Supplementary Material

Unveiling the Hidden Green House Gases Footprint of Amazonian Forest Fires

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Supplementary Table 1. Attributes of permanent plots and censuses used for fitting the exponential regression model to estimate cumulative carbon stock changes after fires. The plots are located across Acre (AC), Mato Grosso (MT), Pará (PA), and Amazonas (AM), in forested areas with varying pre-fire disturbance histories and time since the fires. The cumulative change fraction was calculated between successive censuses.

State	Plot ID	Forest Status before fire	Census treatment	Fire	Cumulative change	Time since fire (years)	Publication
AC	BOL_4	Undisturbed	after after	2010	-0,15	4	Silva et al. 2018
AC	BOL_5	Undisturbed	after after	2010	-0,10	4	Silva et al. 2018

AC	BOL_6	Undisturbed	after after	2010	-0,18	4	Silva et al. 2018
AC	RCM_4	Undisturbed	after after	2010	-0,15	4	Silva et al. 2018
AC	RCM_5	Undisturbed	after after	2010	-0,07	4	Silva et al. 2018
AC	RCM_6	Undisturbed	after after	2010	-0,25	4	Silva et al. 2018
AC	BOL_4	Undisturbed	after after	2010	-0,11	6	Silva et al. 2018
AC	BOL_5	Undisturbed	after after	2010	-0,38	6	Silva et al. 2018
AC	BOL_6	Undisturbed	after after	2010	-0,14	6	Silva et al. 2018
AC	RCM_4	Undisturbed	after after	2010	-0,19	6	Silva et al. 2018
AC	RCM_5	Undisturbed	after after	2010	-0,03	6	Silva et al. 2018
AC	RCM_6	Undisturbed	after after	2010	-0,25	6	Silva et al. 2018
AM	NOC_04	Undisturbed	before after	2015	-0,12	1	Pontes-Lopes et al. 2021
AM	NOC_05	Undisturbed	before after	2015	-0,03	1	Pontes-Lopes et al. 2021
AM	NOC_06	Undisturbed	before after	2015	-0,09	1	Pontes-Lopes et al. 2021
AM	NOC_07	Undisturbed	before after	2015	-0,05	1	Pontes-Lopes et al. 2021
AM	NOC_08	Undisturbed	before after	2015	-0,07	1	Pontes-Lopes et al. 2021
AM	NOC_09	Undisturbed	before after	2015	-0,02	1	Pontes-Lopes et al. 2021
AM	NOC_10	Undisturbed	before after	2015	-0,27	1	Pontes-Lopes et al. 2021
AM	TIC_04	Undisturbed	before after	2015	-0,01	1	Pontes-Lopes et al. 2021
AM	TIC_05	Undisturbed	before after	2015	-0,09	1	Pontes-Lopes et al. 2021
AM	TIC_06	Undisturbed	before after	2015	-0,22	1	Pontes-Lopes et al. 2021
AM	TIC_07	Undisturbed	before after	2015	-0,04	1	Pontes-Lopes et al. 2021
AM	TIC_08	Undisturbed	before after	2015	-0,14	1	Pontes-Lopes et al. 2021
AM	NOC_04	Undisturbed	before after	2015	-0,18	2	Pontes-Lopes et al. 2021
AM	NOC_05	Undisturbed	before after	2015	-0,04	2	Pontes-Lopes et al. 2021
AM	NOC_06	Undisturbed	before after	2015	-0,09	2	Pontes-Lopes et al. 2021
AM	NOC_07	Undisturbed	before after	2015	-0,03	2	Pontes-Lopes et al. 2021

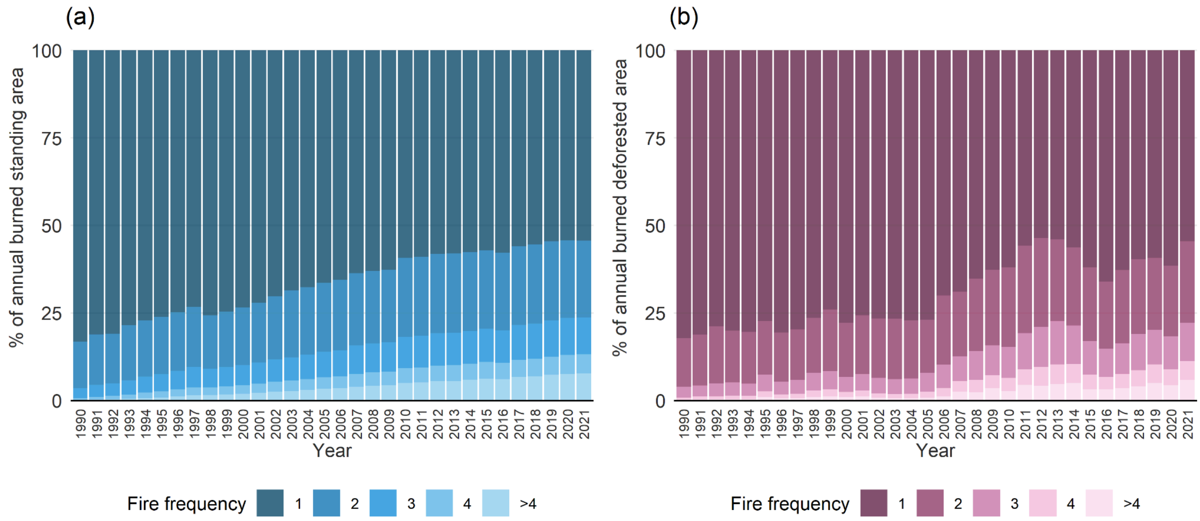
AM	NOC_08	Undisturbed	before after	2015	-0,08	2	Pontes-Lopes et al. 2021
AM	NOC_09	Undisturbed	before after	2015	-0,03	2	Pontes-Lopes et al. 2021
AM	NOC_10	Undisturbed	before after	2015	-0,27	2	Pontes-Lopes et al. 2021
AM	TIC_04	Undisturbed	before after	2015	0,00	2	Pontes-Lopes et al. 2021
AM	TIC_05	Undisturbed	before after	2015	-0,17	2	Pontes-Lopes et al. 2021
AM	TIC_06	Undisturbed	before after	2015	-0,20	2	Pontes-Lopes et al. 2021
AM	TIC_07	Undisturbed	before after	2015	-0,07	2	Pontes-Lopes et al. 2021
AM	TIC_08	Undisturbed	before after	2015	-0,19	2	Pontes-Lopes et al. 2021
AM	NOC_04	Undisturbed	before after	2015	-0,17	3	Pontes-Lopes et al. 2021
AM	NOC_05	Undisturbed	before after	2015	-0,07	3	Pontes-Lopes et al. 2021
AM	NOC_06	Undisturbed	before after	2015	-0,13	3	Pontes-Lopes et al. 2021
AM	NOC_07	Undisturbed	before after	2015	-0,01	3	Pontes-Lopes et al. 2021
AM	NOC_08	Undisturbed	before after	2015	-0,07	3	Pontes-Lopes et al. 2021
AM	NOC_09	Undisturbed	before after	2015	-0,03	3	Pontes-Lopes et al. 2021
AM	NOC_10	Undisturbed	before after	2015	-0,31	3	Pontes-Lopes et al. 2021
AM	TIC_04	Undisturbed	before after	2015	-0,02	3	Pontes-Lopes et al. 2021
AM	TIC_05	Undisturbed	before after	2015	-0,21	3	Pontes-Lopes et al. 2021
AM	TIC_06	Undisturbed	before after	2015	-0,19	3	Pontes-Lopes et al. 2021
AM	TIC_07	Undisturbed	before after	2015	-0,10	3	Pontes-Lopes et al. 2021
AM	TIC_08	Undisturbed	before after	2015	-0,20	3	Pontes-Lopes et al. 2021
MT	EDGE_3Y	Burned	before after	2010	-0,57	1	Brando et al. 2019

MT	EDGE_1Y	Burned	before after	2010	-0,21	1	Brando et al. 2019
MT	FOREST_3Y	Burned	before after	2010	-0,14	1	Brando et al. 2019
MT	FOREST_1Y	Burned	before after	2010	-0,10	1	Brando et al. 2019
MT	EDGE_3Y	Undisturbed	before after	2004	-0,13	1	Brando et al. 2019
MT	FOREST_3Y	Undisturbed	before after	2004	-0,04	1	Brando et al. 2019
MT	EDGE_3Y	Burned	before after	2010	-0,71	2	Brando et al. 2019
MT	EDGE_1Y	Burned	before after	2010	-0,29	2	Brando et al. 2019
MT	FOREST_3Y	Burned	before after	2010	-0,18	2	Brando et al. 2019
MT	FOREST_1Y	Burned	before after	2010	-0,14	2	Brando et al. 2019
MT	EDGE_3Y	Undisturbed	before after	2004	-0,13	2	Brando et al. 2019
MT	FOREST_3Y	Undisturbed	before after	2004	-0,02	2	Brando et al. 2019
MT	EDGE_3Y	Burned	before after	2010	-0,83	4	Brando et al. 2019
MT	EDGE_1Y	Burned	before after	2010	-0,54	4	Brando et al. 2019
MT	FOREST_3Y	Burned	before after	2010	-0,44	4	Brando et al. 2019
MT	FOREST_1Y	Burned	before after	2010	-0,31	4	Brando et al. 2019
MT	EDGE_3Y	Burned	before after	2010	-0,77	6	Brando et al. 2019
MT	EDGE_1Y	Burned	before after	2010	-0,58	6	Brando et al. 2019
MT	FOREST_3Y	Burned	before after	2010	-0,45	6	Brando et al. 2019
MT	FOREST_1Y	Burned	before after	2010	-0,33	6	Brando et al. 2019
PA	357_2	Logged and burned	before after	2015	-0,21	1	Berenguer et al. 2021
PA	260_4	Logged	before after	2015	-0,16	1	Berenguer et al. 2021
PA	260_1	Logged	before after	2015	-0,21	1	Berenguer et al. 2021
PA	69_8	Logged	before after	2015	0,00	1	Berenguer et al. 2021
PA	112_12	Logged	before after	2015	-0,21	1	Berenguer et al. 2021

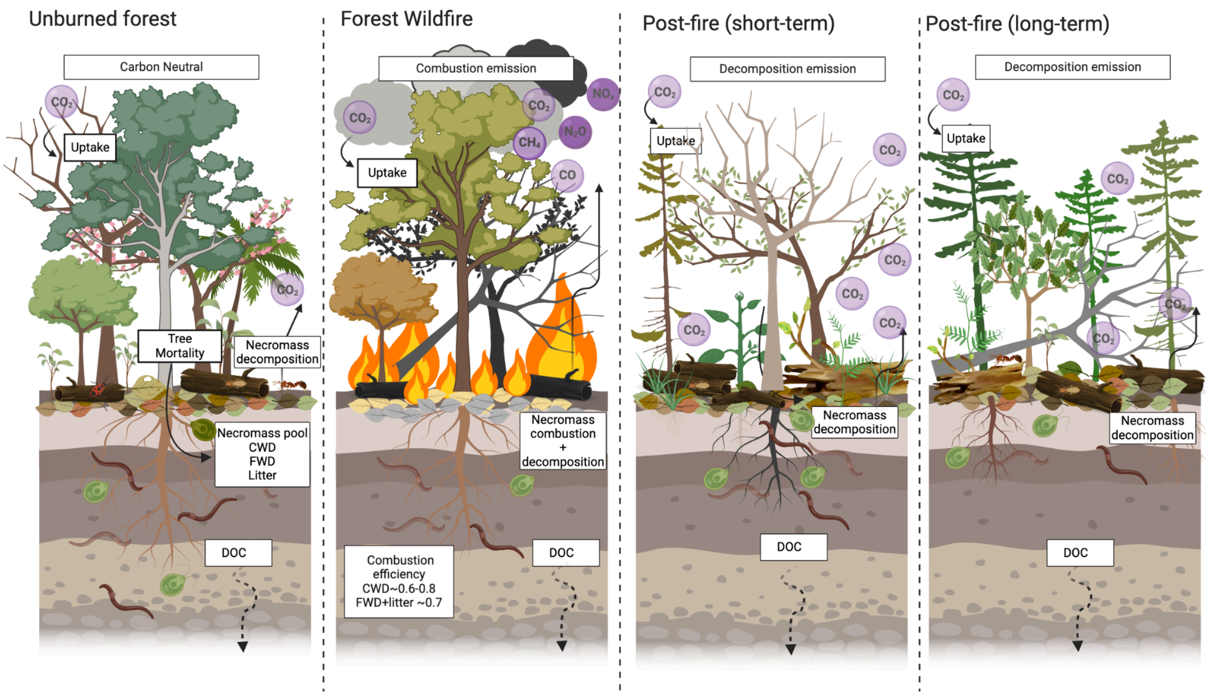
PA	261_10	Undisturbed	before after	2015	-0,09	1	Berenguer et al. 2021
PA	261_9	Undisturbed	before after	2015	-0,17	1	Berenguer et al. 2021
PA	260_5	Logged and burned	before after	2015	-0,41	1	Berenguer et al. 2021
PA	157_2	Logged and burned	after after	2015	-0,14	3	Berenguer et al. 2021
PA	157_8	Secondary	after after	2015	-0,21	3	Berenguer et al. 2021
PA	261_8	Undisturbed	after after	2015	-0,25	3	Berenguer et al. 2021
PA	307_3	Logged and burned	after after	2015	-0,17	3	Berenguer et al. 2021
PA	307_7	Logged and burned	after after	2015	-0,31	3	Berenguer et al. 2021
PA	Extra_2	Undisturbed	after after	2015	-0,23	3	Berenguer et al. 2021
PA	Extra_3	Undisturbed	after after	2015	-0,19	3	Berenguer et al. 2021
PA	TPJ_10	Burned	before after	2015	-0,19	1	Silva et al. 2018
PA	TPJ_7	Burned	before after	2015	-0,14	1	Silva et al. 2018
PA	260_4	Logged	before after	2015	-0,20	3	Berenguer et al. 2021
PA	260_1	Logged	before after	2015	-0,37	3	Berenguer et al. 2021
PA	69_8	Logged	before after	2015	-0,12	3	Berenguer et al. 2021
PA	112_12	Logged	before after	2015	-0,23	3	Berenguer et al. 2021
PA	261_10	Undisturbed	before after	2015	-0,13	3	Berenguer et al. 2021
PA	261_9	Undisturbed	before after	2015	-0,43	3	Berenguer et al. 2021
PA	260_5	Logged and burned	before after	2015	-0,47	3	Berenguer et al. 2021
AC	SUM_1	Undisturbed	before after	2005	-0,05	1	Vasconcelos et al. 2015
AC	SUM_1	Undisturbed	before after	2005	-0,14	4	Vasconcelos et al. 2015

Supplementary Method 1. Fire regime before deforestation

Fires before deforestation are important because it is an unaccounted source of emission. We quantified the number of fire events before deforestation, and we found that 45.4% of all burned forests in the Brazilian Amazon were burned more than one time before being deforested and 45.7% of all burned standing forests were burned multiple times. Repeated fires increase the amount of the carbon loss and GHG emissions and if properly quantified reduces the temporal uncertainty on carbon accounting systems. Our assessment of fire frequency before deforestation is evidence of the lag in emissions accounting. It shows that 45.4% of forests are burned multiple times before deforestation, resulting in more emissions before they are finally accounted for.



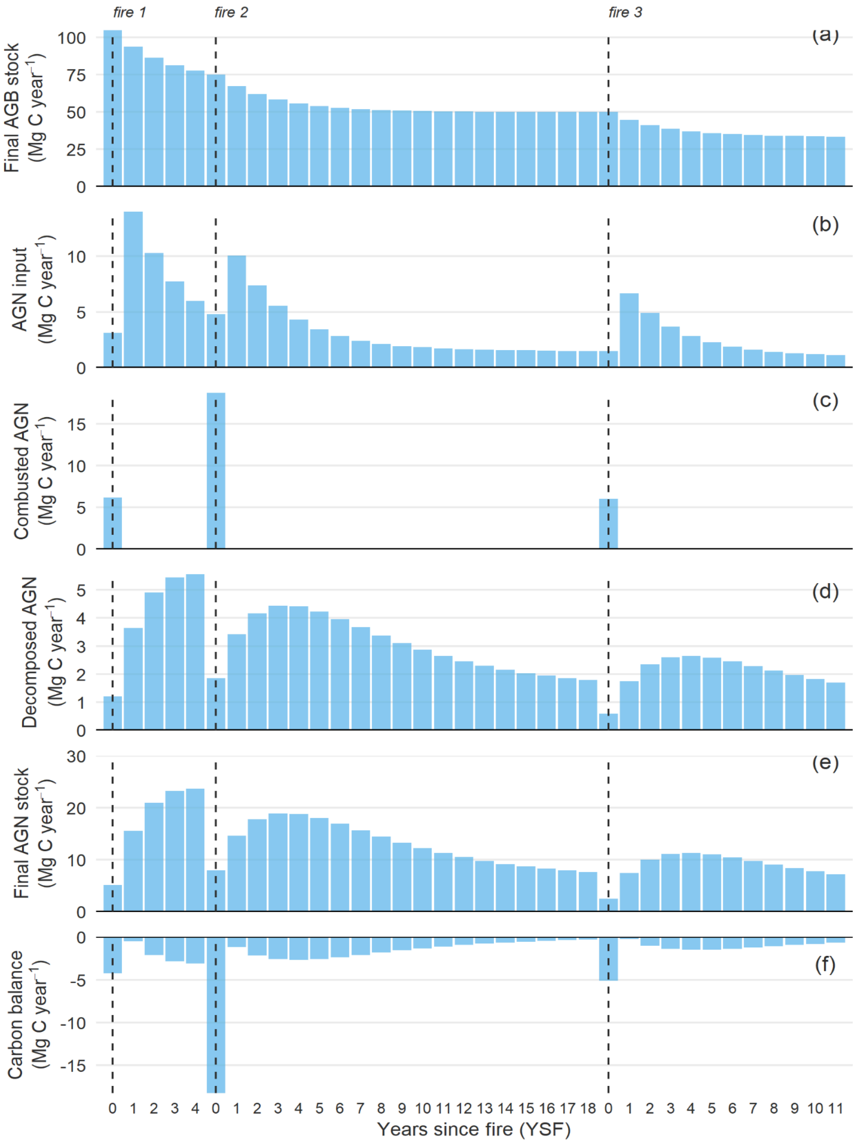
Supplementary Figure 1. Relative frequency (%) of fire frequency categories of all pixels classified as (a) burned standing forests and (b) burned forest with subsequent deforestation. Currently, approximately 50% of burned standing forests were affected by fires more than once. About 50% of burned forests that end up being clear cut are affected by fires more than once.



Supplementary Figure 2. Conceptual model representing the GHG gases fluxes following a forest fire event. Our proposed bookkeeping model estimates the effects of fires on forest carbon pools (aboveground live and dead) and the inflows and outflows of CO_2 and non-CO_2 gas over time. Our model represents two types of emissions components, combustion (emission of CO_2 and non-CO_2) and decomposition of additional organic matter from fire-induced tree mortality (emission of CO_2). The aboveground dead pool (e.g. necromass) is divided into litter plus fine woody debris (FWD) and coarse woody debris (CWD), and each component as a specific combustion efficiency factor.

Supplementary Method 2. Description of the application of bookkeeping model at the pixel level

The bookkeeping model estimates at the pixel level the reduction in the live aboveground carbon stocks (Supplementary figure 4A) according to the negative exponential model fitted with the permanent plots data. The reduction re-starts after a fire event repeats within the same pixel, with the live carbon stocks not recovering but stabilising at a lower level after 16 years. Every year there is a natural input to the dead stocks which is in balance with the annual losses from decomposition. After a fire event, inputs of dead stocks increase due to an increase of stem mortality (Supplementary Figure 4B). If fire is repeated during the phase of increased inputs to dead stocks, large losses from combustions occur (Supplementary Figure 4C). The loss from decomposition is minimum at the year of fire because most losses are from combustion, but in the following years decomposition increases with the increase of dead stocks (Supplementary Figure 4D). In the year of a fire event, dead stocks decrease sharply as losses from combustion apply, but in subsequent years new inputs from stem mortality increase the dead stock recovering the pre-disturbance levels in the long-term (Supplementary Figure 4E). The carbon balance resulting from the bookkeeping model shows high peaks of emissions from combustion at the year of fire, and a pattern of increase followed by a decrease of emissions in the subsequent years up to carbon emissions neutrality in the long-term (Supplementary Figure 4F).



Supplementary Figure 3. Example output of the bookkeeping model for one cell grid with 100 Mg C /ha carbon stock and fire events repeated three times within 4 and 18 years intervals. (a) Final AGB stock reduction after three fires; (b) AGN input with least values at the fire year and increased values at post-fire; (c) Combusted AGN stocks at the fire year; (d) Decomposed AGB stocks increase at post-fire years; (e) Final AGN stocks; (f) Carbon balance remaining negative until reaching neutral state.

Supplementary Table 2. Summary of the AGB, AGN and burned area maps used to initialise and support the model.

Carbon maps	Area-weighted mean (Mg C ha^{-1})	Area-weighted SD (Mg C ha^{-1})	Range (Mg C ha^{-1})	Sources
Initial AGB stock	104.6	34.0	0 - 243.5	Brazilian Fourth National Communication, Ometto et al., 2023

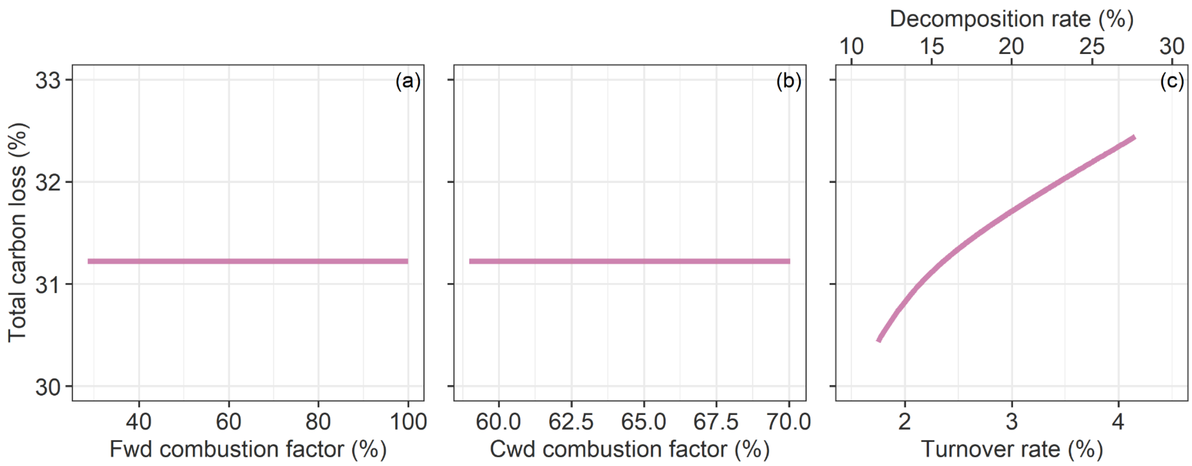
Initial AGN stock (CWD + FWD)	9.4	3.4	0 - 22.9	Brazilian Fourth National Communication
Initial CWD stock (AGN)	9.4	3.4	0 - 22.9	Brazilian Fourth National Communication
Initial FWD stock (AGN)	5.0	2.2	0 - 78.1	Brazilian Fourth National Communication
Fire maps	**Mean Count**	**SD Count**	**Range Count**	**Sources**
Fire frequency	2	2	1-9	MapBiomas Fire, filtered for standing primary forests in 2020
Fire interval	5	4	1-32	Annual burned maps from MapBiomas Fire, filtered for standing primary forests

Supplementary Table 3. Static parameters adopted in the bookkeeping model.

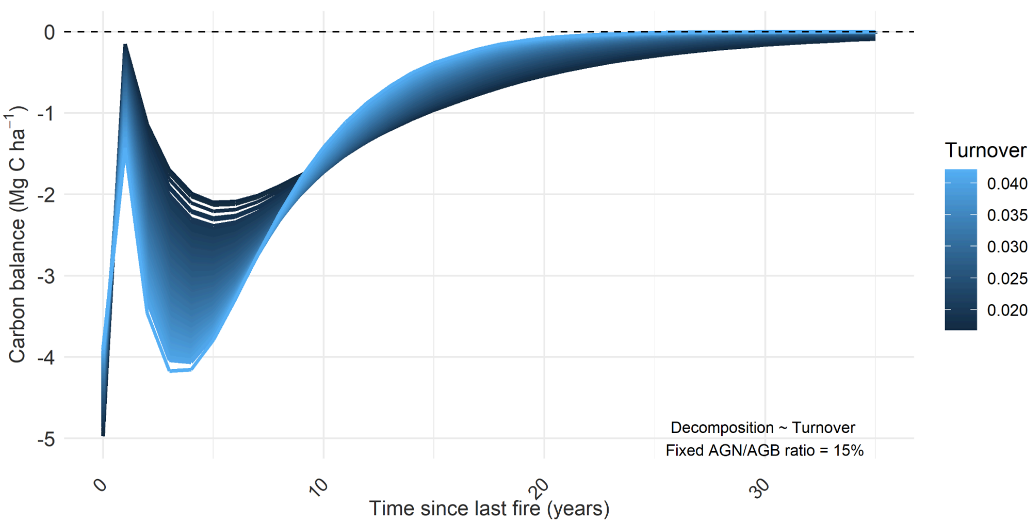
Parameters	Value	Units	Sources
Decomposition	19	%	Chambers et al., 2000
Turnover	3	%	Estimated annual rate applied to AGB to balance out the decomposition of AGN, in a neutral state
FWD combustion factor for single and multiple fires	68.3	%	Paolucci et al. (personal communication)
CWD combustion factor for single fires	64.3	%	Balch et al. 2008, Withey et al. 2018
CWD partitioning for multiple fires	75.7	%	Withey et al., 2018
CWD combustion factor for multiple fires	82.4	%	Balch et al. 2008
C content in dry mass	50	%	-
CO_2 emission factor	1580	g kg^{-1} of dry mass	IPCC, 2006; MCTI, 2015
CO emission factor	104	g kg^{-1} of dry mass	IPCC, 2006; MCTI, 2015
CH_4 emission factor	6,8	g kg^{-1} of dry mass	IPCC, 2006; MCTI, 2015
N_2O emission factor	0,2	g kg^{-1} of dry mass	IPCC, 2006; MCTI, 2015
NO_x emission factor	1,6	g kg^{-1} of dry mass	IPCC, 2006; MCTI, 2015

Supplementary Method 3. Sensitivity analysis of bookkeeping model outputs to parameters

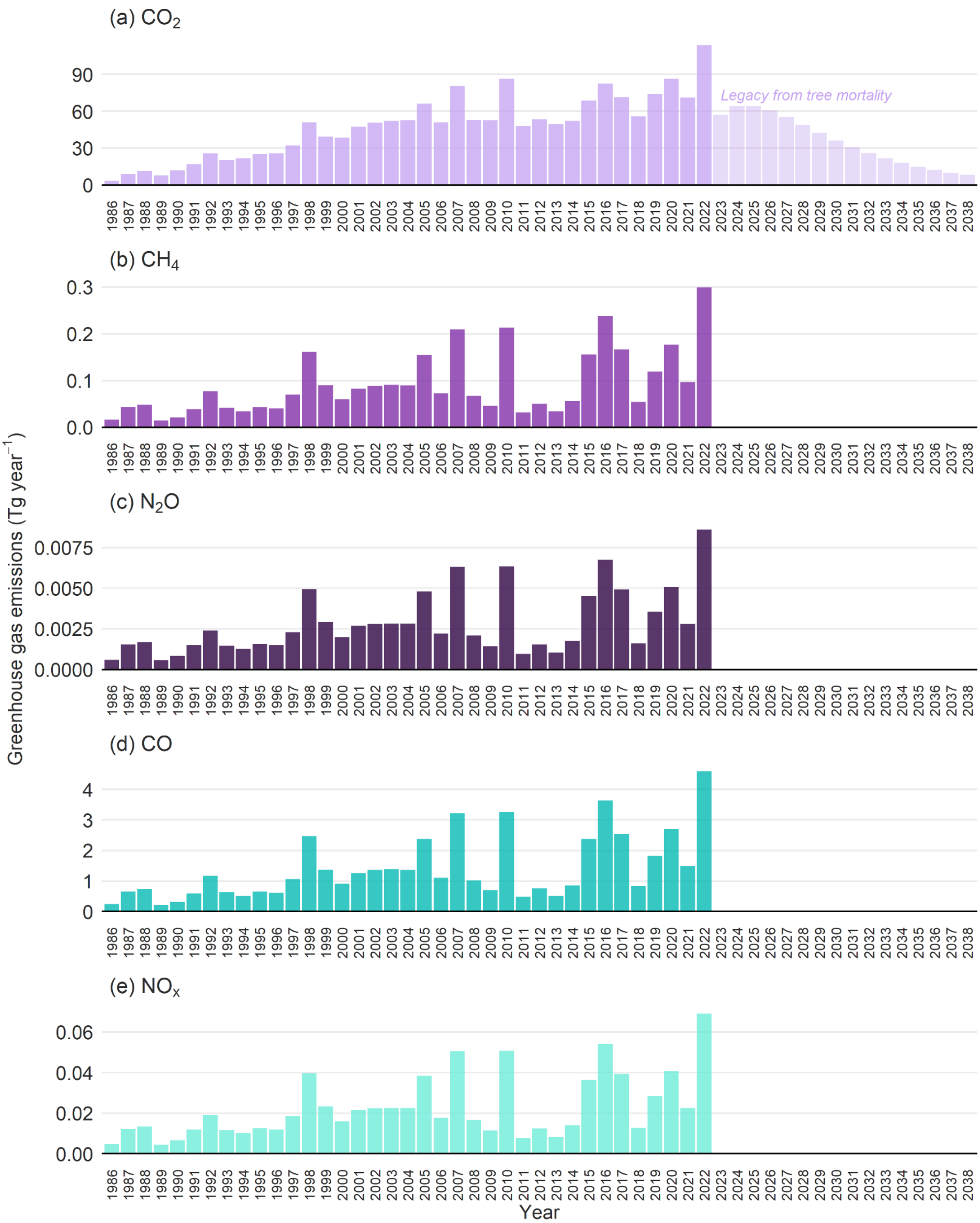
Total carbon loss within 36 years is not sensitive to the combustion factor of dead carbon pools (Supplementary figure 4), however these parameters influence annual emissions of non-CO2 gases (Supplementary Figure 5). We used averaged combustion factors from two experiments in the central-east and southern Amazon (Supplementary Table 3), but more data is needed at the regional scale for future improvements in estimates of annual emissions and the impacts on pollution and global warming potential. The total carbon loss is sensitive to decomposition and input rates (turnover) _ the higher the decomposition and input rates, the higher the total carbon loss during the time frame assessed. However, the size of this effect is considerably small (less than 5%), indicating a change from minimum to maximum in decomposition and input rates would change the total carbon loss from 30.5 to 32.5% (Supplementary Figure 4). This also suggests lower carbon and more dynamic forests in the western Amazon in our model tend to have the maximum carbon loss. While decomposition and input rates have marginal effect on total carbon loss, their effect on annual carbon balance is more prominent. We found higher input/decomposition rates implies higher carbon losses in initial years, while in the long-term the opposite is observed, e.g. higher input/decomposition implies reduced losses (Supplementary Figure 5).



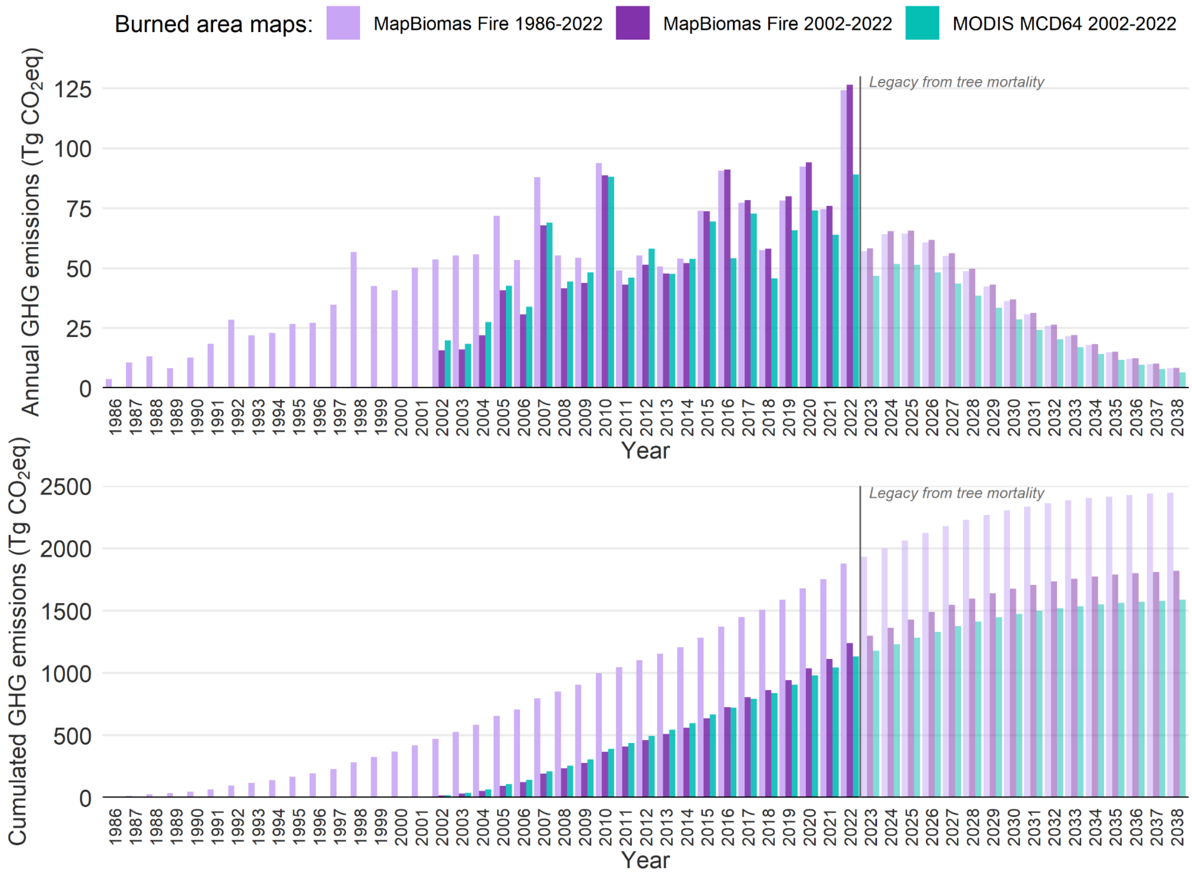
Supplementary Figure 4. Sensitivity analysis to the main parameters in the model, FWD combustion factor (a), CWD combustion factor (b), and coupled turnover-decomposition (c), for one simulated forest-fire event. Total carbon loss (%) is relative to pre-fire AGB and AGN carbon stocks.



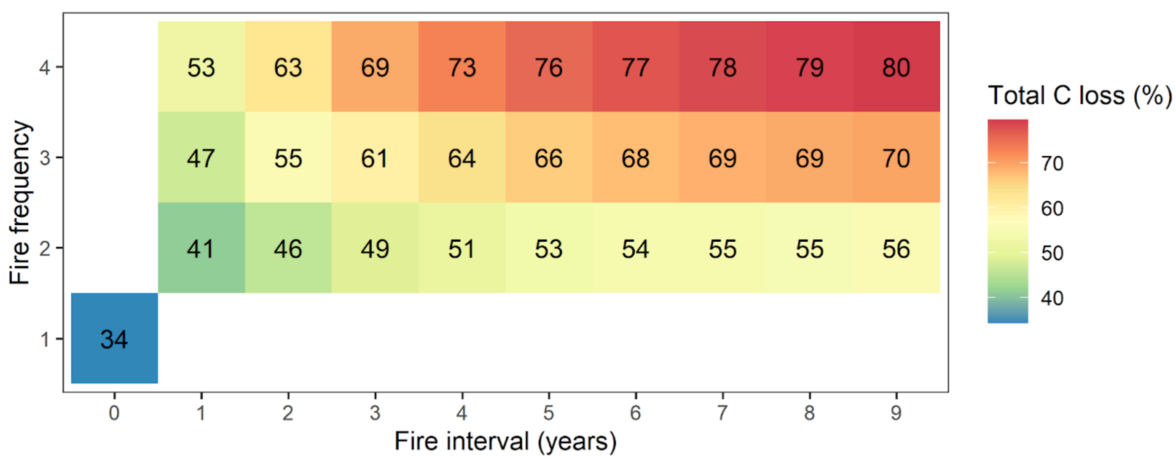
Supplementary Figure 5. Sensitivity of carbon balance (Mg C ha^{-1}) over time since last fire to varying turnover values. Our model used a fixed value of turnover (3%) based on the average decomposition rates (19%) estimated by Chamber et al 2000.



Supplementary Figure 6. Bookkeeping model outputs with Mapbiomas Fire collection 2. Forest fire emissions of each GHG (CO_2, CH_4, and N_2O) (a-c) and trace gas (CO and NOx) (d-e) from 1986 to 2022. CO_2 emissions also expose legacy emissions (2023-2038) from late tree mortality.



Supplementary Figure 7. Annual (upper) and cumulative (lower) emissions from forest fires estimated with burned area from Mapbiomas Fire collection 2 and MODIS MCD64A1. A comparison between the bookkeeping model outputs generated with the two fire datasets. Mapbiomas Fire c2 and MCD64A1 outputs agree in general with the exception of a few years Mapbiomas Fire c2 output resulted in outstanding larger emissions (e.g. 2016, 2018, 2019, 2020 and 2022).



Supplementary Figure 8. A simulation of the total carbon loss (%) under multiple combination scenarios of fire frequency and fire intervals at the cell-grid level.

Supplementary Note 1. Estimation of total carbon loss (%) through a combination of fire frequency and intervals

Fire frequency and fire interval affects the total carbon loss. Our model estimates that in 36 years a forest exposed to a single fire event loses up to 34% of its original carbon stock, and up to 80% when exposed to 4 fire events. We estimated the total carbon losses under different combinations of fire frequency and fire intervals. As forests get exposed to more frequent fires the total carbon loss increases. Longer fire return intervals lead to larger carbon losses as forests would have more time losing carbon until a new fire event restarts the carbon decay function.