Greenhouse gas emissions from alternative futures of deforestation and agricultural management in the southern Amazon

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The Brazilian Amazon is one of the most rapidly developing agricultural areas in the world and represents a potentially large future source of greenhouse gases from land clearing and subsequent agricultural management. In an integrated approach, we estimate the greenhouse gas dynamics of natural ecosystems and agricultural ecosystems after clearing in the context of a future climate. We examine scenarios of deforestation and postclearing land use to estimate the future (2006–2050) impacts on carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions from the agricultural frontier state of Mato Grosso, using a process-based biogeochemistry model, the Terrestrial Ecosystems Model (TEM). We estimate a net emission of greenhouse gases from Mato Grosso, ranging from 2.8 to 15.9 Pg CO_2-equivalents (CO_2-e) from 2006 to 2050. Deforestation is the largest source of greenhouse gas emissions over this period, but land uses following clearing account for a substantial portion (24–49%) of the net greenhouse gas budget. Due to land-cover and land-use change, there is a small foregone carbon sequestration of 0.2–0.4 Pg CO_2-e by natural forests and cerrado between 2006 and 2050. Both deforestation and future land-use management play important roles in the net greenhouse gas emissions of this frontier, suggesting that both should be considered in emissions policies. We find that avoided deforestation remains the best strategy for minimizing future greenhouse gas emissions from Mato Grosso.

carbon | soy | scenarios | ecosystems modeling | conservation policy

Today, just a few frontiers of tropical land-use changes, including the Brazilian Amazon, are responsible for 34% of anthropogenic greenhouse gas emissions (1). The Amazon region has long been recognized for its role in influencing the global carbon and hydrologic cycles, but today the natural landscape is being affected by climate change and rapid agricultural development. Pastures have been and continue to be the dominant land use in the Brazilian Amazon for decades, but recently the rate of formation of new cropland area has surpassed the rate of pasture formation (2, 3). In the last decade, soybean agriculture has boomed in an arc running along the southern extent of the Brazilian Legal Amazon due to advances in crop breeding, global market demand, and national demands for food, fiber, and fuel (4).

Will these trends continue or will new conservation incentives from government and the private sector change the patterns of development in the future? The Amazon Scenarios Project sought to understand the responses of land use, forests, climate, biodiversity, and watersheds to policy interventions (5). The project released a set of scenarios (5) on potential future land-use changes for the period 2000–2050 based on biophysical features, socioeconomic factors, infrastructure development, and different development scenarios related to conservation laws and enforcement. Although these scenarios project the extent and timing of deforestation in the future and associated net carbon loss for the Amazon, they do not account for postclearing land management. There has yet to be an integrated study that includes analyses of greenhouse gas dynamics of areas predominantly covered by natural vegetation types, hereafter referred to as natural vegetation or natural ecosystems, and agricultural ecosystems after clearing beyond carbon losses from deforestation.

Here we examine several questions to help us understand the future of the Amazon frontier, with a focus on the major frontier state of Mato Grosso (6). The overall question that guides this study is: What will regional greenhouse gas emissions be, given future scenarios of deforestation and land use? To address this question, we use a process-based biogeochemistry model, the Terrestrial Ecosystems Model (TEM), with a set of deforestation (5) and land-use scenarios and a conservative climate scenario. We estimate greenhouse gas emissions of carbon dioxide from land clearing, croplands, and pastures, methane from land clearing and cattle, and nitrous oxide from croplands fertilized with nitrogen and from pastures and forests.

Results

Our analyses of the net greenhouse gas balance for Mato Grosso considers carbon and nitrogen fluxes and accounts for historical and current land use and natural ecosystem biogeochemistry in the context of changing climate.

Land-Cover and Land-Use Change. The set of land-cover and land-use change (LCLUC) scenarios we use define alternative, empirically based deforestation trends—business-as-usual (BAU) and governance (GOV) deforestation scenarios (Fig. 1) (5)—under plausible future deforestation policies and postclearing land use that represents bounding conditions for pasture or cropland uses (see *Background and Methods* for scenario details and *SI Text* for areas). The BAU deforestation scenario assumes that the high deforestation trends from the early 21st Century (7) will continue. The GOV scenario is more in line with the lower deforestation rates observed for Mato Grosso in the past few years. The Mato Grosso state government has recently articulated a goal to reduce deforestation rates by 89% by the year 2020 (8, 9), with the 1996–2005 rates reported by INPE (7) as the baseline. Assuming a linear decline in deforestation rates between 2005 and 2020, we estimate that the policy would result in a cumulative deforestation area of

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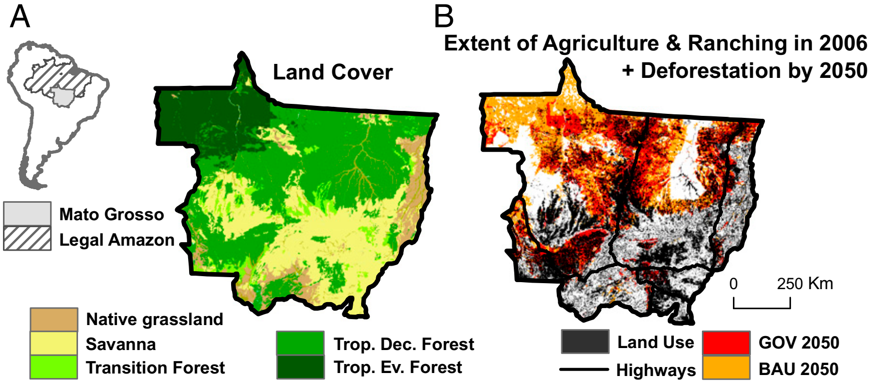

Fig. 1. The state of Mato Grosso with the distribution of natural ecosystems (Native grassland/Campo Limpo, Savanna/Cerrado Stricto Senso, Transition Forest, or Woodland/Cerradão) (29) (*A*), and contemporary (2006) land use (Croplands and ranching) (6, 30, 31) along with projected deforested areas by 2050 as determined by the BAU and GOV deforestation scenarios (5) (*B*). Areas deforested in the GOV scenario are also deforested in the BAU scenario. Detailed maps of 2006 land uses can be found in ref. 6.

60,338 km^2 from 2006 to 2020, inclusive. Interestingly, the GOV scenario sets forth an even stricter policy on deforestation (23,682 km^2 of net deforestation) over the same period. In this study, we also use a control scenario in which no new deforestation or changes in land use occur after 2006 (CONST).

Greenhouse Gas Emissions and Deforestation. During land clearing, carbon is lost through the slash-and-burn process. From 2006 to 2050, the TEM projects large carbon losses in the cases of the most extreme deforestation; 3.0 and 3.1 Pg C for BAUPasture and BAUCrop, respectively. In a future with more modest deforestation (GOVCrop and GOVPasture scenarios), total carbon loss projections range from 0.6 to 0.7 Pg C over the study period, or 75% less carbon lost compared with their BAU counterparts because less land is cleared (Table S1). In our simulations, we assume that 1.1% of the carbon from biomass burning during forest clearing is released as methane (CH_4) and the rest is released as carbon dioxide (CO_2) (10, 11). Methane from land clearing contributes 1.1 Pg CO_2-e over the study period in the most extreme scenario (BAUCrop) and <0.25 Pg CO_2-e in the most conservative scenario (GOVPasture). Thus, total carbon losses from land clearing correspond to a cumulative greenhouse gas forcing of 3.0–12.4 Pg CO_2-e over the period 2006–2050. Of all of the land-use transitions, forest-to-crop transitions have the highest carbon losses, accounting for >95% of carbon lost during clearing, because of the high biomass of the forest and combustion of all slash during clearing. Both cerrado-to-pasture and cerrado-to-crop transitions are a minor source of carbon, releasing a net 0.1 Pg C or less (0.4 Pg CO_2-e or less). In addition to the carbon released immediately to the atmosphere during clearing, a portion is transferred to product pools that then decay slowly over time (Fig. 2).

Greenhouse Gas Budget of Agricultural Systems. ***Carbon dynamics.*** Within the agricultural systems, carbon storage varies by land-use type and the largest agricultural carbon losses are in the BAU scenarios (0.30–0.67 Pg C), with historical land-use management contributing 0.24 Pg C to future emissions (CONST scenario). Emissions from land uses vary mostly as a function of total area in agriculture, rather than by the type of agriculture. The BAUCrop and BAUPasture scenarios have the highest net emissions from soil and vegetation pools (0.3–0.7 Pg C over the study period), largely from soil carbon losses in pasture (0.2–0.8 Pg C or 0.9–2.8 Pg CO_2-e). Enhanced soil carbon losses in pasture are a result of the long-term decay of slash that was transferred to the soil pool during the clearing process.

All scenarios show small losses in soil carbon for areas of single-cropping patterns (0.03–0.15 Pg C), but soil carbon dynamics in double-cropping systems depend on the extent of double-cropping intensification. In the BAUPasture and GOVPasture scenarios, where the majority of croplands are double cropped (99% by 2050; Fig. S1), we estimate small net gains in soil carbon (0.09 Pg C) as a result of N fertilizer application, whereas in BAUCrop and GOVCrop there is a very small decrease (0.04 Pg C) or no change, respectively.

With no change in pasture area, net methane emissions from cattle (CONST, BAUCrop, GOVCrop) range from 25.68 to 80.26 Tg CH_4 (low to high stocking rates; 0.6–2.0 Pg CO_2-e) over the study period or an average of 0.58–1.82 Tg CH_4 y^{-1}. Under the BAUPasture and GOVPasture scenarios, emissions range from 36.44 to 113.87 Tg CH_4 (0.91–2.85 Pg CO_2-e) and 29.19 to 91.23 Tg CH_4 (0.73–2.28 Pg CO_2-e), respectively, between 2006 and 2050. We estimate that future emission rates could be double today's rates.

Globally, ruminants are a methane source of 48.7–74.9 Tg C y^{-1} (12). Currently, Mato Grosso emissions are on the order of 1% of global ruminant methane emissions. Total methane emissions will vary greatly with cattle stocking rates (*SI Text*). A study by Lerner and Matthews (13) used government statistics tracking the number cattle and a methane production rate of 54 kg CH_4 y^{-1} per cattle head and estimated that the center-west region of Brazil (Mato Grosso, Mato Grosso do Sul, Goiás, and the federal capital, Brasilia) emitted 1.6 Tg C y^{-1} in the mid-1980s. Our findings together with the

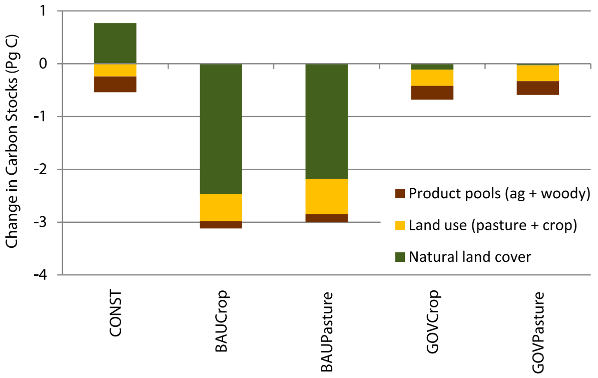

Fig. 2. Change in carbon stocks (2006–2050) from the land perspective (negative changes represent emissions to the atmosphere). For areas of "Natural land cover," the green bar represents the net change in carbon stock by accounting for carbon losses due to land clearing and carbon gains due to CO_2 enhancement. "Land use" represents net carbon balance for postclearing land use and management. Net change in carbon for "Product pools" is the balance of carbon fluxes into these pools from timber or agricultural harvest and out of these pools from decomposition.

work of Lerner and Matthews (13) suggest that (*i*) CH_4 emissions from this region have grown in recent decades and (*ii*) development of pastures in Mato Grosso will result in a large contribution to regional emissions in the future and are potentially large enough to affect the global methane budget.

Nitrous oxide emissions. Annual nitrogen fertilization simulated in TEM ranged from 35.4 to 79.9 kg N ha^{-1} y^{-1} from 2006 to 2050. For all scenarios, the average annual N fertilization rates increased by 20 kg N ha^{-1} y^{-1} between the first decade of the study and the last decade.

The total fertilized cropland area in each scenario, combined with the percentage of N fertilizer applied lost as N_2O (3%; *Background and Methods*), largely determined the N_2O emissions. The BAUCrop scenario had the highest N_2O emissions (0.55 Pg CO_2-e; Table 1) aggregated over 2006–2050, twice as high as the lowest scenario (GOVCrop). While N_2O emissions from fertilized croplands account for 2–5% of greenhouse gas emissions in Mato Grosso, they also make a large contribution to the global N_2O budget. We estimate that current N_2O emissions from fertilized croplands in Mato Grosso account for 3% of global agricultural N_2O emissions (1). We project that N_2O emission from fertilized crops will increase 3- to 6-fold by 2050, depending on the amount of area managed as fertilized cropland. Field studies of N_2O emissions from fertilized croplands, some of which are already underway (14), will improve future regional estimates of N_2O.

Field studies (15, 16) have shown that N_2O emissions from newly developed pastures in forest areas are quite high. Using these established trends, we estimate that N_2O emissions from pastures are a small source of N_2O (0.01–0.20 Tg N for the period 2006–2050) in the regional greenhouse gas budget (0.0–0.1 Pg CO_2-e).

Greenhouse Gas Budgets in Natural Systems. Tropical forests, particularly the Amazon, have long been considered a large carbon sink based on their sequestration of atmospheric carbon dioxide, but their long-term role in global carbon cycling is uncertain given the high rates of land clearing (17). The question has been raised: Will the tropics be a carbon sink or will climate-change impacts make them a source (18)? For the case of Mato Grosso, our simulations show that its natural tropical areas will continue as a carbon sink, perhaps even enhanced by increased atmospheric CO_2 levels, but deforestation negates uptake by natural vegetation in the net C budget of the region. We find that natural vegetation is a carbon sink and 85% of the carbon sequestration is in natural forest and cerradão ecosystems. We project that Mato Grosso would take up an additional 0.77 Pg C (2.82 Pg CO_2-e) from 2006 to 2050, if there were no new deforestation. With changes in land cover and land use, the potential for the natural ecosystems to take up carbon is reduced slightly to 0.65–0.72 Pg C (2.4–2.6 Pg CO_2-e) over the study period.

In addition to their potential for carbon uptake, natural tropical forests are a large source of N_2O (15, 16). We find that natural forests of Mato Grosso make a sizable contribution to natural global N_2O emissions, 1.5% in 2006 (1), while comprising <1% of the earth's land surface. Using an empirical relationship of soil respiration and N_2O production (19), we find that natural forests account for >73–90% of regional N_2O emissions. Recent meta-analysis suggests that this relationship may be robust across tropical regions (20). Natural emissions of nitrous oxide from forest soil are slightly lower, in CO_2-e, than carbon uptake by natural vegetation (Table 1), indicating that with no land-use change, natural forests are a net greenhouse gas sink.

Nitrous oxide emissions from soils in forested areas decline with decreasing forest area (Table 1), so it is no surprise that these emissions are lowest in the BAU scenarios. Annual average emissions start at 0.09 Tg N y^{-1} (averaging 0.03–0.04 Pg CO_2-e y^{-1} over the period 2006–2050) and hold steady (GOV) or decline to 0.06 Tg N y^{-1} (BAU; from 0.04 to 0.03 Pg CO_2-e y^{-1}) by 2050, depending on the extent of deforestation. With no changes in land use, forest N_2O emissions increase slightly over the study period (from 0.09 to 0.10 Tg N y^{-1}) as increased temperatures increases decomposition and therefore nitrogen availability, making the system more open and releasing more N_2O.

Implications for Future Land Management in Mato Grosso. Regional land-use choices in Mato Grosso have global biogeochemical consequences. The annual greenhouse gas emission estimated here may account for ≈1% of future global emissions, largely from deforestation (21) but also with a sizable contribution from natural forests and from agricultural use and management, which can have a lasting legacy. Through the legacy of agriculture established before 2006, Mato Grosso is already committed to a portion of future emissions (2006–2050), 3.7 Pg CO_2-e. Greenhouse gas emissions related to postclearing agricultural management are not trivial, because with increasing land use they will account for 24–49% of estimated future emissions from Mato Grosso, with CH_4 and N_2O alone contributing 12–29%. Postclearing emissions could be even higher under agricultural systems that integrate both pasture and croplands in an intra-

Table 1. Primary sources of greenhouse gas emissions from land cover and land use in Mato Grosso, 2006–2050 in Pg CO_2-e

LCLUC greenhouse gas emissions (Pg CO_2-e)	CONST	BAUCrop	BAUPasture	GOVCrop	GOVPasture
Natural land cover					
Land clearing of natural land cover	0.00	−12.43	−11.26	−3.30	−2.99
N_2O from forest soils	−1.98	−1.48	−1.48	−1.82	−1.82
Uptake by intact natural vegetation	2.82	2.39	2.39	2.64	2.64
Croplands					
Carbon dynamics	−0.15	−1.13	0.16	−0.39	0.16
N_2O emissions from fertilized crops	−0.22	−0.55	−0.31	−0.28	−0.31
Pastures					
Carbon dynamics	−0.88	−0.88	−2.81	−0.88	−1.43
N_2O from pasture soils	0.00	0.00	−0.11	0.00	−0.03
Methane emissions from cattle	−1.32	−1.32	−1.88	−1.32	−1.51
Product pools	−1.12	−0.47	−0.53	−0.99	−1.00
Total	−2.84	−15.86	−15.82	−6.34	−6.29

We present the average value for pasture emissions from cattle and soil, where both a high and low estimate were available. Data are from the land perspective; negative numbers are fluxes from the land to the atmosphere.

annual rotation, as is being experimented on small scales in Mato Grosso. Adjusting previous historical land-use change emissions estimates (22) to account for CH_4 and N_2O emissions, we estimate a net historical and future greenhouse gas emissions range, largely due to differences in deforestation, of 28–42 Pg CO_2-e from Mato Grosso for the 20th century through 2050.

Our results suggest that moratoriums on deforestation for new agricultural cultivation could drastically lower regional greenhouse gas emissions. Since 2006, the Brazilian soy industry has voluntarily agreed to a moratorium on new Amazon deforestation for croplands. Some cattle buyers are now imposing "no new deforestation" for pastures as well. Our results suggest that the intention of the Mato Grosso state government to reduce deforestation by 89% by the year 2020 (9) would be the most effective way to reduce future greenhouse gas emissions.

Conclusions

Anthropogenic emissions from future land clearing are the largest source of greenhouse gas emissions in Mato Grosso. Overall, the extent of deforestation affects the relative sources of greenhouse gas emissions. In the BAU scenarios, land clearing accounts for 71–78% of the regional emissions, whereas in the GOV scenarios, land clearing accounts for only 48–52% of emissions (Table 1). Other important sources of greenhouse gas emissions are N_2O from forest soils, CH_4 emissions from cattle, and CO_2 emissions from agricultural ecosystems. The highest emissions (BAUCrop scenario) are more than five times greater than those if there were no new deforestation or land use after 2006 (CONST scenario).

Without further land clearing in the future, Mato Grosso would become a small net carbon sink, gaining 0.2 Pg C by 2050, after switching from a carbon source to a carbon sink in the year 2014. However, it is not until after 2033 that more carbon is stored in the land ecosystems of Mato Grosso than at the beginning of the simulation. These results suggest that carbon dynamics in natural ecosystems respond to future climate change to sequester atmospheric carbon and compensate for some of the carbon losses associated with land clearing. In addition, these results suggest that land management activities before 2006 have legacy effects on future carbon uptake in the region. This legacy effect translates to 3.7 Pg CO_2-e emitted from 2006 to 2050.

The work presented here emphasizes the importance of including carbon and nitrogen dynamics associated with natural vegetation, the clearing of vegetation, and the postclearing land use. These factors have typically been addressed separately by previous modeling exercises (23–25), but our work shows the importance of an integrated assessment. Further modeling studies should explore other scenarios, such as a range of climate scenarios. Different deforestation and land-use scenarios could be included as patterns and rates of land-cover and land-use change evolve or laws and economic incentives change. Future modeling work could estimate the temporal dynamics of carbon emissions under selective logging and increased fire frequency (4, 26, 27). Alternative agricultural practices (e.g., confined animal feeding operations or biofuels) (28) could affect future greenhouse gas budgets.

Mato Grosso and the Amazon are at a crossroads for development, where now is the time to weigh agricultural development goals and environmental sustainability. To fund reduced deforestation over the next 10 y in Mato Grosso would require 1–5 billion US dollars; a large price tag, but potentially achievable with emerging funding opportunities such as commitments by the United Nations and Norway under the Amazon Fund and an international demand to exclude deforesters from the beef and soy supply chain (32). Both deforestation and postclearing agricultural land use must be considered so that future agricultural development can minimize unintended negative consequences and maximize long-term agricultural sustainability. The type of bottom-up approach presented here reduces uncertainty in tropical sources of greenhouse gases and could be applied to wider regions (e.g., the Amazon) or other hotspots of agricultural change.

Background and Methods

Study Area. Mato Grosso is a large state (925,225 km^2) in the southern Brazilian Amazon, covered by a mix of cerrado and forests, croplands, and pastures (Fig. 1 and Table S1) (6, 29–31). Today, the state is mostly natural vegetation with tropical forests accounting for 41% and cerrado accounting for 23% of the current land cover. The cerrado, considered a global biodiversity hot spot (33), varies in community structure from tree-rich areas (cerradão), to grass-dominated areas (campo limpo), to shrub-dominated areas (cerrado stricto senso).

Beginning in the 1940s and continuing today, there has been large-scale clearing of natural vegetation for pasture and cropland with little transition back to secondary growth and replacement of pastures to grow crops (2, 3). Croplands bring with them important management decisions related to cropping patterns, fertilizer use, and tillage. In Mato Grosso, it is common to shift from single (typically soybean) to double cropping (typically soybean followed by corn) in an effort to increase production on the same amount of farmland, enabled by the use of fertilizers (34, 35). A modified no-tillage regime is most commonly used in this region with a rotational program of 3 y with no-tillage followed by conventional tillage using deep disking plows in the fourth year (34); we refer to this as conservation tillage.

Future Land-Cover and Land-Use Change in Mato Grosso. Soares-Filho et al. (5) developed a set of temporally and spatially explicit Amazon deforestation scenarios for 2000–2050. To model changes in land cover from deforestation, we use the deforestation extent from two scenarios, business-as-usual (BAU) and governance (GOV), modified to consider only new deforestation relative to the land-use footprint of 2006 (Fig. 1) determined by Galford et al. (6). The BAU deforestation scenario assumes that (*i*) trends in deforestation rates of the late 20th century will continue, (*ii*) all planned road development will be carried out, (*iii*) compliance to conservation laws on private land will remain low, and (*iv*) no new protected areas will be created. The GOV deforestation scenario assumes (*i*) implementation of environmental legislation to protect forests and (*ii*) enforcement of legislation, including conservation of forest areas on private lands, land-use zoning, and expansion of protected areas (5).

To explore the postclearing land-use effects on carbon and nitrogen cycling and the magnitude of greenhouse gas emissions, we consider two scenarios for postclearing land use: (*i*) all new land use occurs as pasture (Pasture), and (*ii*) all new land use occurs as cropland (Crop). For the Pasture and Crop scenarios, new lands were cleared each year according to the prescribed deforestation scenario and then put into land use as determined by the respective land-use scenario. To simulate cropland intensification through double-cropping patterns, we allowed croplands to shift from single to double cropping at random, provided that they had at least 3 y in single cropping. Changing from single to double cropping after ~3 y is the common practice in this region (6, 34). The Crop and Pasture land-use scenarios represent the extremes of land-use development—the actual mix of land uses may be somewhere in-between. In all scenarios, no new deforestation or land use was allowed in protected areas.

To understand the legacy of historical land-use change on future carbon dynamics, we conduct an additional simulation (CONST) where no change in land cover and land use is assumed to occur after 2006. The CONST scenario shows the impacts of changing climate and CO_2 on natural vegetation and agricultural systems in the absence of future land-use change. The BAUCrop, BAUPasture, GOVCrop, and GOVPasture scenarios examined the impacts of different deforestation patterns with the range of possible land uses.

Terrestrial Ecosystems Model. We simulate monthly terrestrial carbon and nitrogen dynamics using a version of the process-based Terrestrial Ecosystem Model (TEM) that incorporates the effects of land management observed in Mato Grosso, as detailed by Galford et al. (22). To develop regional estimates of carbon and nitrogen stocks and fluxes, the TEM needs spatially explicit data for elevation, soil texture, land cover, climate, and atmospheric chemistry variables at a spatial resolution of 1 km × 1 km (see *SI Text* for details on TEM datasets). In the TEM, terrestrial carbon sequestration or loss is estimated by the net exchange of carbon dioxide between terrestrial ecosystems, and the atmosphere (NCE) depends on both ecosystem metabolism, as influenced by local environmental conditions, and land management practices:

$$\mathrm{NCE} = \mathrm{GPP} - \mathrm{R} - \mathrm{E_F} - \mathrm{E_P}, \qquad \textbf{[1]}$$

where GPP is gross primary production (i.e., the uptake of atmospheric carbon dioxide by plants during photosynthesis), which is influenced by atmospheric carbon dioxide and ozone concentrations, photosynthetically active radiation, air temperature, evapotranspiration, soil available nitrogen, and canopy stature; R is respiration of both autotrophs (R_A) and heterotrophs (R_H); E_F is the carbon released from burning during land clearing; and E_P is the decay of woody and agricultural products (22). A positive NCE indicates a net carbon sink, whereas a negative NCE indicates a carbon source.

We estimate the impacts of cropland management in TEM using nitrogen fertilizer and soil tillage factors. We assume that no N fertilizer applications occur in single-cropped areas or for the first crop (assumed to be soy) of double-cropped areas, but the second crop (assumed to be corn) is assumed to be optimally fertilized. All croplands were assumed to use conservation tillage, where tillage occurs only once every 4 y (6).

Nitrous Oxide Emissions. We estimate the net N_2O emissions from Mato Grosso by estimating the contributions from forests, fertilized cropland, and pastures separately:

$$\mathrm{N_2O\,emissions} = \mathrm{N_2O_{FORESTS}} + \mathrm{N_2O_{CROPS}} + \mathrm{N_2O_{PASTURES}}. \qquad \textbf{[2]}$$

In cerrado regions, N_2O emissions are small and typically below the detection limits of field measurements (36), so we assume cerrado emissions were zero except for areas of fertilized cropland. The N_2O emission estimates are converted to carbon dioxide equivalents (CO_2-e) by multiplying the emissions by 300, the Global Warming Potential (GWP) of N_2O relative to CO_2 at a 100-y time horizon (21).

For natural tropical forests in the southwestern Amazon, Garcia-Montiel et al. (19) found a strong linear relationship ($P < 0.0001$) of N_2O emissions to soil respiration (R_A, root respiration plus heterotrophic respiration, R_H). We make use of this relationship using the TEM estimates of respiration to relate R_s to N_2O emissions, as follows:

$$\begin{aligned}\mathrm{N_2O_{FORESTS}} = {} & \big(-4.78 + 0.20(\mathrm{R_H} \\ & + \alpha\,[\mathrm{R_A}])\rightarrow\big)(44\,\mathrm{mg\,N_2O}/28\,\mathrm{mg\,N}), \end{aligned} \qquad \textbf{[3]}$$

where α (0.35) (19) is the fraction of autotrophic respiration (R_A) of plants assumed to be root respiration and (44/28) converts the mass of nitrogen in nitrous oxide to the corresponding mass of N_2O. The α term was subjected to sensitivity analysis and validated against field measurements in the original study (19). In TEM, R_A depends on the amount of vegetation biomass, air temperature, and GPP. Heterotrophic respiration (R_H) is dominated by microbial respiration, which is associated with the decomposition of organic matter and is influenced by the amount and C:N ratio of soil organic matter, air temperature, and soil moisture.

The N fertilization rate (N_{FERT}) for second crops in a double cropping pattern is determined by TEM for local conditions (37). Based on recent literature, the yield of N_2O emissions from N fertilizer may range from 1% to 5% (1, 38–41). We assume a 3% N_2O-N yield as determined from field trials that included conservation tillage with the fertilization in a region of the southwestern Amazon and fertilized pastures in Europe (40, 41). We convert this estimate to the corresponding mass of N_2O (N_2O_{CROPS}) by using a factor of (44/28).

Extensive field measurements in pastures of the southwestern Amazon show that N_2O fluxes are quite high in the first 3 y after clearing forest (3.1–5.1 kg N ha^{-1} y^{-1}). In the sixth year as pasture, N_2O fluxes are less than emissions from the forest, measuring just 0.1–0.4 kg N ha^{-1} y^{-1} (15). We use these emission rates to estimate the range of N_2O emissions by pasture age, assuming that pastures 4–5 y of age emitted 0.4–3.1 kg N ha^{-1} y^{-1}. From our spatially explicit land-use time series datasets, we are able to track the annual changes in area of pasture within each age category. To account for the potential range of N_2O emissions from pastures, we use a low and a high emissions rate. We calculate net pasture N_2O emissions ($N_2O_{PASTURE}$) as the sum of the N_2O emissions from each age category.

For low N_2O emissions:

$$\begin{aligned}\mathrm{N_2O_{PASTURE}} = {} & (3.1\,\mathrm{Area_{YOUNG}} + 0.4\,\mathrm{Area_{MID}} \\ & + 0.1\,\mathrm{Area_{OLD}})(44\,\mathrm{kg\,N_2O}/28\,\mathrm{kg\,N}); \end{aligned} \qquad \textbf{[4a]}$$

for high N_2O emissions:

$$\begin{aligned}\mathrm{N_2O_{PASTURE}} = {} & (5.1\,\mathrm{Area_{YOUNG}} + 3.1\,\mathrm{Area_{MID}} \\ & + 0.4\,\mathrm{Area_{OLD}})(44\,\mathrm{kg\,N_2O}/28\,\mathrm{kg\,N}), \end{aligned} \qquad \textbf{[4b]}$$

where $Area_{YOUNG}$ is the area, in hectares, of pastures aged 0–3 y; $Area_{MID}$ is the area of 4- to 5-y-old pastures; and $Area_{OLD}$ is the area of pastures 6 y or older.

Methane Emissions. For methane (CH_4) emissions, we consider two sources of CH_4 emissions: (*i*) CH_4 produced from burning during land clearing of forests and (*ii*) CH_4 emissions from cattle. We convert CH_4 emissions to CO_2-e using a GWP of 25 (21). During land clearing, CH_4 is emitted only from burning forested areas and as a minor component of the total carbon released (42–44). For Amazon forest clearing there is large uncertainty regarding the fraction of carbon emitted as CH_4 (10), but based on published literature we assume a CH_4-C/ CO_2-C emission ratio of 1.1% (10, 11) and convert the estimate to the corresponding mass of methane using a factor of (16 kg CH_4/12 kg C).

A comprehensive methane study in the southern Amazon by Steudler et al. (10) shows that CH_4 emissions from cattle are six times greater than natural emissions from soil and that termite emissions are a minor methane source. Based on the work of Steudler et al. (10), we use an average emission rate of 55 kg CH_4 y^{-1} per cattle head. We estimate emission rates based on both a high stocking rate (1.5 au/ha) associated with well managed pastures and a low stocking rate (0.48 au/ha) currently observed for Mato Grosso (45).

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