modeling studies, but have been evaluated in this study within one model framework. Results from a group of sensitivity modeling experiment show notable contributions from MCFs to land carbon sink and storage, which is mostly due to land use change, fires, and wood harvest. The author also find BVOC has a comparable contribution. This study helps improve understanding of land carbon cycle and shows the importance of the MCFs on the land carbon budget. Overall, the manuscript is well written and could be acceptable for publication in ESD after some minor revisions. Please see my minor comments as below.***

[Reply 2-1] Thank you for this encouraging comment.

Minor comments:

[Comment 2-2] ***(1) Line 17 in the abstract: It is unclear the net biome production was estimated for which period?***

[Reply 2-2] Thank you. The net biome production was estimated for the same period of the previous sentence (i.e. the 2000s). I added "in the same period" after "net biome production".

[Comment 2-3] ***(2) Page 11, Lines:29-30: does it mean that NEP dominate the trend of NBP? As from other estimates that trend in land-use change emission is relatively small. How are***

the fires from, e.g. FEEDs?

[Reply 2-3] Thank you for this comment. In this study, the simulated NEP and NBP show comparable linear trends. The simulated FLUC shows a clear decreasing trend after 2000 and F_{BB} shows a moderate increasing trend. Such compensation may explain a part of the small trend associated with the MCFs. However, a recent study (Andela et al., 2017) indicate a decreasing trend in global burnt area, implying the necessity of further improvement of temporal trends in MCFs. The revised manuscript includes more comparison with observations (Table 2 of the revised manuscript) and discussion about it.

Table 2. Summary of previous estimates of minor carbon flows (MCFs).

MCF	Reference	(Pg C yr^{-1})
F_{LUC}	Houghton et al. (2003): bookkeeping	2.1 ± 0.8
	Le Quéré et al. (2018): GCP 2018 models	1.5 ± 0.6
	Le Quéré et al. (2018): GCP 2018 bookkeeping	1.4 ± 0.7
	This study (EX_{ALL}, 1980–1989 mean ± SD)	0.99 ± 0.02
	(EX_{ALL}, 1990–2015 mean ± SD)	0.60 ± 0.16
F_{BB}	Wiedinmyer et al. (2011): FINN	2.18
	van der Werf et al. (2017): GFED4s	2.2
	van Marle et al. (2017): BB4CMIP6	1.90
	This study (EX_{ALL}, 1990–2015 mean ± SD)	1.69 ± 0.21
F_{BVOC}	Guenther et al. (2012): MEGAN model	0.96
	Sindelarova et al. (2014): MEGAN model	0.76
	This study (EX_{ALL}, 1990–2015 mean ± SD)	0.75 ± 0.036
F_{CH4}	Fung et al. (1991)	0.14
	Saunois et al. (2016): GCP synthesis	0.135
	This study (EX_{ALL}, 1990–2015 mean ± SD)	0.12 ± 0.006
F_{AP}	Bondeau et al. (2007): LPJmL model	2.2
	Ciais et al. (2007)	1.29
	Wolf et al. (2015): FAOSTAT-base	2.05 ± 0.05
	This study (EX_{ALL}, 1990–2015 mean ± SD)	1.45 ± 0.073
F_{WH}	Winjum et al. (1998)	0.98
	Pan et al. (2011): inventory analysis	0.189
	This study (EX_{ALL}, 1990–2015 mean ± SD)	1.03 ± 0.082
F_{DOC}	Meybeck (1993)	0.20
	Dai et al. (2012)	0.17
	This study (EX_{ALL}, 1990–2015 mean ± SD)	0.14 ± 0.004
F_{POC}	van Oost et al. (2007): agricultural soils	0.25
	Regnier et al. (2013)	0.1 ± >0.05
	Galy et al. (2015)	0.157 (0.107–0.231)
	Chappell et al. (2016): displacement by erosion	0.3–1.0

Naipal et al. (2018): ORCHIDEE + RUSLE	0.16 ± 0.06
This study (EX_{ALL}, 1990–2015 mean ± SD): riverine export to the ocean, 20% of soil displacement	0.19 ± 0.011

[Comment 2-4] ***(3) Page 12, Line 7: How the mean residence time (MRT) was calculated? What are the assumptions were used to calculated the MRT for each C pool? Also, why MRT was decreased in the Fig. 4?***

[Reply 2-4] Thank you for this comment. In this study, MRT at a non-equilibrium state was calculated approximately as

MRT (vegetation, yr) = Biomass C stock / NPP

MRT (soil, yr) = Soil C stock / heterotrophic respiration

Such approximation (assuming an equilibrium state at each year) has been adopted in previous studies. The revised manuscript includes the explanation how to calculate MRTs. The decadal decreasing trends in MRT was largely attributable to enhanced respiration rates due to climate change. Because this trend occurred also in EX0, it is not mainly caused by MCFs.

(Sect. 2.3 of the revised manuscript)

"This study focused on the carbon budget of terrestrial ecosystems and analyzed the following variables: GPP, RE, NEP, NBP, biomass carbon stock, and soil carbon stock. The mean residence time (MRT) of the biomass, soil, and total ecosystem carbon stocks at transitional states were approximately calculated in a similar manner to Carvalhais et al. (2014):

$$\mathrm{MRT} = \mathrm{C\ stock} / \mathrm{flux}, \tag{7}$$

where flux is net primary production (NPP) for biomass (= GPP – RA), RH for soil, and the sum of these fluxes (NPP + RH) for the total ecosystem carbon stock."

(Sect. 3.1 of the revised manuscript)

"Note that MRTs also grew shorter in the result of EX0, which ignored MCFs, but including the MCFs increased the difference in MRT among the experiments. For example, the difference in MRT of vegetation biomass between EX0 and EX_{ALL} grew from 0.89 yr in the 1900s to 1.54 yr in the 2000s, and the difference for soil carbon stock grew from 0.10 yr in the 1900s to 0.24 yr in the 2000s. The definition of MRT (Eq. 7) means that shortened MRTs could result from increases of NPP and respiration."

[Comment 2-5] ***(4) Page 16, section 4.5: It is good to see the uncertainty assessment. Because this study is based only one model (i.e., VISIT), and the single-model simulation may cannot avoid propagating the uncertainty of other processes to the minor C flows. For example, the uncertainty in C partitioning among vegetation, litter and soil pools may affect the simulations of FBB and FCH4 in this study. A further discussion on this point is necessary.***

[Reply 2-5] This is an important comment, and I agree to include further discussion on estimation uncertainty. This study used a single model (VISIT) aiming at conducting in-depth analyses on MCFs. Based on model intercomparison studies (e.g., Ito et al., 2016, 2017; Tian et al., 2015), the possible range of uncertainties and their propagation to MCF estimation will be discussed.

(Sect. 1 Introduction of the revised manuscript)

"However, large uncertainties remain in the current accounting of the global carbon budget. Present estimates of terrestrial gross primary production (GPP), the largest component of the ecosystem carbon cycle, range from 105 to 170 Pg C yr^{-1} (Baldocchi et al., 2015), and present estimates of soil organic carbon, a large stock in the global biogeochemical carbon cycle, range from 425 to 3040 Pg C (Todd-Brown et al., 2013; Tian et al., 2015)."

(Sect. 4.5 of the revised manuscript)

"I took the estimation uncertainty into account by perturbing representative parameters, but this study did not examine other sources of uncertainties such as differences among ecosystem models and forcing data. Indeed, many ecosystem models have been developed with different degrees of complexity (e.g., dynamic global vegetation models), and intercomparison studies have shown that existing ecosystem models differ widely in their environmental responsiveness to changes in major carbon flows (e.g., Friend et al., 2014; Huntzinger et al., 2017). For example, the models differ in global GPP by more than 30%, even though the processes contributing to primary production are well understood and increasingly constrained by observations (Anav et al., 2015). This single-model study was necessarily limited in searching the full range of estimation uncertainty, and further studies using multiple MCF-implemented models are highly desirable."

[Comment 2-6] ***(5) Page 14, Line 31: delete "(" or add a ")" after ": : :Chapin et al. (2006)".***

[Reply 2-6] Thank you. Corrected (i.e., ")" added after Chapin et al. (2006)).

[Comment 2-7] ***(6) Fig.3 d and e: Impacts of MCFs on NEP is offset by emissions from***

MCFs?

[Reply 2-7] Figure 3d represents the effect of MCFs on NEP leading to higher CO_2 uptake by terrestrial ecosystems. Figure 3e represents the difference between NEP and NBP including the MCFs. Indeed, when comparing Figure 3a and 3c, the effects would offset each other: a large fraction of carbon uptake by vegetation was lost by MCFs.

[Comment 2-8] ***(7) Fig. 6f: For the CH4 emission (FCH4), have you compared the FCH4 in this study with some other estimates? Why does the East Asia show much higher values in comparison with any other regions? In line 23, you have also mentioned that FCH4 in Asia was mostly from paddy field, could you show more details?***

[Reply 2-8] Thank you for this comment. The high methane emissions in East Asia are largely attributable to a vast extent of paddy fields, i.e. natural wetlands. In my paper (Ito and Inatomi, 2012), the model-estimated methane emissions were compared with previous studies. Also, for wetland emissions in 2000–2012, the VISIT model estimation was compared with other models (Poulter et al., 2017), suggesting validity of the model. Additionally, in my recent work (Ito et al., 2019), the model-estimated methane emissions from East Asian paddy fields were compared with inventory (EDGAR 4.3.2) value, and total F_{CH4} was comparable with that by the GCP synthesis using multiple data sources (Saunois et al., 2016). The revised manuscript includes some more details about the methane emission in East Asia.

(Sect. 2.2.4 of the revised manuscript)

"In the wetland fraction, $F_{wetland}$ was simulated using a mechanistic scheme developed by Walter and Heimann (2000) that uses a multi-layer soil model and simulates gaseous methane emission by physical diffusion, ebullition, and plant-mediated transportation. The same scheme was applied to paddy fields, found mostly in Asia, using seasonal inundation by irrigation."

(Sect. 3.2 of the revised manuscript)

"For F_{CH4}, major sources included monsoon-affected parts of Asia dominated by paddy fields, tropical wetlands including floodplains of big rivers, and northern wetlands, whereas other uplands were weak sinks."

(Sect. 3.3 of the revised manuscript)

"In Asia (Fig. 7e), F_{POC} and F_{AP} had the largest effects, and F_{CH4} emissions from the vast area of paddy fields were considerable."

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Disequilibrium of terrestrial ecosystem CO_2 budget caused by disturbance-induced emissions and non-CO_2 carbon export flows: a global model assessment

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Abstract. The global carbon budget of terrestrial ecosystems is chiefly determined by major flows of carbon dioxide (CO_2) such as photosynthesis and respiration, but various minor flows exert considerable influence in determining carbon stocks and their turnover. This study assessed the effects of eight minor carbon flows on the terrestrial carbon budget using a process-based model, the Vegetation Integrative SImulator for Trace gases (VISIT), which included non-CO_2 carbon flows, such as methane and biogenic volatile organic compound (BVOC) emissions and subsurface carbon exports and disturbances such as biomass burning, land-use changes, and harvest activities. The range of model-associated uncertainty was evaluated through parameter-ensemble simulations and the results were compared with corresponding observational and modeling studies. In the historical period of 1901–2016, the VISIT simulation indicated that the minor flows substantially influenced terrestrial carbon stocks, flows, and budgets. The simulations estimated mean net ecosystem production in the 2000–2009 as 3.21 ± 1.1 Pg C yr[−1] without minor flows and 6.85 ± 0.9 Pg C yr[−1] with minor flows. Including minor carbon flows yielded an estimated net biome production of 1.62 ± 1.0 Pg C yr[−1] in the same period. Biomass burning, wood harvest, export of organic carbon by water erosion, and BVOC emissions had impacts on the global terrestrial carbon budget amounting to around 1 Pg C yr[−1] with specific interannual variabilities. After including the minor flows, ecosystem carbon storage was suppressed by about 440 Pg C, and its mean residence time was shortened by about 2.4 yr. The minor flows occur heterogeneously over the land, such that BVOC emission, subsurface export, and wood harvest occur mainly in the tropics, and biomass burning occurs extensively in boreal forests. They also differ in their decadal trends, due to differences in their driving factors. Aggregating the simulation results by land-cover type, cropland fraction, and annual precipitation yielded more insight into the contributions of these minor flows to the terrestrial carbon budget. Considering their substantial and unique roles, these minor flows should be taken into account in the global carbon budget in an integrated manner.

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1 Introduction

The terrestrial ecosystem is a substantial sink of atmospheric carbon dioxide (CO_2) at decadal or longer scales and is mainly responsible for interannual variability of the global carbon budget (Schimel et al., 2001; Le Quéré et al., 2018). The current and future carbon budgets of terrestrial ecosystems have a feedback effect on the ongoing climate change, and they thus affect the effectiveness of climate mitigation policies such as the Paris Agreement (Friedlingstein et al., 2014; Seneviratne et al., 2016; Schleussner et al., 2016). Many studies have been conducted to elucidate the present global carbon budget, which is necessary for making reliable climate predictions (e.g., Sitch et al., 2015). Advances in flux-tower measurement networks, satellite observations, and data-model fusion have greatly improved our understanding of the terrestrial carbon budget and our ability to quantify it (Ciais et al., 2014; Li et al., 2016; Sellers et al., 2018).

However, large uncertainties remain in the current accounting of the global carbon budget. Present estimates of terrestrial gross primary production (GPP), the largest component of the ecosystem carbon cycle, range from 105 to 170 Pg C yr^{-1} (Baldocchi et al., 2015), and present estimates of soil organic carbon, a large stock in the global biogeochemical carbon cycle, range from 425 to 3040 Pg C (Todd-Brown et al., 2013; Tian et al., 2015). The implication is that detecting deviations of a few Pg C with high confidence is problematic. Recent products of remote sensing and up-scaled flux measurement data (e.g., Zhao et al., 2006; Tramontana et al., 2016) are fairly consistent in their spatial patterns of terrestrial carbon flows, but they still differ in their average magnitudes and interannual variability. Observations of isotopes and co-varying tracers (e.g., carbonyl sulfide) provide supporting data (e.g., Welp et al., 2011; Campbell et al., 2017), but estimates have not converged to a consistent value. Quantifying the net carbon balance is even more difficult, primarily because it is a small difference between large sink and source fluxes that vary spatially and temporally. A recent synthesis of the global carbon budget using both top-down and bottom-up data (Le Quéré et al., 2018) gives a plausible estimate for the terrestrial carbon budget, a net sink of 3.0 ± 0.8 Pg C yr^{-1} in 2007–2016; however, it has the largest range of uncertainty among the components of the global carbon cycle.

The uncertainty in the terrestrial carbon budget arises not only from inadequacies in the observational data, but also from an over-simplified conceptual framework. A common index of the net ecosystem carbon budget, net ecosystem production (NEP), is defined as the difference between GPP and ecosystem respiration (RE), which places plant and soil CO_2 exchange, as determined by their physiological properties, in the sole controlling role (Gower, 2003). NEP is expected to be equal to the change in the ecosystem carbon stocks of biomass and soil organic matter. This conceptual framework has been widely used in flux-measurement, biometric, and modeling studies. However, as quantification of the carbon budget has become more sophisticated and accurate, minor carbon flows (MCFs), consisting of relatively small non-CO_2 flows and disturbance-associated emissions, have grown in importance to close the budget. Among these, emissions and ecosystem dynamics associated with wildfires and land-use change have been investigated for decades in various ecosystems such as tropical and boreal forests (e.g., Houghton et al., 1983; Randerson et al., 2005). Subsurface riverine export from the land to the ocean also has been long investigated from biogeochemical and agricultural perspectives (e.g., Meybeck, 1993; Lal, 2003). Many subsequent studies have addressed the biogeochemical mechanisms and spatial-temporal patterns of different MCFs at ecosystem to global scales (e.g., Raymond et al., 2013; Galy et al., 2015; Arneth et al., 2017; Saunois et al., 2017). Accordingly, a revised concept of the net terrestrial carbon budget called net biome production (NBP) has been proposed (Schulze et al., 2000) to account for the effects of MCFs. Because NBP covers non-CO_2, disturbance-induced emissions, and lateral

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transportations, this term is applicable to both natural and managed agricultural ecosystems. Although there remain controversies in the conceptual framework (Randerson et al., 2002; Lovett et al., 2006), NEP and NBP provide a useful basis for integrating carbon flows, carbon pools, and the carbon budget.

Few studies have assessed the importance of MCFs in the global carbon cycle in a quantitative, integrated manner. Several studies have implied that the magnitude of MCFs, while small in comparison with gross flows (about 100 Pg C yr^{-1}), is comparable to the net budget (around 1 Pg C yr^{-1}). It appears, then, that neglecting MCFs can lead to serious accounting biases and misunderstanding of regional carbon budgets. Previous studies of carbon observations (e.g., Chu et al., 2015; Webb et al., 2018) and syntheses (e.g., Jung et al., 2011; Piao et al., 2012; Zhang et al., 2014) have recognized the significance of certain MCFs, such as land-use emissions, but have not integrated them into a single framework (Kirschbaum et al., 2019).

This study estimated MCFs and assessed their influence on the global terrestrial carbon budget in an integrated manner. In this paper I describe a series of simulations conducted with a process-based terrestrial biogeochemical model, in which various MCFs were incorporated into the carbon balance, to distinguish the effect of each MCF and its driving forces. The temporal variability and geographic patterns of these MCFs were clarified. Finally, I discuss methodological uncertainty, potential leakage and duplication in the MCF accounting, linkages with observations and climate predictions, and future research opportunities.

2 Methods

2.1 Model description

This study adopted the Vegetation Integrative SImulator for Trace gases (VISIT), a process-based terrestrial ecosystem model that is more fully described elsewhere (Ito, 2010; Inatomi et al., 2010; a schematic diagram is shown in Fig. S1). In comparison to other carbon cycle models, the model has a computationally efficient structure, making it feasible to conduct large numbers of long-term simulations. The model has participated in several model intercomparison projects, making it possible to assess the limitations of a single-model study. The model is composed of biophysical and biogeochemical modules that simulate atmosphere–ecosystem exchange and matter flows within ecosystems. The hydrology module simulates land-surface radiation and water budgets using forcing meteorological data such as incoming radiation, precipitation, air temperature, humidity, cloudiness, and wind speed, and biophysical properties such as fractional vegetation coverage, albedo, and soil water-holding capacity. The land-surface water budget is simulated using a two-layer soil water scheme that calculates evapotranspiration by the Penman-Monteith equation and runoff discharge by the bucket model (Manabe, 1969). Snow accumulation and melting are also simulated.

The carbon cycle is simulated with a box-flow scheme composed of eight carbon pools (leaf, stem, and root carbon for both C_3 and C_4 plants, plus soil litter and humus) and gross and net carbon flows. An early version of the model simulated only major carbon flows related to CO_2 exchange (Ito and Oikawa, 2002), such as photosynthesis, plant (autotrophic) respiration (RA), and microbial (heterotrophic) respiration (RH). Net ecosystem production (NEP) is defined as follows:

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下へ移動 [1]: The version used in this study includes various MCFs, which play unique and important roles in terrestrial ecosystems. Net ecosystem production (NEP) is defined as follows:

$$NEP = GPP - RA - RH. \quad (1)$$

The total respiratory CO_2 efflux (RA + RH) is called ecosystem respiration (RE). Thus, NEP represents net CO_2 exchange with the atmosphere through ecosystem physiological processes (Gower, 2003). In the model, these processes are calculated using equations that include terms for responsiveness to environmental conditions such as light, temperature, CO_2 concentration, and humidity.

Following carbon fixation by GPP, photosynthate is partitioned to the six plant carbon pools on the basis of production optimization and allometric constraints at every time step. Plant leaf phenology from leaf display to shedding is simulated in deciduous forests and grasslands, using an empirical procedure based mainly on threshold cumulative temperatures. From each vegetation carbon pool, a certain fraction of carbon is transferred to the soil litter pool, which has a specific turnover rate or residence time representing the decomposition of litter carbon into soil humus and eventually CO_2. The VISIT model includes a nitrogen dynamics module that simulates nitrous oxide emission from the soil surface and other nitrogen flows, but this study was primarily focused on the carbon budget.

Note that the model has two separate layers, one for natural ecosystems and another for croplands. Almost all biogeochemical processes are simulated separately in the two layers and then weighted by their respective areas to obtain mean values for each grid cell. A transitional change in the fractions of natural ecosystems and cropland, associated with land-use conversion, results in interactions between the layers.

The VISIT model has been calibrated and validated with field data mostly related to the carbon cycle, such as plant productivity, biomass, leaf area index, and ecosystem CO_2 fluxes (e.g., Ito and Oikawa, 2002; Inatomi et al., 2010; Hirata et al., 2014). Also, at regional to global scales, the model has been examined by comparisons with network and remote-sensing data (e.g., Ichii et al., 2013; Ito et al., 2017). Furthermore, the model has been part of model intercomparison projects. One was the Multi-scale Terrestrial Model Intercomparison Project, which examined terrestrial models in terms of the CO_2 fertilization effect on GPP and its seasonal-cycle amplitude (Huntzinger et al., 2017; Ito et al., 2016) and soil carbon dynamics (Tian et al., 2015). Another was the Inter-Sectoral Impact Model Intercomparison Project, which compared terrestrial impact assessment models with various observational data such as satellite- and ground-measured GPP for benchmarking (Chen et al., 2017), responses to El Niño events (Fang et al., 2017), and turnover of carbon pools (Thurner et al., 2017). Moreover, the model participated in the TRENDY vegetation model intercomparison project and then contributed to the global CO_2 synthesis (Le Quéré et al., 2018).

2.2 Minor carbon flows

The VISIT version used in this study includes various MCFs, which play unique and important roles in terrestrial ecosystems. Eight MCFs were included in the VISIT model in a common manner (Fig. 1): emissions associated with land-use change (F_{LUC}), biomass burning by wildfire (F_{BB}), emission of biogenic volatile organic compounds or BVOCs (F_{BVOC}), methane emissions from wetlands and methane oxidation in uplands (F_{CH4}), agricultural practices from cropping to harvesting (F_{AP}),

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wood harvesting in forests (F_{WH}), export of dissolved organic carbon (DOC) by rivers (F_{DOC}), and displacement of soil particulate organic carbon (POC) by water erosion (F_{POC}). The net carbon balance including MCFs, called net biome production (NBP: Schulze et al., 2000), is more closely related than NEP to the changes in the ecosystem carbon pool. Note that NBP has similarities with and differences from other terms such as NEP, which has scale dependence (Randerson et al., 2002), and net ecosystem carbon balance (Chapin et al., 2006). As discussed later (Sect. 4.4), there remain inconsistencies in the definition of net terrestrial productions, including riverine export, inland water sedimentation, and human harvest and consumption. In this study, NBP is defined as:

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$$NBP = NEP - (F_{LUC} + F_{BB} + F_{BVOC} + F_{CH4} + F_{AP} + F_{WH} + F_{DOC} + F_{POC}). \quad (2)$$

The MCFs differ markedly in their biogeochemical properties and therefore should be evaluated individually. For example, the first four flows are vertical exchanges with the atmosphere (F_{LUC}, F_{BB}, F_{BVOC}, and F_{CH4}), whereas the second four are lateral transportations induced by water and human activities (F_{AP}, F_{WH}, F_{DOC}, and F_{POC}). Flows associated with disturbances, such as wildfire (F_{BB}) and land-use conversion (F_{LUC}), are heterogeneous in space and time. To avoid double counting, these two flows were calculated separately: F_{LUC} includes burning of debris after deforestation, and F_{BB} excludes human-induced ignition.

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2.2.1 Land-use change (F_{LUC})

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Carbon emissions associated with land-use conversion were estimated for the historical period on the basis of a protocol proposed by McGuire et al. (2001), using the Land Use Harmonization (LUH) dataset (Hurtt et al., 2006). The LUH dataset provides both land-use states and their mutual transition matrix. First, the annual transition rate from primary and secondary lands to other land-use types was determined by the LUH dataset. This transition rate was multiplies by the average carbon stock in natural lands simulated by the VISIT model to estimate the amount of carbon affected by land-use conversion. This carbon was then separated into three components with different residence times from less than 1 yr (detritus) to 100 yr (wood products). The detritus, including dead root biomass, was transferred to the soil litter pool and then decomposed. The fractions of wood products with 10-yr and 100-yr residence times are biome dependent (McGuire et al., 2001). Note that wood harvest not associated with land-use change (e.g., selective cutting) was separately evaluated as the F_{WH} term (Sect. 2.2.6). The VISIT model has been used to assess the effects of land-use change from the point scale (Adachi et al., 2011; Hirata et al., 2014) to the global scale (Kato et al., 2013; Arneth et al., 2017).

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2.2.2 Biomass burning (F_{BB})

Wildfire and associated biomass burning have been studied with respect to their effects on land disturbance, carbon biogeochemistry, and climatic interactions (e.g., Randerson et al., 2006; Knorr et al., 2016). The biomass burning scheme of the VISIT model has been described and evaluated by Kato et al. (2013). Biomass burning emission was calculated as follows:

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$$F_{BB} = fBurnt \times DC \times BI \times EF_{BB}, \quad (3)$$

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where fBurnt is the burnt area fraction in natural vegetation, DC is the area-based carbon density, BI is the burnt intensity (fraction of fire-affected carbon), and EF_{BB} is the emission factor (emission per unit burnt biomass). fBurnt is estimated in a prognostic manner using an empirical fire scheme originally developed by Thonicke et al. (2001) for the Lund-Potsdam-Jena dynamic global vegetation model. This scheme estimates the length of the fire season and the corresponding burnt area fraction from monthly values of soil water content and fuel load. Agricultural waste burning and prescribed fires for ecosystem management are not considered here. Differences in fire susceptibility among biomes are characterized by a parameter of critical moisture content for fire ignition. DC, fuel carbon stock per area, is obtained from the VISIT simulation; it is assumed that the plant leaf, stem, root, and soil litter stocks are subject to biomass burning. BI is a biome- and stock-specific parameter obtained from Hoelzemann et al. (2004), ranging from 0.0 for humid forest root to 1.0 for forest and grassland litter. Emission factor EF_{BB} is also a biome- and stock-specific parameter and differs among emission substances; this study considered CO_2, carbon monoxide, black carbon, and methane. EF_{BB} values for each biome and stock were obtained from Hoelzemann et al. (2004). Other carbon flows associated with biomass burning, such as production and burial of charcoal, were not considered.

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2.2.3 BVOC emission (F_{BVOC})

Emissions of BVOCs, such as isoprene and monoterpene, attract particular attention from atmospheric chemists, and several emission schemes have been developed. Here, a convenient scheme of Guenther (1997) was incorporated into the VISIT model with a few modifications. The scheme estimates BVOC emission as follows:

$$F_{BVOC} = EF_{BVOC} \times FD \times DL \times fPPFD \times fTMP \times fPhenology, \quad (4)$$

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where EF_{BVOC} is the emission factor of BVOC, FD is foliar density, DL is day length, and fPPFD, fTMP, and fPhenology are scalar coefficients for light (photosynthetic photon flux density), temperature, and phenological factors, respectively. EF_{BVOC} was derived from Lathiére et al. (2006) for representative species such as isoprene, monoterpene, methanol, and acetone. FD, leaf carbon stock per ground area, and DL were from the VISIT simulation. Due to the difference in biochemical pathways, only isoprene emission is responsive to light intensity (fPPFD = 0–1), while other species are insensitive (fPPFD = 1). BVOC emission increases with temperature, and fTMP differs between isoprene and other monoterpene families. fPhenology, the effect of leaf aging, differs between evergreen and deciduous vegetation. Here, based on the model simulation, leaf age distribution was modified to consider this difference explicitly; fPhenology values ranged from 0.05 for immature leaves (leaf age < 1 month) to 1.2 for mature leaves (leaf age 2–10 months for deciduous and 3–24 months for evergreen leaves). Emission reduction due to leaf senescence is evaluated by decreasing fPhenology value. F_{BVOC} was extracted from the leaf carbon pool in the model, and impacts of released BVOCs on atmospheric chemistry and their climatic feedback were ignored.

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2.2.4 Methane emission (F_{CH4})

Methane is a greenhouse gas second to CO_2 in importance, but here I focus on methane exchange in terms of the carbon budget. Land surface CH_4 exchange was simulated separately for wetland ($F_{wetland}$, source) and upland (F_{upland}, sink) fractions within each grid cell, as described in Ito and Inatomi (2012):

$$F_{CH4} = f_{wetland} \times F_{wetland} - (1 - f_{wetland}) \times F_{upland}, \qquad (5)$$

where $f_{wetland}$ is the wetland fraction within a grid cell. In the wetland fraction, $F_{wetland}$ was simulated using a mechanistic scheme developed by Walter and Heimann (2000) that uses a multi-layer soil model and simulates gaseous methane emission by physical diffusion, ebullition, and plant-mediated transportation. The same scheme was applied to paddy fields, found mostly in Asia, using seasonal inundation by irrigation. In this study, the top 1 m of soil was divided into 20 layers, and methane gas diffusion was solved numerically with a finite-difference method including the vertical gradient of diffusivity. Microbial methane production occurs below the water table and is sensitive to moisture, temperature, and plant activities (substrate supply). It is assumed to increase exponentially with the temperature, and it stops below the freezing point. Ebullition is assumed to occur when the methane concentration exceeds 500 μmol L^{-1}. Plant-mediated transport depends on the methane concentration gradient between the atmosphere and soil layers and is strongly influenced by plant type and rooting depth. Above the water table, methane oxidation by aerobic soil is calculated as a function of soil temperature and the methane concentration of the air space. In the upland fraction such as forests and grasslands, F_{upland} is calculated using a semi-mechanistic scheme (Curry, 2007) that calculates methane uptake as a vertical diffusion process affected by soil porosity and microbial activity. The wetland fraction $f_{wetland}$ was derived from the Global Lake and Wetland Dataset (Lehner and Döll, 2004) was held fixed throughout the simulation period. Temporal variations of the inundation area and water table depth in the wetland fraction are key factors in estimating $F_{wetland}$. In this study, seasonal variation of the inundated area was prescribed by satellite data by microwave remote sensing (Prigent et al., 2001), and temporal variability of water table depth was determined by the water budget estimated by the VISIT model (Ito and Inatomi, 2012). Therefore, interannual variability in inundation area, such as that due to droughts and floods, could have been underrepresented in this study.

2.2.5 Agricultural carbon flows (F_{AP})

Agricultural practices, including cropping, harvesting, and consumption, are an important component in the global carbon budget (Ciais et al., 2007; Wolf et al., 2015). The VISIT model uses a simplified agriculture scheme, in which global croplands are aggregated, on the basis of physiology and cultivation practices, into three types: C_3-plant cropland (e.g., wheat), C_4-plant cropland (e.g., maize), and paddy field. The scheme assumes a single-cropping cultivation system in temperate regions, where the growing period is determined by a critical mean monthly temperature of 5°C. In tropical regions (annual mean temperature > 20°C), a continuous (non-seasonal) cropping system is assumed in which planting and harvesting occur at constant rates in every month. Irrigation is not explicitly included in the model; instead the water-stress factor for cropland plants is relaxed

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from its value for natural vegetation. At the start of the growing period, a certain amount of carbon is added to plant biomass pools to represent planting. The crops are harvested when the surface temperature falls below the critical temperature. This study used a single value of 0.45 for the harvest index (fraction of harvested biomass); however, this index varies among crop types and regions, and the uncertainties in this parameter are considered in Sect 4.5. Residual plant biomass was transferred to the litter pool as agricultural detritus, and this study ignored manure production and consumption processes. Harvested crops were exported from the ecosystem, and the complexities of horizontal food displacement and consumption were also ignored.

2.2.6 Wood harvest (F_{WH})

Timber harvest by logging in forested lands was evaluated primarily from the LUH dataset (Hurtt et al., 2006), in which the annual wood harvest rate was derived from national data compiled by the United Nations Food and Agricultural Organization. Hurtt et al. (2006) estimated the spatial pattern of wood harvest in each country from land-use data. In this study, regrowth and carbon accumulation of forests after logging was simulated as a recovery of the carbon stock to its previous level of mature forest. As was done for crops, the harvested wood biomass was assumed to be exported from the ecosystem, specifically the stem carbon pool; horizontal transportation to and consumption in other grid cells were ignored. Note that emissions from harvested timber associated with land-use change were evaluated as part of the F_{LUC} term.

2.2.7 Dissolved organic carbon export (F_{DOC})

Production and consumption of DOC are important processes in terrestrial ecosystems, in terms of soil formation and riverine transport (Nelson et al., 1993). In this study, the VISIT model included a simple scheme of DOC dynamics developed by Grieve (1991) and Boyer et al. (1996), in which the DOC concentration in soil water is determined by the balance of production, decay, and export. The production and decay rates are determined by soil temperature, and the export rate is determined by runoff discharge. In this study, net carbon export by DOC was extracted from the mineral soil pool. Because the VISIT model does not include a river routing scheme, DOC extraction was independently evaluated at each grid cell, and lateral transportation and decay processes were not simulated.

2.2.8 Particulate organic carbon export (F_{POC})

Export of POC is assumed to occur mainly in association with soil displacement by water erosion, which can cause soil degradation. The VISIT model incorporates the Revised Universal Soil Loss Equation (Renard et al., 1997) to estimate the rate of soil displacement by water erosion (Ito, 2007). Annual displacement of soil carbon is calculated by:

$$F_{POC} = fC \times R \times L \times S \times K \times C \times P, \qquad (6)$$

where fC is soil carbon content and R, L, S, K, C, and P are coefficient factors of rainfall, slope length, slope steepness, soil erodibility, vegetation coverage, and conservation practices, respectively, as described in Ito (2007). fC is obtained from the

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VISIT simulation, and F_{POC} is extracted from the soil surface litter pool. Although it was developed for management of local croplands, this practical scheme and its derivatives have been used for continental-scale studies (e.g., Yang et al., 2003; Schnitzer et al., 2013; Naipal et al., 2018). Transport of terrestrial carbon to inland waters or the ocean is, however, a complicated process (Berhe et al., 2018); for example, large fractions of displaced soil are redistributed in riverbanks, lakeshores, and estuaries. The fate of eroded carbon is assumed to be 20% in CO_2 evasion by decomposition, 60% in sedimentation, and 20% in export to lakes and oceans (Lal, 2003; Kirkels et al., 2014). The export fraction is highly uncertain and is discussed further in the parameter uncertainty analysis of Sect. 4.5.

2.3 Simulations and analyses

Global simulations were conducted from 1901 to 2016 at a spatial resolution of 0.5° × 0.5° in latitude and longitude. The VISIT model was applied to each grid cell, and lateral interactions such as riverine transport, food and timber export, and animal migration were ignored. To obtain the initial stable carbon balance, a spin-up calculation under stationary conditions was conducted for each grid cell for 300 to 3000 years, depending on climate conditions and the biome type. This section describes sensitivity simulations to analyze the impacts of different forcing variables, ensemble perturbation simulations to assess the effect of parameter uncertainty, and several supplementary simulations.

All simulations used climate conditions from CRU TS 3.25 (Harris et al., 2014), consisting of monthly temperature, precipitation, vapor pressure, and cloudiness. The historical change in atmospheric CO_2 concentration was taken from observations (e.g., Keeling and Whorf, 2009). The global distribution of natural vegetation was determined by Ramankutty and Foley (1998) for potential vegetation types and Olson et al. (1983) for actual vegetation types. This study classified natural vegetation into 28 types after Olson et al. (1983). Historical land-use status, transitional changes, and wood harvest in each grid cell were derived from the LUH data (Sect. 2.2.1). Until 2005, land-use data were compiled on the basis of statistics and various ancillary data, and after 2006 the data were extended by using an intermediate projection scenario (RCP4.5) produced with an integrated assessment model. The distribution of dominant crop types was determined from the global dataset of Monfreda et al. (2008) and used to calculate F_{AP} and F_{CH4} (for paddy field). For the calculation of F_{CH4}, the wetland fraction in each grid cell was determined from the GLWD (Sect. 2.2.4). For the estimation of F_{POC}, slope factors (L and K) were calculated from the GTOPO30 topography data (https://lta.cr.usgs.gov/GTOPO30), and the erodibility factor (S) was calculated from soil composition data (Reynolds et al., 1999). Vegetation coverage (C) and conservation practice (P) factors were determined from the dominant natural vegetation and cropland types, also considering the difference in management intensity between developed and developing countries.

This study focused on the carbon budget of terrestrial ecosystems and analyzed the following variables: GPP, RE, NEP, NBP, biomass carbon stock, and soil carbon stock. The mean residence time (MRT) of the biomass, soil, and total ecosystem carbon stocks at transitional states were approximately calculated in a similar manner to Carvalhais et al. (2014):

$$MRT = C\ stock\ /\ flux, \qquad (7)$$

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where flux is net primary production (NPP) for biomass (= GPP – RA), RH for soil, and the sum of these fluxes (NPP + RH) for the total ecosystem carbon stock.

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2.3.1 Sensitivity simulations

To evaluate and separate the effects of MCFs, 12 simulation experiments were conducted:

- EX0: no MCF was included, and the terrestrial carbon budget was determined by GPP, RA, and RH, such that NBP was identical to NEP.
- EX_{LUC}: only F_{LUC} was added to EX0.
- EX_{BB}: only F_{BB} was added to EX0.
- EX_{BVOC}: only F_{BVOC} was added to EX0.
- EX_{CH4}: only F_{CH4} was added to EX0.
- EX_{AP}: only F_{AP} was added to EX0.
- EX_{WH}: only F_{WH} was added to EX0.
- EX_{DOC}: only F_{DOC} was added to EX0.
- EX_{POC}: only F_{POC} was added to EX0.
- EX_{ALL}: all eight MCFs were considered, equivalent to the baseline simulation.
- EX_{BGC}: biogeochemical flows (F_{BVOC}, F_{CH4}, F_{DOC}, and F_{POC}) were added to EX0.
- EX_{ATP}: anthropogenic (human-dominated) flows (F_{LUC}, F_{BB}, F_{AP}, and F_{HW}) were added to EX0.

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The differences between EX0 and the next eight simulations indicate the effects of individual MCFs, and the difference between EX_{ALL} and EX0 shows the combined effect of these MCFs. Interactions among the MCFs through changes in the terrestrial carbon stock may mean that their effects are not linearly additive. For example, land-use changes have indirect impacts on biomass burning, BVOC emission, and water erosion (e.g., Nadeu et al., 2015). Also, inclusion of the MCFs affects the major flows of primary production and respiration. For example, BVOC emission reduces the carbon stored in leaves, which leads to reductions of light absorption and GPP. In croplands, planting and harvest substantially influence GPP and respiration. The last two simulations (EX_{BGC} and EX_{ATP}) sought to evaluate the relative contributions of what are conventionally considered biogeochemical and human-affected processes.

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2.3.2 Parameter ensemble simulations

Large uncertainties remain in the estimates for each MCF and its impacts. These uncertainties can emerge among different models, forcing data, and parameters, and evaluating them is important but difficult. The schemes used in this study include empirical formulations and parameters, some of which are not well constrained by observational data. Upscaling locally adapted schemes and parameters can lead to biased results at the global scale. To characterize the range of uncertainty caused by poorly determined parameters, I conducted a set of ensemble simulations, based on EX_{ALL}, in which the values of the following representative parameters of the eight MCFs were randomly perturbated at the same time: annual deforestation rate in F_{LUC}, biomass burning emission factors in F_{BB}, BVOC emission factors in F_{BVOC}, wood harvest rate in F_{WH}, crop harvest index in F_{AP}, methane production and oxidation potentials in F_{CH4}, DOC export rate in F_{DOC}, and erodibility and land-export fraction in F_{POC}. It should be noted here that other parameters have their own uncertainties and that this study focused on these eight representative parameters for explanatory purposes. Also, these uncertainties may increase as they incorporate the differences among models with differing structures and assumptions. A total of 146 ensemble simulations were conducted (Fig. S2) in which these parameters were perturbed by randomly selecting values from the Gaussian distribution within the range of ±30%. All other configurations were those of EX_{ALL}. Means, medians, and 95% confidence intervals were calculated from the 146 resulting terrestrial carbon budgets.

2.3.3 Supplementary simulations

To further investigate the characteristics and influence of MCFs, five supplementary simulations were conducted. In the first, based on the protocol of EX_{ALL}, land-use status was held fixed at its initial state in 1901 (EX_{fxLUC}). This simulation differs from EX_{LUC} by also removing the effects of land-use change on F_{AP} and F_{POC} from alterations in cropland area. In the second, the climate condition was held fixed at its initial state in 1901 (EX_{fxCL}). This simulation removed the effect of temperature and precipitation changes on MCFs and the terrestrial carbon budget. Many carbon flows, including the major ones (GPP, RA, and RH) as well as minor ones (F_{BB}, F_{BVOC}, F_{CH4}, F_{AP}, F_{DOC}, and F_{POC}), are more or less influenced by climate conditions. In the third simulation, atmospheric CO_2 concentration was held fixed at its level in 1901 (EX_{fxCO2}). Although no MCFs are directly sensitive to ambient CO_2 conditions, the fertilization effect of rising CO_2 concentration affects GPP and related carbon dynamics, including MCFs.

The fourth and fifth simulations focused on biomass burning. As explained earlier, the fire scheme in the VISIT model does not explicitly consider human activities such as prescribed fires and fire prevention, probably leading to biases in burnt area and subsequent emission patterns. For example, the fire scheme poorly captures the recent declining trend in burnt area (Andela et al., 2017) due to human suppression. These two simulations used satellite remote sensing data to evaluate the effect of model-estimated burnt area. In the fourth simulation, based on EX_{ALL}, interannual variability in burnt area was prescribed by the Global Fire Emission Database 4s (GFED4s) remote sensing product (Randerson et al., 2012) during the period 1998–2016 (EX_{BB1}). In the fifth simulation (EX_{BB2}), the simulated mean burnt area for 1901–2016 was adjusted with respect to GFED4s. For example, if the control run (EX_{ALL}) had estimated burnt areas that averaged 20% higher than GFED4s, an adjustment coefficient of 100/120 would have been applied to the burnt area simulated in this run to remove the systematic overestimation.

3 Results

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3.1 Global terrestrial carbon budgets

The mean annual global terrestrial GPP in 1990–2013 (a period when comparative estimates were available) was simulated as 144.0 ± 4.4 Pg C yr^{-1} in EX0 and 125.4 ± 4.0 Pg C yr^{-1} in EX_{ALL} (mean ± standard deviation of interannual variability). Ecosystem respiration (RE) was simulated as 141.0 ± 3.6 Pg C yr^{-1} in EX0 and 118.8 ± 3.2 Pg C yr^{-1} in EX_{ALL}. Mean vegetation and soil carbon storage differed in the two simulations: EX0 produced 648 Pg C in vegetation and 1560 Pg C in soil organic matter, and EX_{ALL} produced 477 Pg C in vegetation and 1290 Pg C in soil organic matter. The mean annual net CO_2 budget determined by the major flows, NEP (= GPP – RE), was simulated as 2.99 ± 1.18 Pg C yr^{-1} in EX0 (which ignores MCFs) and 6.57 ± 1.07 Pg C yr^{-1} in EX_{ALL}. Because both simulations used the same climate, atmospheric CO_2, and land-use data, these differences — lower carbon stocks, smaller GPP and RE flows, and a large sink by NEP — are attributable to inclusion of the MCFs.

The individual MCFs had different impacts on the global terrestrial carbon budget. For the vegetation carbon stock, impacts were negligible (< 1 Pg C) from methane emission, DOC and POC exports by water movement, and agricultural practices, whereas impacts were substantial from land-use change (–88.5 Pg C), biomass burning (–46.4 Pg C), wood harvest (–28.5 Pg C), and BVOC emission (–24.2 Pg C). For the soil carbon stock, the two largest negative impacts were from land-use change (–108 Pg C) and biomass burning (–71.2 Pg C). Interestingly, inclusion of BVOC emission reduced the soil carbon stock (–18.1 Pg C) through the loss of photosynthate carbon and decreased carbon supply to the soil. Inclusion of agricultural carbon flows (planting and harvesting, other than land-use change) decreased the soil carbon stock (–55.6 Pg C), although planting enhanced vegetation productivity and carbon supply to the soil. Inclusion of DOC and POC exports moderately reduced the soil carbon stock (–5.9 and –3.6 Pg C, respectively).

Most of the difference in GPP between EX0 and EX_{ALL} was attributable to land-use change (–12.8 Pg C yr^{-1}), wood harvest (–0.9 Pg C yr^{-1}), and BVOC emission (–0.9 Pg C yr^{-1}). Biomass burning, though it has substantial impacts on biomass, also slightly decreased GPP (–0.75 Pg C yr^{-1}). The simulated impacts of MCFs on RE were mostly similar to those for GPP. The relatively high NEP in EX_{ALL} was largely attributable to compensatory regrowth in response to biomass burning (2.03 Pg C yr^{-1}), BVOC emission (0.69 Pg C yr^{-1}), and wood harvest (0.41 Pg C yr^{-1}).

Human activities (EX_{ATP}) had greater impacts on terrestrial carbon stocks than biogeochemical processes (EX_{BGC}), as mean ecosystem carbon stock decreased by 172 Pg C in EX_{BGC} and 296 Pg C in EX_{ATP}. The sum of these two depressions in carbon stock, 467 Pg C, was larger than that estimated in the all-inclusive experiment (EX_{ALL}), 440 Pg C, which points to nonlinear offsetting effects among the MCFs.

The carbon budget including the MCFs (NBP) in 1990–2013 was estimated as 1.36 ± 1.12 Pg C yr^{-1} of net sink in EX_{ALL}, that is, 20.7% of NEP (see Table 1 for decadal summary). Figure 2 shows the temporal change in global annual NEPs and NBPs in each experiment for the 1901–2016 study period (see Fig. S3 for details of the 1990–2013 period). The inclusion of MCFs considerably altered the mean state of the terrestrial carbon budget through the simulation period. Little difference was found among the experiments in interannual variability and decadal trends. For example, linear trends of NBP in 1980–2013 were estimated as (0.0783 Pg C yr^{-1}) yr^{-1} in EX0 and (0.0890 Pg C yr^{-1}) yr^{-1} in EX_{ALL}. Interestingly, the larger differences

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削除: 6 … Pg C yr^{-1}), wood harvest (–0.9 Pg C yr^{-1}), and BVOC emission (–0.7 … Pg C yr^{-1}). Biomass burning, though it has substantial impacts on biomass, only …lso slightly decreased GPP (–0.08 …5 Pg C yr^{-1}). The simulated impacts of MCFs on RE were mostly similar to those for GPP. The relatively high NEP in EX_{ALL} was largely attributable to compensatory regrowth in response to biomass burning (1.…33 …3 Pg C yr^{-1}), BVOC emission (0.67 …9 Pg C yr^{-1}), and wood harvest (0.42 ... [3]

削除: 137 …72 Pg C in EX_{BGC} and 170 …96 Pg C in EX_{ATP}. The sum of these two depressions in carbon stock, 308 …67 Pg C, was larger than that estimated in the all-inclusive experiment (EX_{ALL}), 281 … ... [4]

削除: net …arbon budget including the MCFs (NBP) in 1990–2013 was estimated as 2.…04 …6 ± 1.15 …2 Pg C yr^{-1} of net sink in EX_{ALL}, that is, 42…0.5…% of NEP (see Table 1 for decadal summary). Figure 2 shows the temporal change in global annual NEPs and NBPs in each experiment for the 1901–2016 study period (see Fig. S3 for detailed …etails of the 1990–2013 period). The inclusion of MCFs considerably altered the mean state of the terrestrial carbon budget through the simulation period. Little …ittle difference was found among the experiments in interannual variability and decadal trends. For example, linear trends of NBP in 1980–2013 were estimated as (0.0757 …783 Pg C yr^{-1}) yr^{-1} in EX0 and (0.0761 ... [5]

among experiments for NEP (±1.15 Pg C yr^{-1}, standard deviation among EX0 to EX$_{ALL}$) than for NBP (±0.52 Pg C yr^{-1}) indicated a convergence of estimated carbon budgets after including MCFs.

The spatial distribution of carbon budgets shows that EX0 identified a vast area of tropical, temperate, and boreal forests as moderate net carbon sinks (Fig. 3a). The inclusion of MCFs in EX$_{ALL}$ (Fig. 3b) intensified this net sink in tropical forests and parts of the temperate and boreal forests, but it decreased NEP in grasslands and pastures in central North America and Europe, turning parts of them into net carbon sources (Fig. 3d). The spatial distribution of NBP in EX$_{ALL}$ (Fig. 3c) was a heterogeneous pattern of sink and source. Several tropical and subtropical forests had negative NBP, although NEP in these areas was estimated as positive or neutral. As shown in Fig. 3e, with the addition of MCFs, a large part of the terrestrial ecosystem was simulated to lose carbon. The contributions of each flow are described in the next section.

The decrease in carbon stocks in terrestrial ecosystems after the addition of MCFs indicates that the mean residence time (MRT) of these stocks became shorter than would be estimated solely from major carbon flows (see Fig. S4 for the spatial distribution of stocks and MRTs). As shown in Fig. 4, simulated terrestrial carbon stocks in EX$_{ALL}$ were steady or slightly declining until around 1960, especially when land-use change (e.g., tropical deforestation) was included. After 1960, carbon stocks in vegetation and soil began to gradually increase. As described earlier, the simulated carbon stocks differed among the experiments by as much as 440 Pg C as a consequence of including MCFs. Also, the inclusion of MCFs made large impacts on GPP and RE (Fig. S5) by altering vegetation structure and soil carbon storage. Simulated MRTs grew clearly shorter (i.e., turnover was accelerated), as a result of global changes such as temperature rise enhancing respiratory emissions. Note that MRTs also grew shorter in the result of EX0, which ignored MCFs, but including the MCFs increased the difference in MRT among the experiments. For example, the difference in MRT of vegetation biomass between EX0 and EX$_{ALL}$ grew from 0.89 yr in the 1900s to 1.54 yr in the 2000s, and the difference for soil carbon stock grew from 0.10 yr in the 1900s to 0.24 yr in the 2000s. The definition of MRT (Eq. 7) means that shortened MRTs could result from increases of NPP and respiration.

3.2 Simulated patterns of MCFs

Figure 5 shows the temporal changes in the eight simulated MCFs in their individual sensitivity simulations (EX$_{LUC}$ to EX$_{POC}$) as well as the EX$_{ALL}$ simulation. The emissions associated with land-use change (F$_{LUC}$) peaked around the 1950s at 1.2–1.4 Pg C yr^{-1} and then gradually decreased. Biomass burning emission (F$_{BB}$) remained around 1 Pg C yr^{-1} until the 1970s and then increased slightly to 1.5 Pg C yr^{-1}, with a large interannual variability. BVOC emission (F$_{BVOC}$) increased gradually from 0.5 Pg C yr^{-1} in the early 20th century to 0.6 Pg C yr^{-1} in the 21st century. Methane emission (F$_{CH4}$) gradually increased from 0.11 Pg C yr^{-1} in the first decades of the 1900s to 0.13 Pg C yr^{-1} in the 2000s (representing 160 – 170 Tg CH_4 yr^{-1}). Wood harvest (F$_{WH}$) likewise increased from 0.5 Pg C yr^{-1} in the 1900s to 1.1 Pg C yr^{-1} in the 2000s, as did POC export by water erosion (F$_{POC}$), which increased from 0.55 Pg C yr^{-1} in the 1900s to 0.95 Pg C yr^{-1} in the 2000s. Crop planting and harvest (F$_{AP}$) had a mixed effect on the terrestrial carbon budget, because planting enhances productivity, whereas the harvesting is a direct carbon loss. As a result, F$_{AP}$ had both negative (net uptake) and positive (net emission) values. DOC export (F$_{DOC}$) remained steady at around 0.14 ± 0.004 Pg C yr^{-1} through the simulation period.

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The supplementary simulations showed that temporal changes in the MCFs were caused by different forcing factors. For example, when the atmospheric CO_2 concentration was fixed at its level in 1901 (EX_{fxCO2}, data not shown), the increasing trend in F_{BVOC} (Fig. 5c) nearly vanished, whereas other flows such as F_{WH} and F_{POC} were insensitive to CO_2. When climate conditions were held fixed (EX_{fxCL}), F_{BB} showed only a decadal trend in response to changes in fuel load, and climate-induced interannual variability in burnt area and fire-induced emissions (Fig. 5b) disappeared.

The MCFs considered in this study showed distinct spatial patterns (Fig. 6). F_{LUC} occurred mainly in the tropical forests of South America, Africa, and South Asia. F_{BB} occurred in subtropical areas in Africa, tropical forests in South America and Southeast Asia, the Mediterranean area, and boreal forests in North America and East Siberia. F_{BVOC} was highest in tropical forests and elevated in other forested areas. For F_{CH4}, major sources included monsoon-affected parts of Asia dominated by paddy fields, tropical wetlands including floodplains of big rivers, and northern wetlands, whereas other uplands were weak sinks. For F_{AP}, croplands in Europe, East Asia, and North America exported large amounts of carbon (see Fig. 6f for the crop harvesting effect alone). F_{WH} occurred mainly in tropical forests in southern East Asia, South America, and southern North America. F_{POC} occurred mainly in humid and steep areas such as mountainous regions of monsoon Asia and cultivated areas. F_{DOC} occurred mainly in warm and humid areas such as tropical forests in South America, Africa, and Southeast Asia.

3.3 Effects of MCFs on the carbon budget

The effects of the eight studied MCFs on the global carbon budget, resulting in a lower net sink by NBP than by NEP, were dominated by five MCFs: biomass burning (F_{BB}), wood harvest (F_{WH}), POC export by water erosion (F_{POC}), BVOC emission (F_{BVOC}), and emission caused by land-use change (F_{LUC}) (Fig. 7a). The contributions of MCFs differed among regions. F_{AP} and F_{BB} had dominant effects in Europe (Fig. 7b) and North America (Fig. 7g), where the effects of F_{LUC} and F_{DOC} were negligible. In Africa (Fig. 7c), South America (Fig. 7h), and the global tropics (Fig. 7i), all five MCFs had similar effects. In Asia (Fig. 7e), F_{POC} and F_{AP} had the largest effects, and F_{CH4} emissions from the vast area of paddy fields were considerable. In semi-arid regions (Fig. 7j), F_{AP} and F_{BB} were the largest.

Certain spatial tendencies become clearer in a global aggregation of the simulated results (Fig. 8) related to the dominant land-cover type in each grid cell, the cropland fraction, and aridity represented by annual precipitation. In forest-dominated grid cells (Fig. 8a), F_{BB} made the largest (>30%) contribution, followed by F_{WH}, F_{BVOC}, and F_{LUC}, and in cropland-dominated cells, about half of the influence of MCFs was due to agricultural practices (F_{AP}). Because grassland-dominated cells contain fractions of woodland and cropland, F_{AP} and F_{WH} as well as F_{POC} made contributions in these cells. In desert-dominated cells, F_{BB} made up the majority of the contributions. In cells with small fractions of cropland including tropical forests (Fig. 8b), F_{WH}, F_{BB}, and F_{BVOC} made strong contributions, whereas in cells dominated by crops, F_{CH4} made a substantial contribution reflecting the vast area of paddy fields in Asia. F_{POC} made large contributions at all cultivation intensities, but particularly in moderately cultivated areas. An analysis based on precipitation was also informative (Fig. 8c). In arid areas (annual precipitation < 500 mm), F_{BB} had the largest impacts, as expected from the dominance of fire-prone ecosystems such as boreal

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forests and subtropical woodlands. In wet areas (precipitation > 1500 mm), F_{LUC} and F_{POC} made large contributions, and F_{BB} had a minor effect. The influence of F_{WH} was strongest in moderately humid to wet areas.

4 Discussion and conclusions

4.1 Comparison with previous carbon studies

This study showed that MCFs have notable impacts on the terrestrial carbon budget; they disequilibrate ecosystem carbon stocks and affect MRTs. Most of the simulated magnitudes of MCFs were comparable to results of previous studies (Fig. 5 and Table 2), and their impacts on the carbon budget were consistent with other model studies (e.g., Yue et al., 2015; Naipal et al., 2018). In terms of F_{LUC}, the model estimated clearly lower emissions than the GCP synthesis (Le Quéré et al., 2018) and other studies, surely because this study did not use actual land-use data after 2005. Updated data would likely improve the VISIT model's performance. The fact that the simulated F_{BB} was slightly low compared to previous estimates implies that there is a need to refine the fire module in the model (discussed further in Sect. 4.5). The simulated F_{POC} was comparable to results in other studies, but there remain inconsistencies in the fate terms (riverine transport, burial, and CO_2 evasion) and the ratio of ocean and inland water export. Similarly, the simulated F_{AP} and F_{WH} appear comparable to results in other studies, but this study largely ignored their transport and consumption. Further detailed comparisons and comprehensive assessments are clearly required.

Most models have been calibrated and validated with observational data of major carbon flows (e.g., GPP, RE, and NEP) and carbon stocks. Although recent models have begun to take account of land-use change and biomass burning, most still ignore the contributions of many other minor flows. The global GPP simulated in this study is similar to a satellite-based product of the Breathing Earth System Simulator (BESS) of Jiang and Ryu (2016): for the 2001–2013 period, the coefficient of determination (R^2) was 0.77 for EX0 and 0.71 for EX_{ALL} (Fig. S5). All three simulations show increasing trends. In contrast, the up-scaled flux measurement data of FLUXCOM (Tramontana et al., 2016) and the MOD15 satellite product (Zhao et al., 2006) show smaller interannual variability and trends, and they were only weakly correlated with the VISIT simulations (R^2 = 0.21 – 0.39). Compared with the terrestrial carbon budget in the integrated synthesis of the Global Carbon Project (GCP) for 1959–2016 (Le Quéré et al., 2018), the simulated NEP in EX_{ALL} was much higher in the same period: 5.7 Pg C yr^{-1} in EX_{ALL} and 2.1 Pg C yr^{-1} in GCP. Removing the land-use emission of 1.3 Pg C yr^{-1} would reduce the provisional NBP from GCP to 0.85 Pg C yr^{-1}, putting it closer to the simulated NBP in EX_{ALL} (0.68 Pg C yr^{-1}) than to the NBP in EX0 (2.33 Pg C yr^{-1}). (Figures S6 and S7 compare the results of NEP and F_{LUC} from the individual models in the GCP synthesis.) EX_{ALL} successfully captured the large aboveground vegetation biomass stock in the tropics and the small stock in boreal zones seen in observations (Fig. S8a). A similar comparison of soil carbon (Fig. S8b) also indicates the model's ability to capture the spatial gradient in this stock; an overestimation in the northern mid-latitudes (around 30°N) is attributable to high soil carbon accumulation in the Tibetan Plateau simulated by the model in frigid regions. It is not clear, however, whether EX_{ALL} (with MCFs) captured the global patterns with greater accuracy than EX0 (without MCFs), because observational datasets show considerable discrepancies, and the differences between the model simulations were relatively small. The estimated MRT of the ecosystem

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carbon stock in EX_{ALL} (14–17 yrs) was shorter than the MRT of 23 yr (95% confidence interval, 18–29 yr) found by the data-oriented study of Carvalhais et al. (2014). This difference is attributable to the high soil carbon stock in the latter study (2397 Pg C) rather than to differences in the vegetation carbon stock and flows; both studies had similar spatial patterns of MRT.

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Considering the remaining uncertainties in observational terrestrial carbon accounting, it is still difficult to perform a conclusive validation. Nevertheless, this study demonstrated the possibility of integrating various carbon flows into a single model framework.

4.2 Impacts of MCFs on regional and global carbon budgets

The simulated MCFs affect the amount of the terrestrial carbon stock by as much as 440 Pg C. The size of this difference is comparable to differences, or the model estimation uncertainty, found among biome models (e.g., Friend et al., 2014; Tian et al., 2015). By definition, NBP including the effect of MCFs is likely to correspond closely to carbon stock change as well as carbon budgets obtained by atmospheric inversions. MCFs affect the carbon budget in two major ways: first by their instantaneous carbon exports and second by the ensuing carbon uptake during recovery from these disturbances, which occurs with time lags of decadal to centennial scale, depending on the types of disturbance and their intensities (e.g., Fu et al., 2017). Assessments of MCFs would help characterize the "missing sink", which is now primarily ascribed to terrestrial carbon uptake (Houghton et al., 1998; Le Quéré et al., 2018) by mechanisms that are still arguable. Although previous studies (e.g., Jung et al., 2011; Zscheischler et al., 2017) have noted the potential importance of MCFs and the difference between NEP and NBP (or corresponding metrics such as the net ecosystem carbon balance of Chapin et al. (2006)), these issues have not been comprehensively evaluated by global and regional carbon syntheses, such as the REgional Carbon Cycle Assessment and Processes (RECCAP; Sitch et al., 2015). Indeed, biome models used to simulate the terrestrial carbon cycle in RECCAP differ in how they parameterize the MCFs, and their estimations of net budget are not easily compared.

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In the VISIT model simulation, interannual variability of NBP and NEP were closely correlated (Fig. S9), although several MCFs such as F_{BB} and F_{CH4} did not share in that correlation. These interannual variations were largely determined by the major flows, except for extreme events such as huge fires in 1997 and 2015 (e.g., Huijnen et al., 2016). Therefore, establishing an empirical model may make it possible to approximately estimate NBP from NEP. To evaluate the similarities and differences between these two quantities, further observation data are required for each flow and its determinant processes.

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This study demonstrated that the VISIT modeling approach is effective in integrating the major and minor carbon flows into a single framework and obtaining a consistent carbon budget, although this approach has its own uncertainties and biases, as shown by benchmarking and intercomparison studies (e.g., Arneth et al., 2017; Huntzinger et al., 2017). Biogeochemical models like VISIT have advantages in reconciling inconsistencies, filling gaps, and specifying underlying mechanisms, as well as reconstructing historical changes and making future projections. Intimate collaborations between modeling and observational studies (Sitch et al., 2015; Schimel et al., 2015) should lead to more reliable carbon accounting.

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4.3 Ancillary impacts on hydrology

This study focused on the terrestrial carbon budget, but the MCFs also affect the hydrological properties of land systems. As shown in Fig. S10, land-use change, biomass burning, and BVOC emission lead to a loss of vegetation leaf area, except in croplands. The loss in turn decreases evapotranspiration and increases runoff discharge regionally by as much as 20 mm yr^{-1}. In the simulation, runoff discharge increased through time, more steeply in EX$_{ALL}$ than in EX0. This effect was evident in many tropical to temperate regions, implying the importance of comprehensive understanding of carbon–water interactions.

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However, it should be noted that the actual impacts of MCFs on land systems can be much more complicated than assumed here. For example, loss of soil organic carbon by biomass burning and water erosion may decrease the water-holding capacity of soils, leading to higher runoff discharge and lower tolerance to droughts. Also, several MCFs should change along with translocations and biogeochemical reactions of nutrients such as nitrogen and phosphorus, followed by changes in vegetation productivity and water use. To fully include these processes in the model, comprehensive understanding of biogeochemistry and ecohydrology is required.

4.4 Complexities of MCF accounting

Although this study incorporated some of the known MCFs, fully or partially, others are unrecognized or assumed to be negligible. Indeed, many studies have investigated MCFs that were not included in this and most previous carbon cycle studies (Table 3). Few studies have taken comprehensive account of all carbon flows. For example, for lack of parameterization data, this study did not explicitly consider carbon sequestration in pyrogenic organic matter or charcoal (e.g., Santín et al., 2015), in phytoliths (Song et al., 2017), or by means of abiotic geochemical processes (Schlesinger, 2017). This study tried to include the effects of DOC and POC exports and obtained results comparable to other studies (e.g., Dai et al., 2012; Galy et al., 2015; Chappell et al., 2016). However, this study did not explicitly consider lateral displacement of carbon between adjacent grid cells and associated emissions, such as river transport and international commerce (e.g., Battin et al., 2009; Bastviken et al., 2011; Peters et al., 2012), and reservoir effects on riverine transport (e.g., Mendonça et al., 2017). In this regard, modeling of agricultural practices should be improved to obtain more reliable regional carbon budgets. It is particularly important to evaluate efforts to enhance harvest index and to raise carbon sequestration into cropland soils, as proposed by the “4 per 1000” initiative (Dignac et al., 2017; Minasney et al., 2018).

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More clarity is needed in the parameterization of disturbances. This study considered the impacts of wildfires and land-use conversion, but in a conventional manner, possibly leading to biased results (see Sect. 4.5 for biomass burning). Other potentially influential disturbances, such as pest outbreaks and drought-induced dieback associated with climate extremes, were not explicitly considered, although they can perturb ecosystem carbon budgets (Reichstein et al., 2013). In the long term, ecosystem degradation induced by forest fragmentation, overgrazing, and soil loss by wind erosion can further affect carbon budgets (e.g., Paustian et al., 2016; Brinck et al., 2017). Integration of these processes awaits future studies.

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4.5 Uncertainties and possibility of constraints

This study is an early attempt to evaluate the effects of various MCFs. The results have convinced me that changes in MCFs will have considerable influences on the global carbon budget (e.g., Piao et al., 2018; Lal et al., 2019; Pugh et al., 2019), and more such attempts are required to improve our understanding of the global carbon cycle, which plays a critical role in future climate projections. However, given the imperfect state of knowledge about these MCFs, their inclusion can introduce other errors and biases. I took the estimation uncertainty into account by perturbing representative parameters, but this study did not examine other sources of uncertainties such as differences among ecosystem models and forcing data. Indeed, many ecosystem models have been developed with different degrees of complexity (e.g., dynamic global vegetation models), and intercomparison studies have shown that existing ecosystem models differ widely in their environmental responsiveness to changes in major carbon flows (e.g., Friend et al., 2014; Huntzinger et al., 2017). For example, the models differ in global GPP by more than 30%, even though the processes contributing to primary production are well understood and increasingly constrained by observations (Anav et al., 2015). This single-model study was necessarily limited in searching the full range of estimation uncertainty, and further studies using multiple MCF-implemented models are highly desirable.

Considering the shortcomings of broad-scale and long-term observations of MCFs, estimation uncertainties could be larger than presently thought. For example, each of the coefficient factors of the erosion scheme (Eq. 6) can be expected to have large ranges of uncertainty, and few data are available to constrain for the fate of laterally transported POC and DOC. Data related to land-use changes (e.g., gross vs. net land-use transition) and procedures to implement them in models are not standardized (e.g., Fuchs et al., 2015). One exception is that multiple satellites have produced long global records of biomass burning. Indeed, a comparison of F_{BB} in the VISIT model simulation and these observations clearly shows a problem in this study (Fig. 5b): the VISIT model systematically underestimated fire-induced CO_2 emission in most years relative to the BB4CMIP6 multi-satellite (combined with proxies) product of biomass burning (van Marle et al., 2017). It also showed an increasing trend of fire activity after 1998, a trend inconsistent with a recent analysis of global burnt area (Andela et al., 2017) that showed a declining trend of burnt area due to human activities such as agricultural expansion and intensification.

To evaluate the bias caused by this inconsistency, a simulation was conducted (EX_{BB1}) in which interannual anomalies of burnt area were prescribed by the GFED4s satellite product in 1998–2016 (Fig. S11, green line). As a result, the model-simulated F_{BB} showed a decreasing trend, implying that prognostic modeling of fire regimes is problematic. Additionally, the high fire-induced emission in 1998, a strong El Niño year, was appropriately captured. The model, however, was likely to overestimate average burnt area (561×10^6 ha yr^{-1}) relative to satellite-based estimates. Therefore, another simulation was conducted (EX_{BB2}) in which not only anomalous but also average burnt area were prescribed by GFED4s. That simulation (Fig. S11, orange line) yielded an even lower F_{BB} resulting from a smaller burnt area (437×10^6 ha yr^{-1}), although its interannual variability was little changed. The low F_{BB} despite a large burnt area indicates that fire intensity or emission factors in the model were not properly determined. Such estimation biases and uncertainties can remain in other carbon flows and should be clarified and reduced using observational data.

4.6 Implications for observations

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This study has implications not only for improving models, but also for strategic observations of the carbon cycle. MCFs may account for much or all of the discrepancy among top-down atmospheric inversions, CO_2 flux measurements, and bottom-up biometric carbon stock surveys (e.g., Jung et al., 2011; Kondo et al., 2015; Takata et al., 2017). Furthermore, investigations of MCFs may help reveal the mechanisms underlying the apparent net carbon sequestration by mature forests (Luyssaert et al., 2008), as observed in CO_2 flux measurements and biometric surveys. Major carbon flows (GPP, RE, and NEP) have been observed using the standardized FLUXNET method at many flux measurement sites (Baldocchi et al., 2001). These observations have given us an overview of the terrestrial carbon budget and its tendencies (e.g., Jung et al., 2017). Recent satellite observations allow us to monitor vegetation coverage and biomass globally at fine spatial resolutions (e.g., Saatchi et al., 2011; Baccini et al., 2017). Nevertheless, it is still difficult to directly observe some MCFs, including non-CO_2 trace gases, disturbance-induced non-periodic emissions, and subsurface transport and sequestration. For example, flux measurements of BVOC emissions are technically challenging (Guenther et al., 1996; Geron et al., 2016) because of the low concentrations of BVOC compounds, their wide variety, and their spatial and temporal heterogeneity. Quantification of DOC and POC dynamics at the landscape scale appears to require intensive observation networks (e.g., Dai et al., 2012; Raymond et al., 2013). Emissions associated with land-use change, which have attracted much attention from researchers, still have large uncertainties (Houghton and Nassikas, 2017; Erb et al., 2018). Further integrated studies of ground-based, airborne, and satellite observations of carbon flows are necessary that include minor flows, pools, and relevant properties (e.g., isotope ratios). The spatial and temporal patterns of influential MCFs obtained in this study will be useful for planning effective observational strategies.

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Code and data availability. Simulation code and data are available on request from the author. The CRU TS3.25 dataset was from the Climatic Research Unit, University of East Anglia (https://crudata.uea.ac.uk/cru/data/hrg/). The land-use dataset was from the University of Maryland (http://luh.umd.edu/data.shtml). The Global Lake and Wetland Database was from the World Wildlife Fund (https://www.worldwildlife.org/pages/global-lakes-and-wetlands-database).

Author contribution. AI designed the research, conducted the analyses, and drafted the manuscript.

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Table 1. Decadal summary of simulation results of net global terrestrial carbon budget (Pg C yr^{-1}).

	1990-1999		2000-2009		2010-2017	
	NEP	NBP	NEP	NBP	NEP	NBP
EX0	2.35	2.35	3.21	3.21	3.95	3.95
EX$_{LUC}$	2.61	1.70	3.43	2.80	4.13	3.67
EX$_{BB}$	4.33	1.99	5.28	2.82	6.07	3.55
EX$_{BVOC}$	3.03	2.21	3.91	3.04	4.66	3.75
EX$_{CH4}$	2.39	2.35	3.24	3.21	3.98	3.95
EX$_{AP}$	2.88	2.23	3.76	3.08	4.47	3.82
EX$_{WH}$	2.74	1.65	3.63	2.48	4.42	3.18
EX$_{DOC}$	2.49	2.34	3.35	3.19	4.09	3.93
EX$_{POC}$	2.50	2.32	3.37	3.17	4.10	3.91
EX$_{ALL}$	5.88	0.64	6.85	1.62	7.60	2.34
EX$_{BGC}$	5.30	1.87	6.28	2.67	7.08	3.38
EX$_{ATP}$	3.45	0.96	4.33	2.00	5.03	2.80
EX$_{fxCO2}$	2.81	-1.85	2.85	-1.65	2.61	-1.73
EX$_{fxCL}$	6.37	1.35	7.19	2.19	8.13	3.03
EX$_{fxLUC}$	5.37	1.03	6.36	1.87	7.14	2.50

NEP, net ecosystem production; NBP, net biome production.

Model designations are defined in the text.

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Table 2. Summary of previous estimates of minor carbon flows (MCFs).

MCF	Reference	($Pg\ C\ yr^{-1}$)
F_{LUC}	Houghton et al. (2003): bookkeeping	2.1 ± 0.8
	Le Quéré et al. (2018): GCP 2018 models	1.5 ± 0.6
	Le Quéré et al. (2018): GCP 2018 bookkeeping	1.4 ± 0.7
	This study (EX_{ALL}, 1980–1989 mean ± SD)	0.99 ± 0.02
	(EX_{ALL}, 1990–2015 mean ± SD)	0.60 ± 0.16
F_{BB}	Wiedinmyer et al. (2011): FINN	2.18
	van der Werf et al. (2017): GFED4s	2.2
	van Marle et al. (2017): BB4CMIP6	1.90
	This study (EX_{ALL}, 1990–2015 mean ± SD)	1.69 ± 0.21
F_{BVOC}	Guenther et al. (2012): MEGAN model	0.96
	Sindelarova et al. (2014): MEGAN model	0.76
	This study (EX_{ALL}, 1990–2015 mean ± SD)	0.75 ± 0.036
F_{CH4}	Fung et al. (1991)	0.14
	Saunois et al. (2016): GCP synthesis	0.135
	This study (EX_{ALL}, 1990–2015 mean ± SD)	0.12 ± 0.006
F_{AP}	Bondeau et al. (2007): LPJmL model	2.2
	Ciais et al. (2007)	1.29
	Wolf et al. (2015): FAOSTAT-base	2.05 ± 0.05
	This study (EX_{ALL}, 1990–2015 mean ± SD)	1.45 ± 0.073
F_{WH}	Winjum et al. (1998)	0.98
	Pan et al. (2011): inventory analysis	0.189
	This study (EX_{ALL}, 1990–2015 mean ± SD)	1.03 ± 0.082
F_{DOC}	Meybeck (1993)	0.20
	Dai et al. (2012)	0.17
	This study (EX_{ALL}, 1990–2015 mean ± SD)	0.14 ± 0.004
F_{POC}	van Oost et al. (2007): agricultural soils	0.25
	Regnier et al. (2013)	0.1 ± >0.05
	Galy et al. (2015)	0.157 (0.107–0.231)
	Chappell et al. (2016): displacement by erosion	0.3–1.0
	Naipal et al. (2018): ORCHIDEE + RUSLE	0.16 ± 0.06
	This study (EX_{ALL}, 1990–2015 mean ± SD): riverine export to the ocean, 20% of soil displacement	0.19 ± 0.011

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Table 3. Summary of studies on other minor carbon flows.

Process	Flow (Pg C yr^{-1})	Reference
Fragmentation of tropical forests	0.34	Brinck et al. (2017)
Pyrogenic organic matter production in boreal regions	~0.1	Satín et al. (2015)
Mangrove production including burial, POC and DOC export, and others	~0.218 ± 0.072	Bouillon et al. (2008)
In-reservoir burial and mineralization	0.048±0.011	Maavara et al. (2017)
Lake and reservoir burial	0.15 (0.06–0.25)	Mendonça et al. (2017)
Export to inland water	5.1	Drake et al. (2018)
C sequestration in phytoliths	0.042 ± 0.025	Song et al. (2017)
Chemical weathering of rocks	0.237	Hartmann et al. (2009)
Uptake by cryptogamic covers	3.9 (2.1–7.4)	Elbert et al. (2012)
Cement carbonation (in urban areas)	0.1–0.25	Xi et al. (2016)

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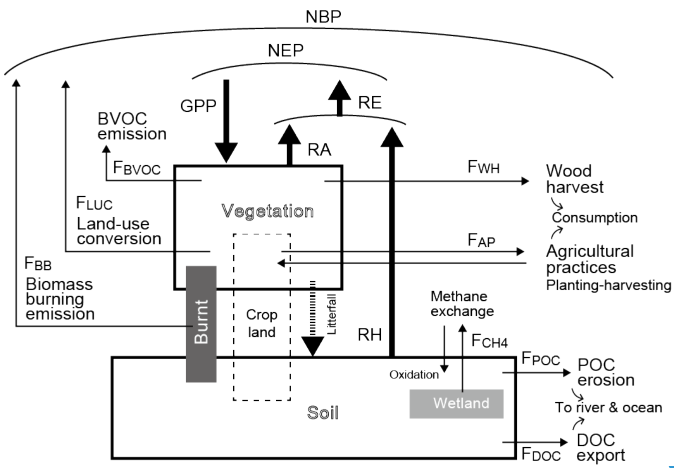
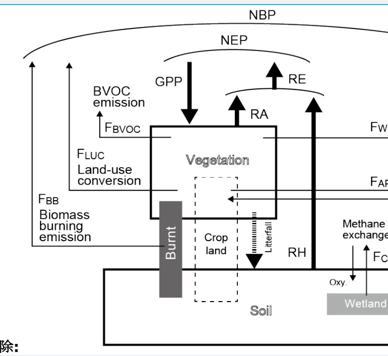


Figure 1. Schematic diagram of the carbon budget of the terrestrial ecosystem as simulated in this study. Thick lines show major carbon flows, and thin lines show minor carbon flows.



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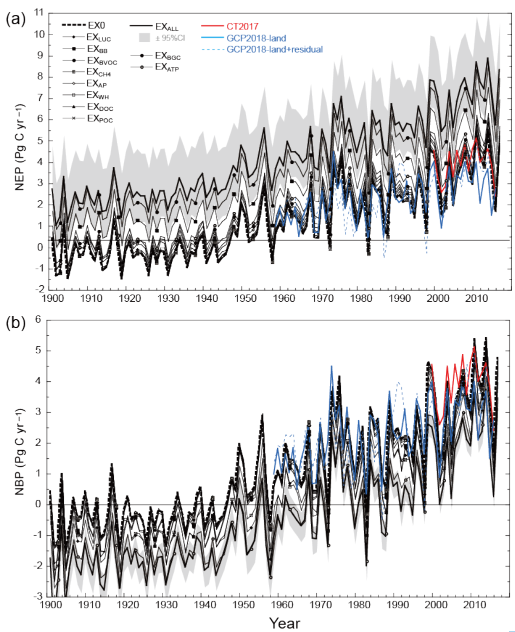
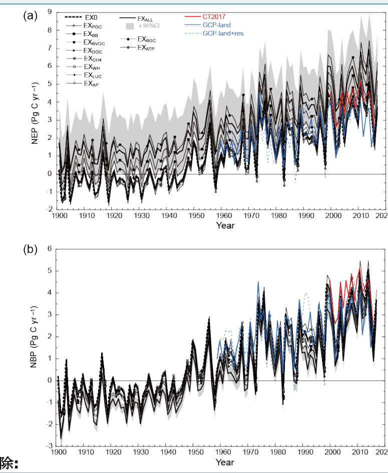


Figure 2. Temporal changes in the simulated global terrestrial carbon budget from this study (black lines), CarbonTracker 2017 (CT2017; Peters et al., 2007; red lines), and the Global Carbon Project (GCP; blue lines). (**a**) NEP and (**b**) NBP. See the text for the simulation experiments. Figure S3 presents extracted results for the period 1980–2016.



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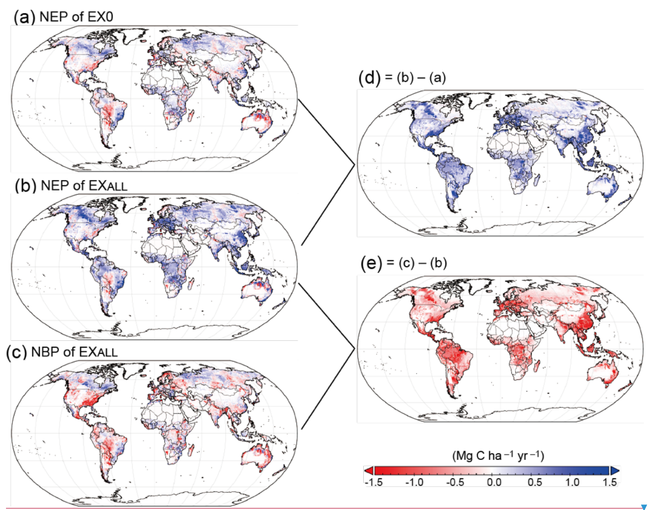

Figure 3. Global distribution of simulated terrestrial carbon budget in the 2000s. (**a**) NEP in EX0, (**b**) NEP in EX_{ALL}, (**c**) NBP in EX_{ALL}, (**d**) difference between (**b**) and (**a**) showing the apparent effects of MCFs on NEP, and (**e**) difference between (**c**) and (**b**) showing the apparent effects of MCFs on NBP.

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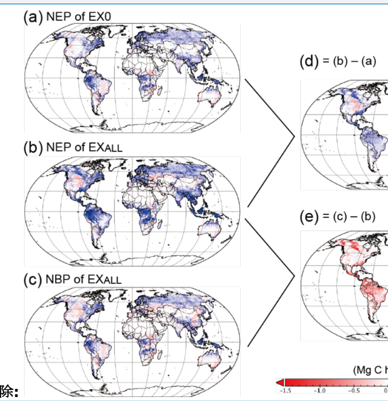

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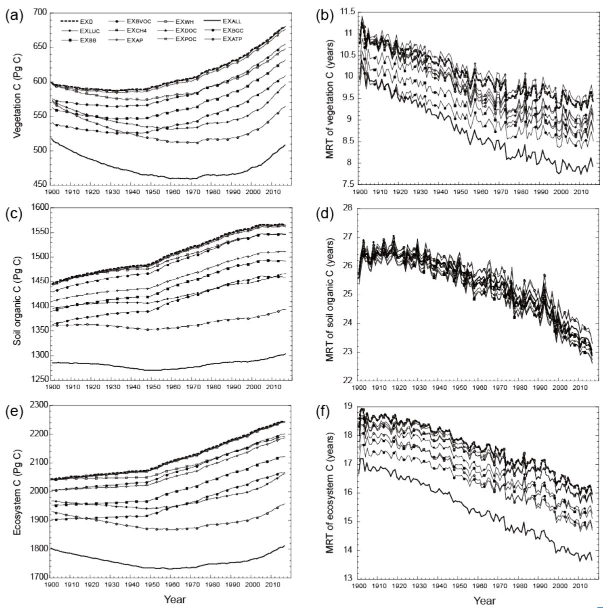
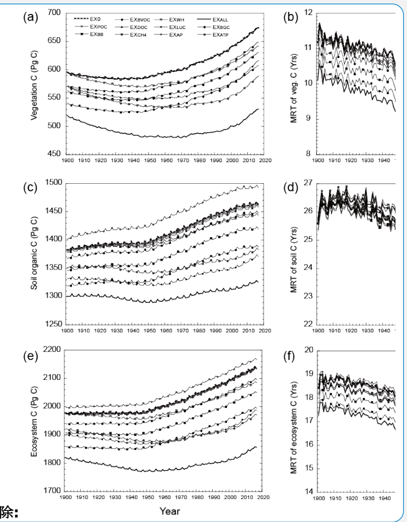


Figure 4. Time series of simulated carbon stocks and their mean residence time (MRT) in different experiments. (**a**) Vegetation biomass and (**b**) its MRT, (**c**) soil organic carbon and (**d**) its MRT, and (**e**) total ecosystem carbon stock and (**f**) its MRT.



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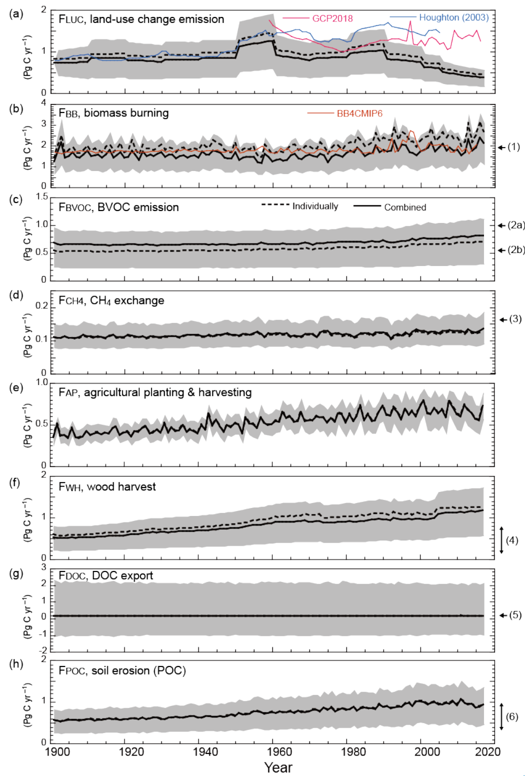

Figure 5. Time series of minor carbon flows simulated by the VISIT model and previous studies. Dashed lines are results of individually simulated flows, and solid lines are results of the EX_{ALL} simulated, and shading shows the 95% confidence interval for the EX_{ALL} result obtained from ensemble simulations (Fig. S2). Blue and red lines in (**a**) show data of the Global Carbon Project (GCP2018) and Houghton (2003). Orange line in (**b**) shows data of BB4CMIP6 (van Marle et al., 2017). Arrows indicate the values of (1) biomass burning emission by Randerson et al. (2012), (2a) total BVOC and (2b) isoprene emissions by Guenther et al. (2012), (3) wetland and paddy methane emission by Saunois et al. (2017), (4) wood harvest by Arneth et al. (2017), (5) DOC export by Dai et al. (2012), and (6) soil erosion by Chappell et al. (2016).

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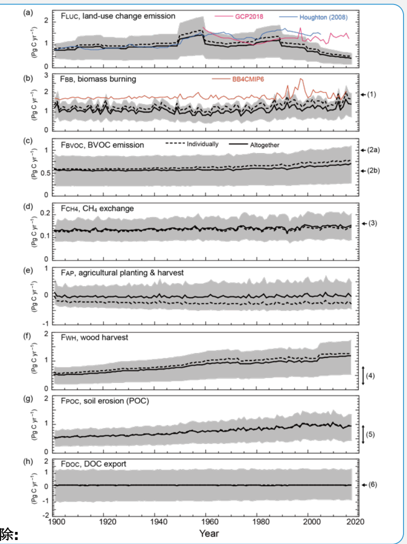

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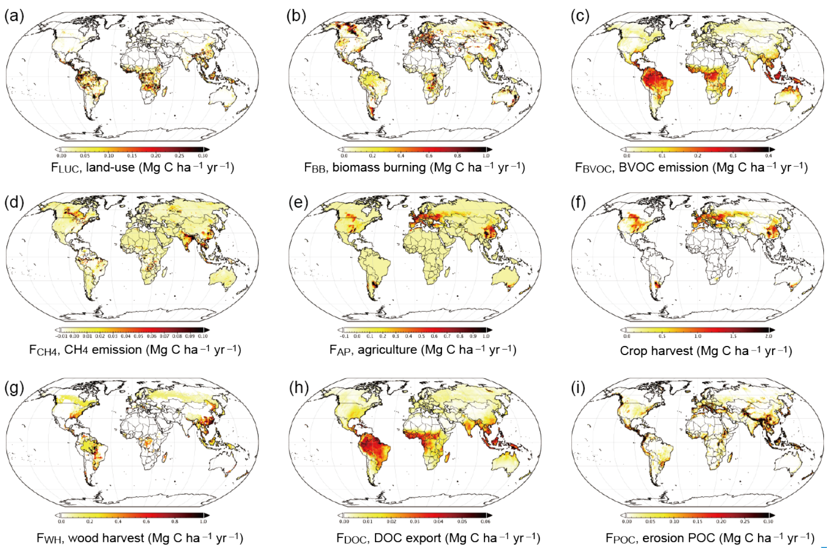

Figure 6. Global distribution of the simulated MCFs (plus crop harvest) in 2000–2009. Results of EX_{ALL} are shown.

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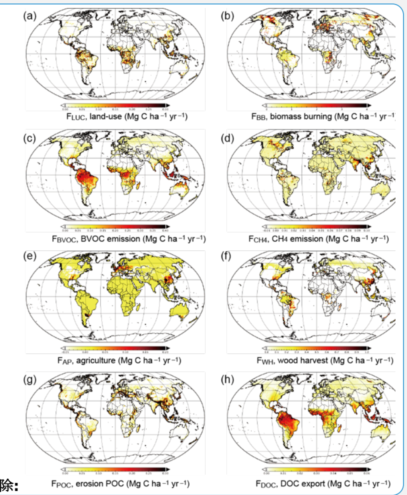

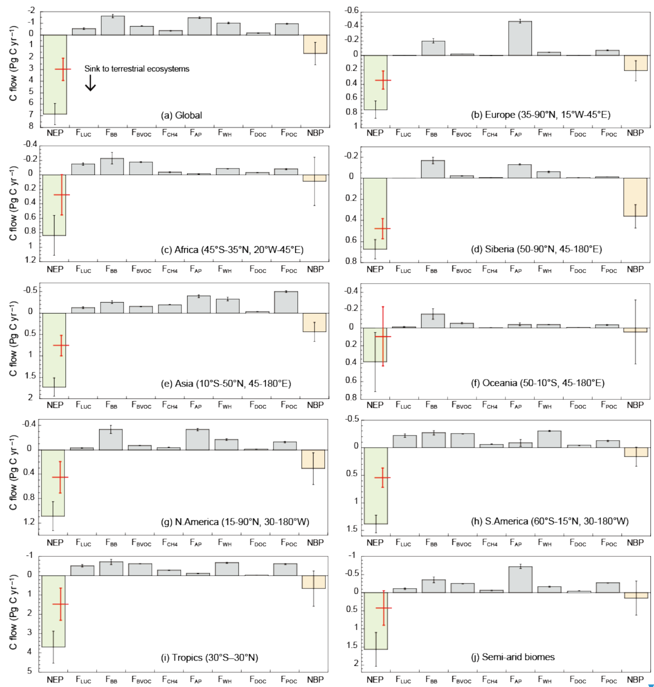

Figure 7. Regional portions of the terrestrial carbon budget in 2000–2009. Columns show the mean results of EXALL and error bars show the standard deviation of interannual variability. Red lines show the mean and standard deviation of NEP in EX0. Note the differences in vertical scale.

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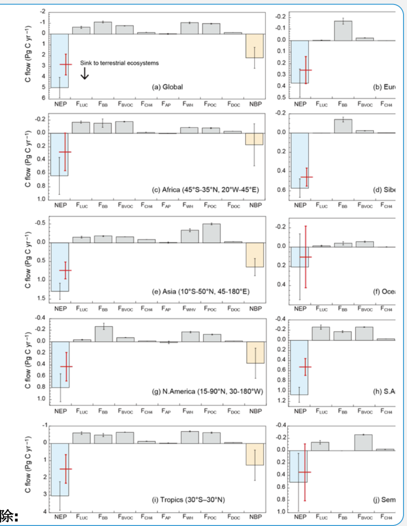


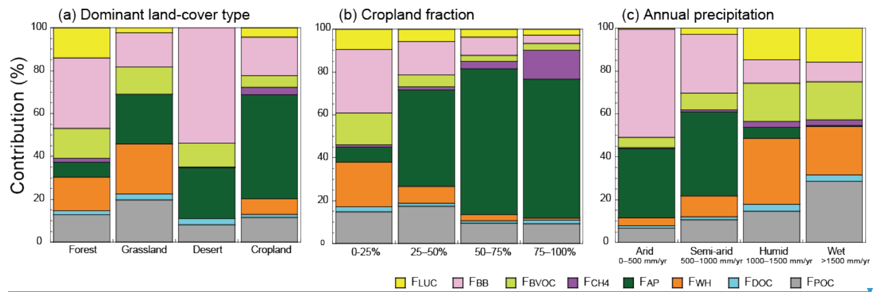
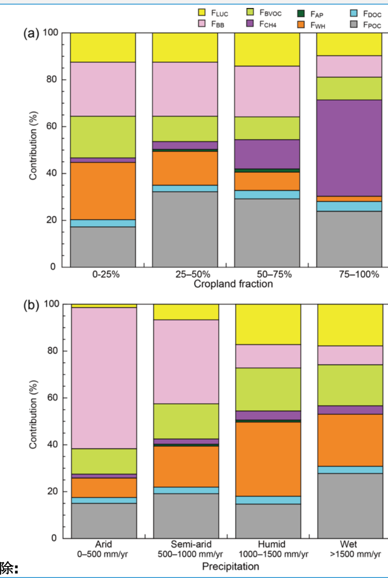


Figure 8. Relative contribution of MCFs to the terrestrial carbon budget simulated by EX_{ALL} in 2000–2009: (a) aggregated by dominant land cover type, (b) aggregated by cropland fraction within grid cells, and (c) aggregated by annual precipitation.



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Supplementary material

Disequilibrium of terrestrial ecosystem CO_2 budget caused by disturbance-induced emissions and non-CO_2 carbon export flows: a global model assessment

Akihiko Ito[1,2]

[1]National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, 3058506, Japan
[2]Japan Agency for Marine-Earth Science and Technology, 3173-25 Showa-machi, Kanazawa-ku, Yokohama, 2360001, Japan

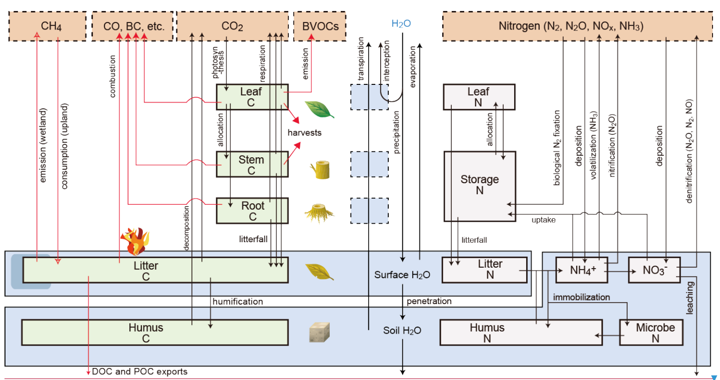
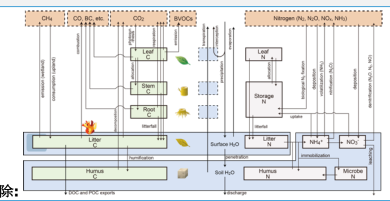


Figure S1. Schematic diagram of the VISIT model. Red arrows indicate minor carbon flows.



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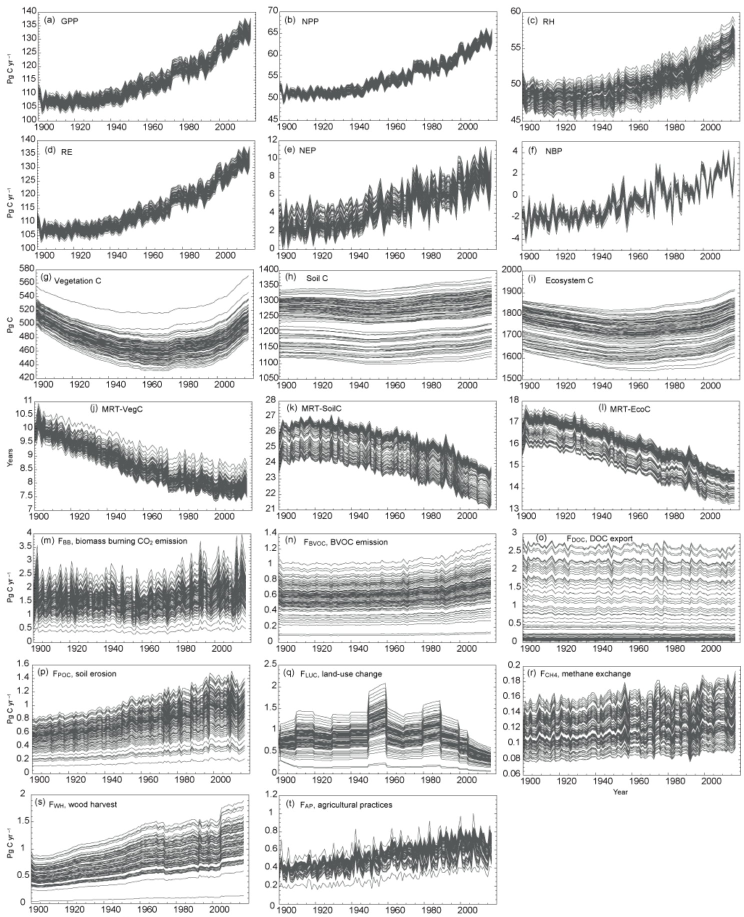
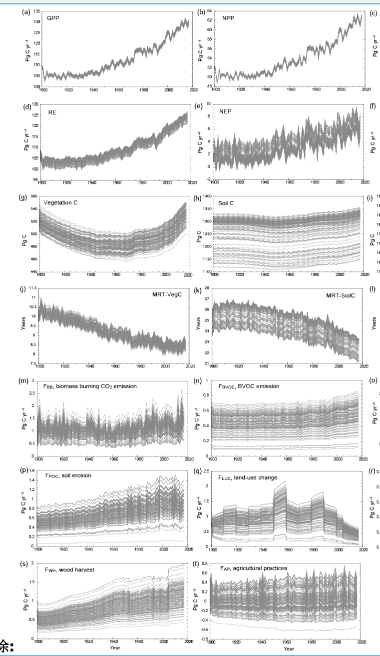


Figure S2. Results of 146 ensemble simulations using perturbed parameter values for MCFs.



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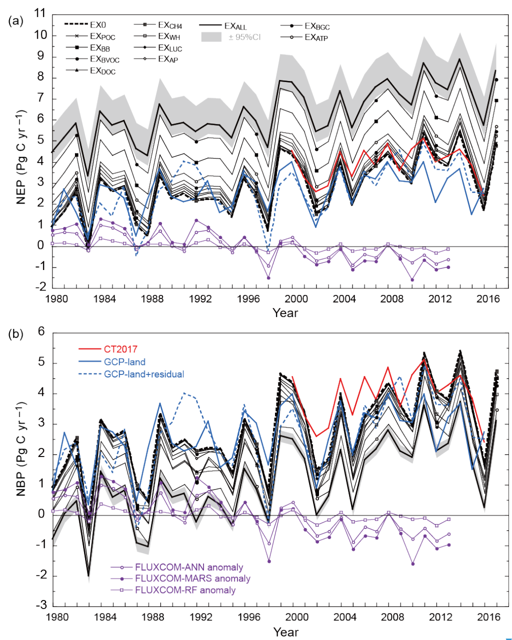
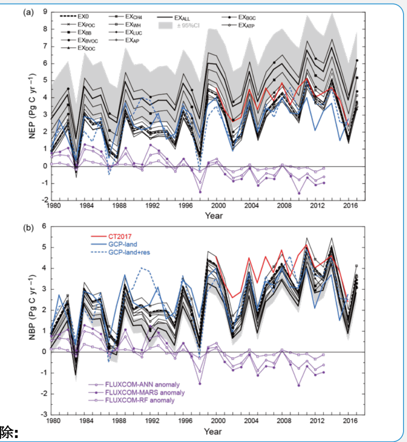


Figure S3. Time series of simulated terrestrial carbon budget in late decades. (**a**) NEP and (**b**) NBP simulated in various experiments. Shaded areas show the 95% confidence interval for EX_{ALL}. Also shown are estimates from CarbonTracker 2017 (CT2017), two Global Carbon Project (GCP) syntheses (land and land + residual), and FLUXCOM data (anomalies from the mean) as rendered by three upscaling methods.



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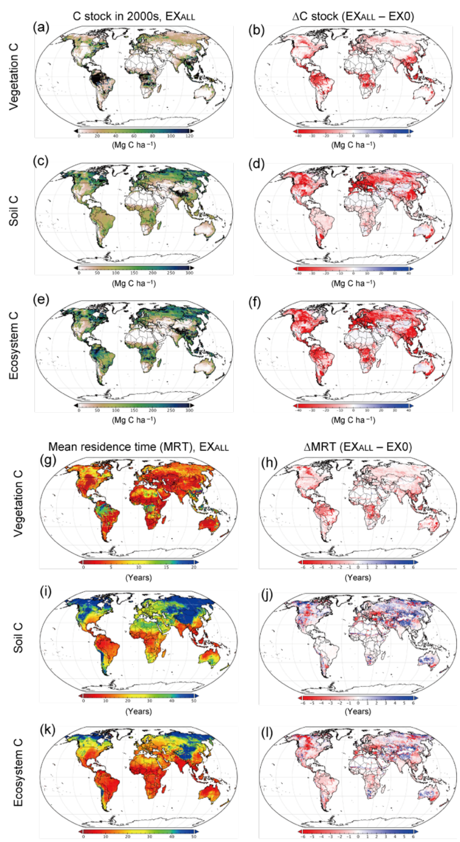

Figure S4. Maps of vegetation carbon, soil organic carbon, and ecosystem carbon in 2000–2009 from EX_{ALL} showing their distributions (top three plots, left column) and mean residence times (bottom three plots, left column) and their differences from EX0 estimates (right column).

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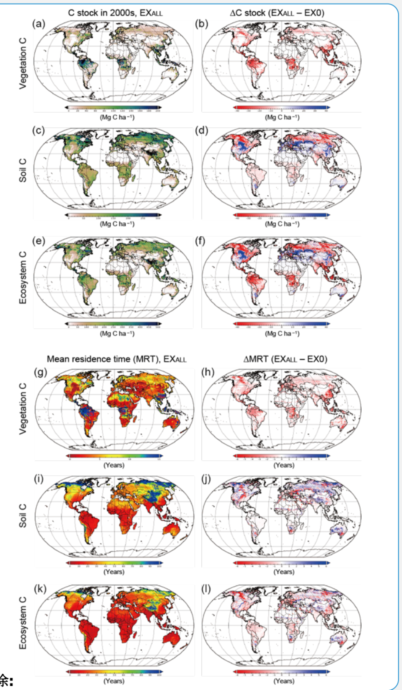

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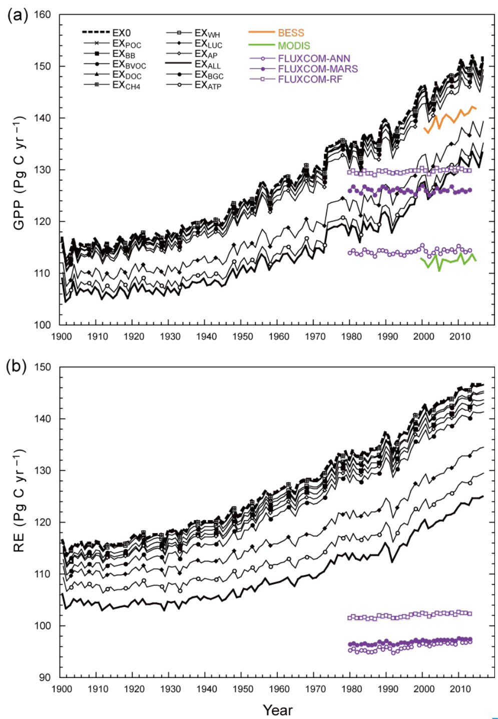
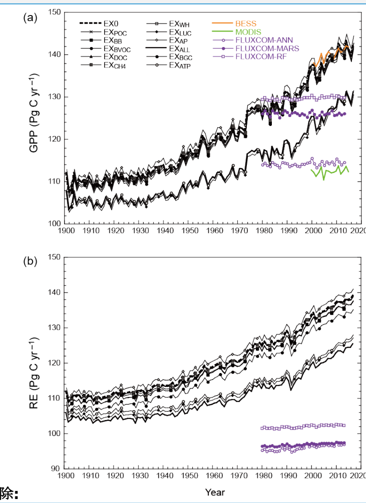


Figure S5. Time series of (**a**) GPP and (**b**) RE simulated by VISIT in various experiments plus estimates from BESS (Jiang and Ryu, 2016), MODIS (Zhao et al., 2006), and FLUXCOM data as rendered by three upscaling methods (Tramontana et al., 2016).



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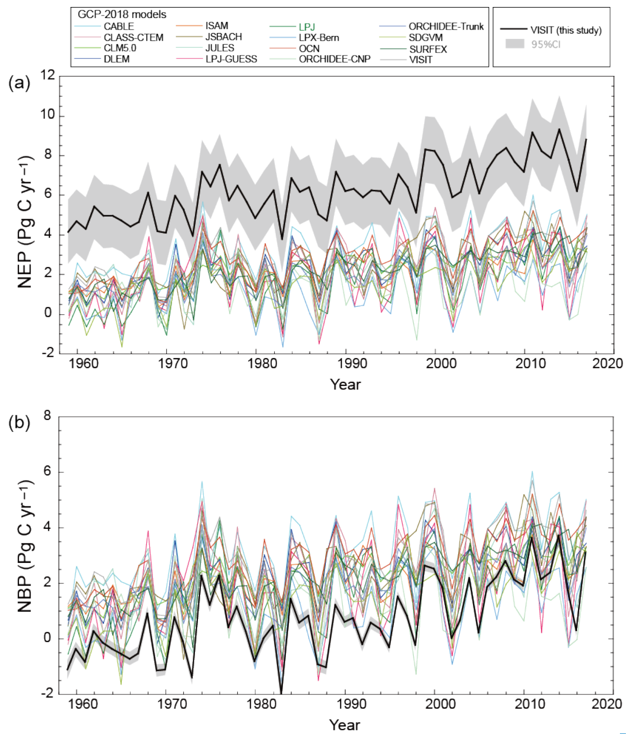

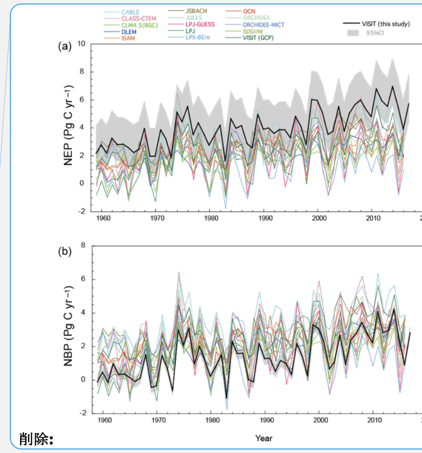

Figure S6. Comparison of (**a**) NEP and (**b**) NBP from simulations by VISIT and other models in the GCP synthesis (Le Quéré et al., 2018).

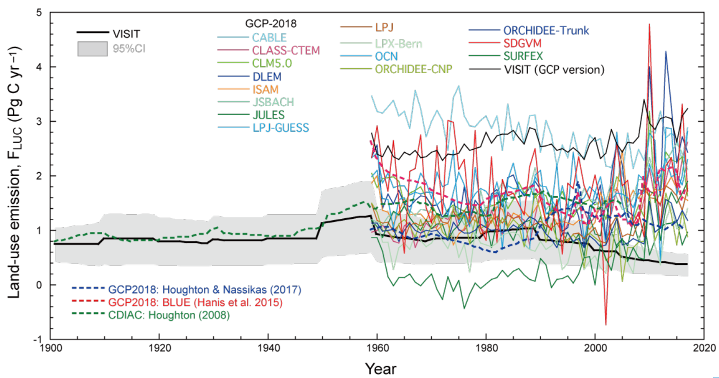

Figure S7. Comparison of simulated land-use emissions (F_{LUC}) from VISIT and other models in the GCP synthesis (Le Quéré et al., 2018).

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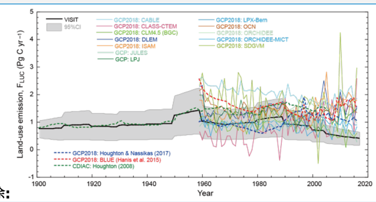

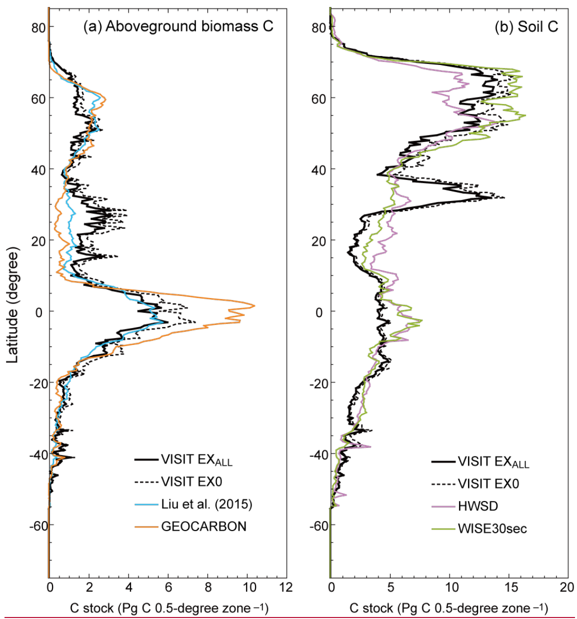

Figure S8. Latitudinal distribution of (**a**) aboveground biomass carbon and (**b**) soil organic carbon simulated by VISIT in EX0 and EX$_{ALL}$ experiments. Also shown in (**a**) are distribution from Liu et al. (2015) and GEOCARBON (Avitabile et al., 2014). Also shown in (**b**) are distributions from the Harmonized World Soil Database (FAO/IIASA/ISRIC-CAS/JRC, 2012) and WISE30sec (Batjes, 2016).

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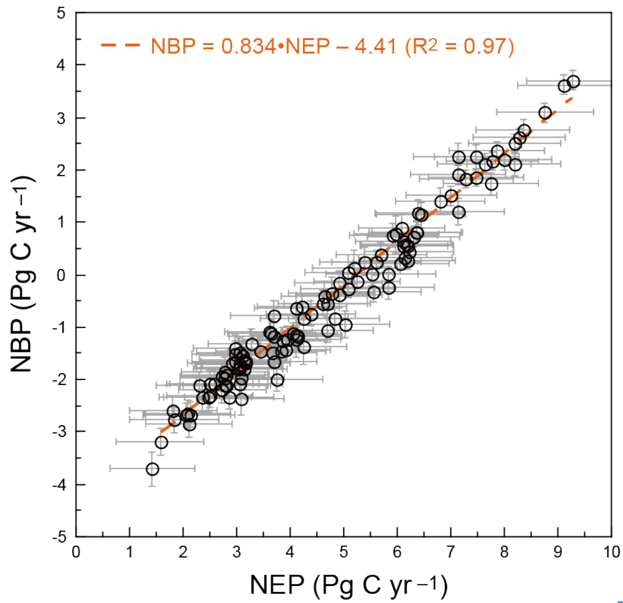
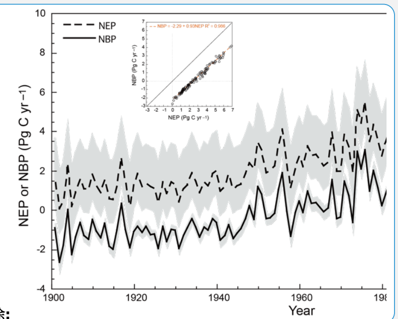


Figure S9. Scatter diagram of global annual NEP and NBP for the period 1901–2016. Error bars shown in grey. Red dashed line shows the linear regression (R^2 = 0.97).



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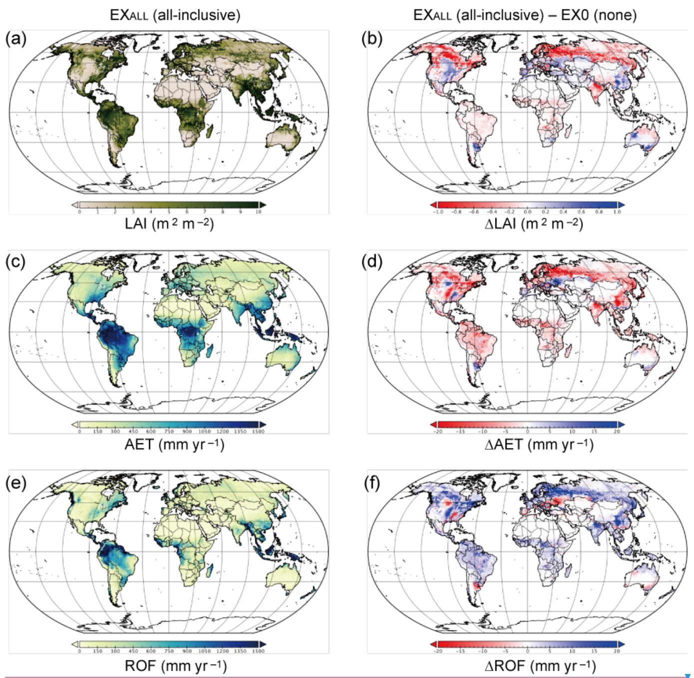

Figure S10. Global distribution of the simulated water budget from EX$_{ALL}$ for 2000–2009. (**a**) Mean annual leaf area index (LAI) and (**b**) its difference from EX0, (**c**) actual evapotranspiration (AET) and (**d**) its difference from EX0, and (**e**) runoff discharge (ROF) and (**f**) its difference from EX0.

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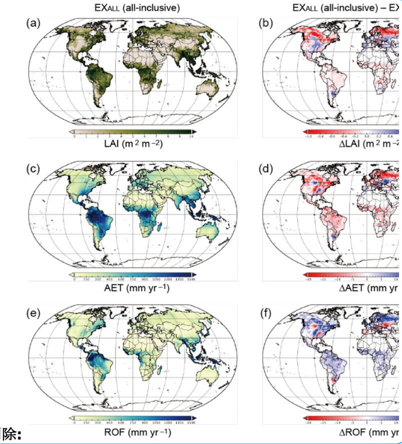

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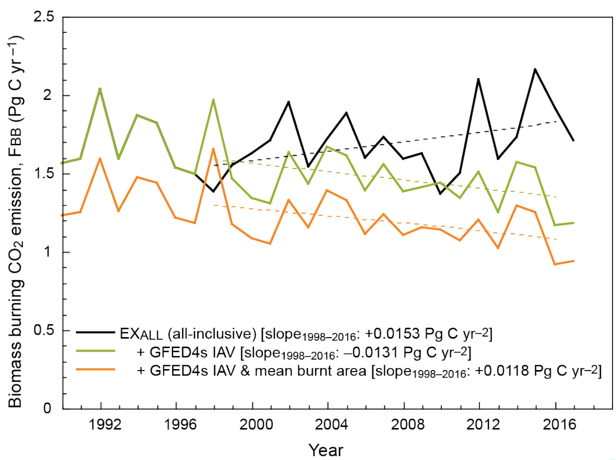
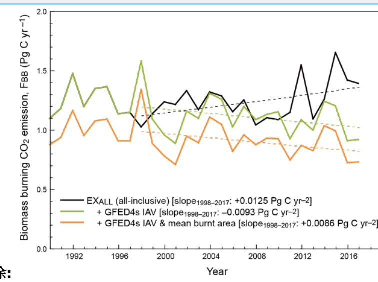


Figure S11. Time series of F_{BB} in the EX_{ALL} simulation, the interannual variability (IAV) constrained by satellite data (GFED4s), and the IAV and mean burnt area constrained by the observational data. Regression curves for 1998–2017 are shown by dashed lines.



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