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Reducing Amazon Deforestation through Agricultural Intensification in the Cerrado for Advancing Food Security and Mitigating Climate Change

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Abstract: Important among global issues is the trilemma of abrupt climate change, food insecurity, and environmental degradation. Despite the increasing use of fossil fuel, about one third of global C emissions come from tropical deforestation and indiscriminate use of agricultural practices. Global food insecurity, affecting one in seven persons, aggravates environmental degradation. The importance of judicious land use and soil sustainability in addressing the trilemma cannot be overemphasized. While intensifying agronomic production on existing land, it is also essential to identify suitable eco-regions for bringing new land under production. Based on 35-years of data from Brazil, we report that C emissions from agroecosystems are 4 to 5.5 times greater by bringing new land under production in Amazon than in the Cerrado for pastures and cropland production, respectively. The data presented indicate that agricultural intensification is feasible in the Cerrado, and the forest in Rondônia and Mato Grosso states must be protected and restored for nature conservancy. Now is the time to think beyond COP 21—Paris 2015 and take concrete actions to address these issues of global significance.

1. Introduction

Important global issues of the 21st century include abrupt climate change, food insecurity, and environmental degradation. Food insecurity affects about 815 million people [1] challenging the 2030 Agenda for Sustainable Development and the UN Decade of Action on Nutrition (2016–2025) to accomplish the global goals of ending hunger, malnutrition and poverty by 2030 [1]. Moreover, there exists a close relationship between food insecurity and environmental degradation, and soil degradation can exacerbate climate change [2]. Thus, climate change is a multiplier of existing threats to food security. By 2050, the risks of hunger and child malnutrition could increase by up to 20% due to climate change compared to a no-climate change scenario [2].

Climate change is caused by emission of greenhouse gases (GHGs) through anthropogenic activities including land use change, deforestation, biomass burning, draining of wetlands, soil cultivation and fossil fuel combustion [3]. Despite the increasing use of fossil fuel, about 31% of global carbon (C) emissions come from tropical deforestation and indiscriminate use of agricultural practices [4]. Changes in C storage in vegetation and/or soils can have significant implications to atmospheric concentration of GHGs [5]. Soil C stocks are controlled by a variety of climate and biogeochemical factors, and by land use practices, in particular by the conversion of native vegetation to agroecosystems [6]. One striking example of such changes is the replacement of rainforest and Cerrado by pasture and cropland in the Amazon Basin [7].

Achieving food security under a changing and uncertain climate requires enhanced access to adequate and nutritious food and capacities to cope with the risks posed by climate change on the one hand, as well as substantial increases in food production on the other. Thus, increasing food production requires identification of suitable eco-regions for bringing new land under production in addition to the intensification of agronomic production on existing agricultural lands [8]. However, bringing new land under production implies deforestation of native ecosystems (e.g., tropical rainforest).

The Amazon Basin encompasses 700 million hectares (M ha), and the central part lies entirely within the Brazilian territory [9]. This region has one of the highest rates of deforestation in the world (0.66 M ha year^{-1}—2016–2017) [10] despite important reduction occurred in the recent past [10,11]. Cattle pastures represent the largest single use (about 70%) of cleared lands in the Amazon. These lands are characterized by poor management of the pasture and animals, and absence or low inputs of liming and fertilizers. Thus, most of these lands are degraded or in the process of degradation [12]. In the Cerrado, soybean (*Glycine max*)-maize (*Zea mays*) rotation is the predominant cropping system in cleared lands. Therefore, large amounts of C and N are lost from biomass by deforestation and emitted into the atmosphere as GHGs [13]. In addition, decline in soil C stocks is almost universally observed when tropical forest [14–16] and Cerrado [17–19] are converted to agroecosystems (i.e., pastures or croplands). There are also other sources of emissions associated with cropland including tillage, fertilizer and lime applications and with grazing systems, especially the enteric fermentation which is responsible for approximately 56% of GHG emissions of agricultural sector [20].

Agroecosystems based on the use of best management practices (BMPs) have the potential to add large amounts of organic matter into the soil [21], thereby increase soil C concentrations in surface horizons of soil under pastures developed from tropical rainforest in the Amazon Basin [16]. Adoption of no-till (NT) farming and integrated crop-livestock (ICL) or integrated crop-livestock-forest (ICLF) systems also have the potential to increase soil C stocks in comparison with soil managed by conventional tillage [15,18,22]. The rate of increase in the soil organic carbon (SOC) stock, through land use change and adoption of BMPs, follows a sigmoid curve, attains the maximum level in 5 to 20 years after adoption, and continues to accrue C until the SOC stock attains another equilibrium [21].

The potential C sink capacity being finite, it is essential to evaluate where and how agricultural expansion may be feasible and where should the native vegetation be protected and restored for nature conservancy. We believe that agriculture expansion is relatively more environmentally friendly in Cerrado than in the Amazon areas, and that adoption of BMPs to recover degraded pasturelands and intensify the agroecosystems is an important strategy of mitigating environmental and social-economics debts caused by the land use change. Therefore, the objectives of this study were to: (1) assess the C emissions upon conversion of natural into agricultural ecosystems in the Amazon and the Cerrado regions, Brazil over 35 years between 1970 and 2005, and (2) identify BMPs for the Cerrado which can sequester C while enhancing and sustaining agronomic production so as to reduce pressure of deforestation in the Amazon, and decreasing emissions of GHGs and the attendant risks of climate change.

2. Material and Methods

2.1. Study Region

The Rondônia and Mato Grosso states, Brazil (Figure 1) are located in southwest part of the "Amazon deforestation arc", one of the world's biggest hotspots of land use change to agriculture expansion in the past decades [11]. Rondônia state (237,576.3 km^2) is primarily covered by Amazon biome (Figure 1A), comprising of a highly exuberant vegetation belonging to the largest and more diverse rainforest of the planet. Mato Grosso state (903,202.4 km^2) is also partially covered by Amazon forest, but a significant area is covered by Cerrado biome (Figure 1B), a type of tropical savannah, characteristically formed by a mix of small to medium trees with twisted trunks, bushes and grasses in varying proportions.

Considering the previous and projected expansion of agricultural uses in this region, it is important to inventory the impacts of the land use change in both biomes (i.e., Amazon and Cerrado) and delineate BMPs which can mitigate these environmental and social-economic impacts towards a more sustainable and efficient agriculture in Brazil.
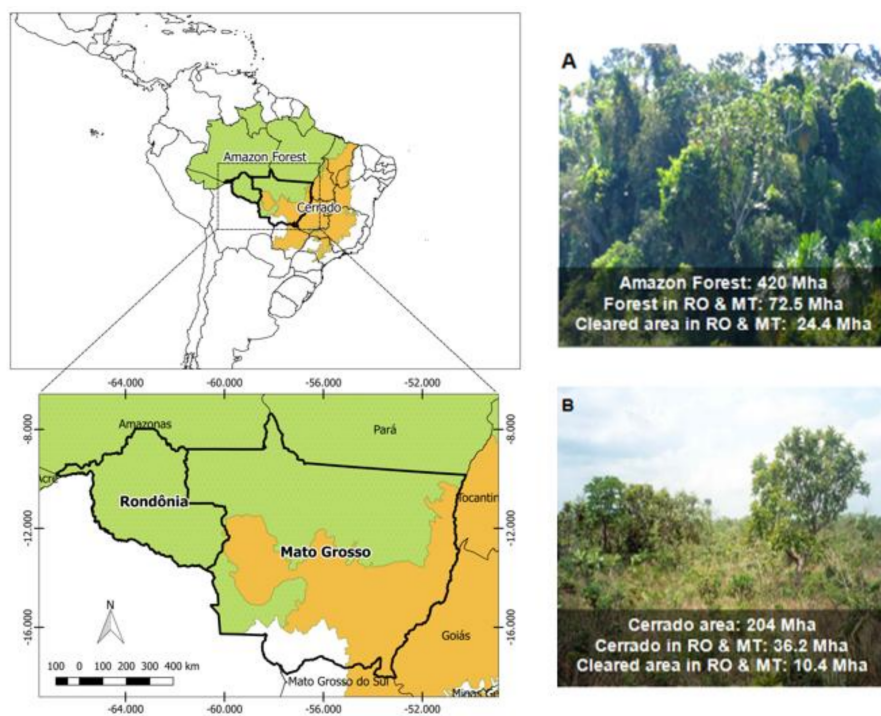

Figure 1. Geographic location of study region in Brazil, highlighting the main native vegetation types in Rondônia (RO) and Mato Grosso (MT) states, Brazil. (**A**) Amazon rainforest in Rondônia state. (**B**) Cerrado in Mato Grosso state.

2.2. Estimates of GHG Emissions

Emissions of GHGs were estimated from 1970 to 2005, which corresponds to the period of most intensive land use change in the Brazilian Amazon, and the states of Rondônia and Mato Grosso account for about 40% of its total deforested area. However, adequate datasets are not available for more recent years. Therefore, the data for the most recent year (2005) were obtained from Brazil's national land use Census.

○   Livestock and agriculture

Estimates of emissions of GHGs made included: CH_4 from enteric fermentation, CH_4 and N_2O from manure management, N_2O from range and paddock by grazing animals and N_2O from urine

and dung deposited on pasture. Similarly, the estimates of GHG emissions associated with agriculture sector included: CO_2 emissions from lime and urea applications, N_2O emissions from fertilizer application, and N_2O emissions from crop residues.

All GHG emissions were calculated for the time period of 1970 to 2005 and using the methodologies provided by IPCC (2006) guidelines for estimating the national GHG emission inventories and the "Brazil's Initial National Communication" [23] using preferably the Tier 2 approach. The results were expressed in C equivalent, and the Global Warming Potential (GWP) was assessed according to the recommendations listed in the Second Assessment Report of the Intergovernmental Panel on Climate Change [24], which adopts the GWP coefficient of 310 for N_2O and 21 for CH_4.

Activity data on livestock and agricultural crops were obtained primarily from the Agricultural Census of Brazil [25], and also from systematic surveys of agriculture and livestock provided by the Brazilian Institute of Geography and Statistics (IBGE) that includes, for example, herds (e.g., buffaloes, equines, mules, goats, sheep, dairy herds and poultry), and also the agricultural areas and production of main cultures such as soybean (*Glycine max*), maize (*Zea mays*), bean (*Phaseolus vulgaris*), rice (*Oryza sativa*), cotton (*Gossypium hirsutum*), sugar cane (*Saccharum* spp.), wheat (*Triticum aestivum*), coffee (*Coffea arabica*), and orange (*Citrus sinensis*). The amounts of N-fertilizers and limestone were obtained from the National Association for the Dissemination of Fertilizers (ANDA) [26] and the Brazilian Association of Agricultural Limestone Producers (ABRACAL) [27].

○   Soil organic carbon (SOC) and GHG emissions by deforestation

Changes in SOC stock for Amazon forest-to-pasture and Cerrado-to-cropland sequences were obtained from the study of Maia et al. [28], which estimated the soil carbon changes for Mato Grosso and Rondônia states taking into account the main land use conversions. These researchers also performed the uncertainty analysis using Monte Carlo simulation. The detailed methodology is described by Maia et al. [28].

The emissions from above and belowground were included in assessing the total GHG emissions from deforestation according to the following equations:

Aboveground estimates were computed by using Equation (1):

$$GHG_{ABOVE} = \left(A_V \times B_V \times C \times Eq \times EF_Q \right) + \left(A_V \times B_V \times C \times Fd_A \times EF_{DA} \right) \tag{1}$$

where GHG_{ABOVE} = amount of GHG emitted due to deforestation and burning (Mg); A_v = deforested area for each type of vegetation (ha); B_v = aboveground biomass for each type of vegetation (Mg ha^{-1}); C = average carbon content in plant biomass (dimensionless); Eq = combustion factor (dimensionless); EF_Q = emission factor for each GHG (CO_2, CH_4, N_2O) due to burning (Mg CO_2/Mg C burned); Fd_A = biomass fraction decomposed after the burning (dimensionless); EF_{DA} = emission factor of CO_2 due to aboveground biomass decomposition (Mg CO_2/Mg C decomposed).

The belowground estimates were obtained by using Equation (2):

$$GHG_{BELOW} = A_V \times B_V \times C \times Fd_R \times EF_{DR} \tag{2}$$

where GHG_{BELOW} = amount of GHG emitted due to deforestation and burning (Mg); A_v = deforested area for each type of vegetation (ha); B_v = belowground biomass for each type of vegetation (Mg ha^{-1}); C = average carbon content in plant biomass (dimensionless); Fd_R = belowground biomass fraction decomposed after the burning (dimensionless); EF_{DR} = emission factor of CO_2 due to belowground biomass decomposition (Mg CO_2/Mg C decomposed).

The estimate of the deforested area in Mato Grosso and Rondônia was obtained from Fearnside et al. [29]. These researchers estimated the GHG emissions due to deforestation in Rondônia and Mato Grosso states only for the period 2006–2007, using the Amazon biome data from the PRODES Project of the National Institute of Space Research (INPE) [10]. The information for Cerrado was based on the data from PROBIO—Project for Conservation and Sustainable Use of Brazilian

Biological Diversity [30]. These data were updated for 2007 by the Laboratory of Image Processing and Geoprocessing (LAPIG) of the Federal University of Goiás [31]. In the present study, the estimates were obtained for the period from 1970 to 2005, and based on the Monte Carlo Method, as described below.

○   GHG fossil fuel

The estimates reported herein were based on the results calculated for the National Carbon Balance in the Energy sector [32]. The emission from fossil fuel combustion was calculated using both bottom-up and top-down approaches for the 1970–2005 period, and also compared with the results of the BINC values [32]. The latter concluded that their results systematically underestimate the values from the BINC by about 5%. Therefore, in our calculations, the estimates for the Energy sector for CO_2 and CH_4 derived from their proposed values for the year 2000 and 2005 were corrected by 5%. For the other emissions of the Energy sector (Fugitive emissions, and N_2O emissions from fossil fuel combustion), a conservative approach was used taking into consideration the baseline data for 1994 (i.e., last year reported by the "Brazil's Initial National Communication" [23]).

○   Uncertainty analysis

The uncertainty analysis for GHG estimates from deforestation was performed using the Monte Carlo simulation, which is a numerical approach for assessing the model uncertainty. This method generates a distribution of results from a model based on randomly selecting the model input values from probability density functions (PDFs) [33–35]. In the present study, PDFs represent the distributions of uncertain input values for the above and belowground equations. We simulated 20,000 [35] changes in GHG emissions for each biome, and then summed the outputs to produce an empirical distribution for each biome and the entire region. Of the 20,000 estimates, we used the average to approximate the GHG emissions, and obtained the estimates at the 2.5 and 97.5 percentiles to derive a 95% confidence interval [34]. The only input parameter (Equations (1) and (2)) that was not considered in uncertainty level was the deforested area; because the dataset of deforestation used [29] do not provide the levels of uncertainty associated with these surveys. The parameters used and their respective uncertainties are presented in Table 1.

Table 1. Mean values of variables and their respective uncertainty level used to estimate the greenhouse gas (GHG) emissions from deforestation.

	Amazon Forest	Cerrado	Source
Eq (%)	50.8 ± 18.1 (35.7)	70.7 ± 25.2 (35.7) [1]	[29,36]
C (%)	47.0 ± 1.99 (4.25)		[37]
EF_Q—CO_2 (Mg CO_2)	3.36 ± 0.19 (5.7)	3.43 ± 0.20 (5.9)	
EF_Q—CH_4 (Mg CO_2)	0.368 ± 0.11 (29.4)	0.122 ± 0.05 (39.1)	[37,38]
EF_Q—N_2O (Mg CO_2)	0.127 ± 0.06 (47.6)	0.133 ± 0.06 (47.6)	
Fd_A (%)	47.0 ± 18.8 (40.0) [2]	23.3 ± 9.32 (40.0) [2]	[29]
EF_{DA}—CO_2 (Mg CO_2)	3.67 ± 1.46 (40.0) [3]		[39]
EF_{DA}—CH_4 (Mg CO_2)	0.003 ± 0.001 (40.0) [3]		
Fd_R (%)	95.5 ± 38.2 (40.0) [4]	79.5 ± 31.8 (40.0) [4]	
EF_{DR}—CO_2 (Mg CO_2)	3.67 ± 1.47 (40.0) [5]		[39]

[1] It adopted the same uncertainty level as used for the Amazon forest; [2] Values based on the data of the combustion factors (Eq), since there are no specific uncertainty values for this variable; [3] Values based on the data of EF_Q-CH_4, since there are no specific uncertainty values for these variables; [4] It adopted the same uncertainty level as used for Fd_A; [5] It adopted the same uncertainty level as used for EF_{DA}.

2.3. Best Management Practices (BMPs) Scenarios

We delineated scenarios based on the adoption of BMPs to estimate their potential for sequestering C into the soil (i.e., a 20-year time span) and mitigating impacts derived from land use change and current agricultural management practices adopted in the states of Rondônia e Mato Grosso, Brazil. These BMPs are included into the Low-Carbon Agriculture plan "Plano ABC", launched by Brazilian

Federal Government to promote a low-emission agriculture in the country [40]. The scenarios and their rationales are described below:

- SC1: Restoration of 9% of the degraded pastures in the states of Rondônia and Mato Grosso, by adopting the "Plano ABC". It is a realistic projection based on the available government funding for farmers and ranchers for adopting BMPs into the "Plano ABC" scope. In Rondônia and Mato Grosso states, degraded pasture area was estimated at 9.1 M ha in Amazon forest and in 6.7 M ha in Cerrado [28]. Thus, 9% of this area represents 793,900 ha in Amazon forest and in 584,000 ha in Cerrado. The soil C sequestration rate used for conversion from degraded pasture to improved pasture was 0.665 Mg ha^{-1} year^{-1} from Maia et al. [41].

- SC2: Restoration of the total area (100%) under degraded pastures (i.e., 9.1 M ha in Amazon forest and 6.7 M ha in Cerrado). It estimates the maximum potential of C accumulation by adopting BMPs in degraded pastures of Rondônia and Mato Grosso. The soil C sequestration rate is the same as that used in SC1.

- SC3: Conversion of the total area under degraded pasture to integrated crop-livestock (ICL) system. This scenario estimates the impacts of intensification of tropical agricultural lands incorporating low-productivity degraded pastures into productive integrated system that included a cropland phase (i.e., mainly soybean or corn cultivation) followed by a pasture phase (i.e., mainly tropical grasses (e.g., *Urochloa* spp. (syn. *Brachiaria* spp.) with moderate grazing intensity). The soil C sequestration rate used for conversion from degraded pasture to ICL was 0.47 Mg ha^{-1} year^{-1} (derived from Maia et al. [41]).

- SC4: Conversion of the total area under conventional to no tillage system. Conventional tillage areas account for 378,400 ha in Amazon forest and 645,100 ha in Cerrado within Rondônia and Mato Grosso states, respectively. This scenario estimates the potential soil C sequestration by adopting NT system, using the C sequestration rate of 0.477 Mg ha^{-1} year^{-1} from Maia et al. [41].

- SC5: Conversion of the total area under no tillage to integrated crop-livestock system. It estimates the potential soil C sequestration induced by intensification NT areas though ICL adoption. The total cultivated area under NT in Rondônia and Mato Grosso was estimated in 1.89 M ha in Amazon forest and 4.27 M ha in Cerrado. The soil C sequestration rate used for conversion of all area under NT to ICL was 0.278 Mg C ha^{-1} year^{-1} (derived from Maia et al. [41]).

- SC6: Conversion of the total area under conventional tillage to integrated crop-livestock. For this scenario, the cultivation areas described in SC4 were considered. However, the soil C sequestration rate was 0.755 Mg C ha^{-1} year^{-1} (derived from Maia et al. [41]).

- SC7: Conversion of the total area under conventional tillage to NT system and conversion the total area under NT to integrated crop-livestock system. It is a combination of the SC4 and SC5 scenarios. The calculations followed those described for the scenarios 4 and 5.

- SC8: Conversion of the total area under NT and under conventional tillage to integrated crop-livestock systems. It is a combination of the SC5 and SC6 scenarios. The calculations followed those described for the scenarios 5 and 6.

2.4. C Footprint of Grain and Beef in Amazon Forest and Cerrado Areas

The calculation of the C footprint to produce a kilogram of grain and beef in Amazon forest and Cerrado areas of Rondônia and Mato Grosso states was based on the data on GHG emission and productivity of grains and beef. The GHG emission per hectare in each biome was derived from data calculated according to described above. The average productivity of grain and beef used in the calculation were 2965.3 kg ha^{-1} year^{-1} and 49.9 kg ha^{-1} year^{-1} [25], respectively.

2.5. Food Security Benefits of BMPs Adoption

Adopting the scenarios of BMPs in Amazon forest and Cerrado areas of Rondônia and Mato Grosso states an extra amount of food (grains and beef) would be produced contributing directly to Brazilian and

global food security. Thus, we calculated the number of additional people that potentially could be fed in each scenario. These calculations were based on a global average per capita consumption of 41 kg year^{-1} of beef and 332 kg year^{-1} of grains (estimate for the year 2015 [42]), as well as on the average per capita consumption of 32 kg year^{-1} of beef and 265 kg year^{-1} of grains in developing countries (estimate for the year 2015 [42]). In addition, the impact of adoption of BMPs to the future food security was assessed by assuming an average consumption of 45 kg person^{-1} year^{-1} of beef and 344 kg person^{-1} year^{-1} of grains (estimates for the year 2030 [42]).

3. Results and Discussion

3.1. GHG Emissions

The data show C emissions for conversion of Amazon forest in Rondônia and Mato Grosso of 3751.7 Tg Ceq (Tg = teragram = 10^{12} g = 1 million metric ton) from pasture (20.73 M ha) and 632.5 Tg Ceq from cropland (3.65 M ha). In comparison, conversions of the Cerrado areas into pastures and cropland caused emissions of 300.6 Tg Ceq from 7.37 M ha and 102.3 Tg Ceq from 3.04 M ha between 1970 and 2005, respectively (Table 2).

The data presented herein show that emissions from agroecosystems, on unit area basis (Mg Ceq ha^{-1}), are 4 to 5.5 times greater from conversion of Amazon forest into pastures than that from Cerrado into cropland (Figure 2). For example, the amount of C emitted upon conversion of Amazon forest into cropland (4.93 Mg C ha^{-1} year^{-1}) and pasture (5.20 Mg C ha^{-1} year^{-1}) are much higher than those for conversion of Cerrado into cropland (0.96 Mg C ha^{-1} year^{-1}) and pasture (1.21 Mg C ha^{-1} year^{-1}) in the states of Rondônia and Mato Grosso. The data presented herein are based on full accounting of C losses in the soil–plant–atmosphere system, and include the losses associated with the above- and belowground biomass in the conversion of forest (almost 80% of the relative C emissions) and Cerrado (more than 45% of C emissions) into agroecosystems (Table 2).

Accounting for C lost upon clearance of the native vegetation and burning of the biomass indicated a large negative C balance (C debt), which cannot be restored even with high rates of soil C sequestration. The rates of C emissions from cutting and burning of tropical forest in the Amazon obtained in this study (Figure 2) are similar to those of 58 to 102 Mg ha^{-1} reported by Kauffman et al. [43] and 100 to 200 Mg ha^{-1} by Dias-Filho et al. [44]. In addition, conversion of native vegetation to agroecosystems adversely affects numerous other ecosystem services such as sustaining agronomic production, maintaining freshwater supply and soil quality, regulating climate and air quality, ameliorating infectious diseases and preserving biodiversity [45–48].

Total GHG emission estimates (Table 2) result from the sum of the estimates made specifically for this study, which included emissions due to deforestation, livestock/agriculture and fossil fuel, with the estimates made by Maia et al. [28] for the SOC stock change rates. In the mentioned work [28], SOC estimates were performed using a procedure similar to that used to estimate emissions from deforestation (i.e., the Monte Carlo Method with 20,000 simulations). Specific parameters for the studied region were adopted, such as emission factors, soil cover maps, soil maps, and reference soil C stocks, which allowed to refine the SOC-related estimates and calculate the associated uncertainties. According to Maia et al. [28], the mean SOC flux is 2.3 Tg year^{-1}, but the values vary substantially depending on the region (Amazon and Cerrado), as well as on the period evaluated. For the estimates of GHG emissions from deforestation, the greatest limitations are associated with lack of data, especially, more specific information for the biomass burning emission factors and rates of residues decomposition, since the available data [37–39] are not specific to the region of this study or need to be refined and updated. Thus, clearly these aspects should be prioritized in future studies in order to improve the GHG estimates, and contribute for developing best management practices scenarios, and consequently subsidize decision-makers in the adoption of these practices.

Table 2. Estimates of C emissions from clearing Amazon forest and Cerrado in Rondônia and Mato Grosso states, Brazil between 1970 and 2005.

	Source	Amazon Forest			Cerrado		
		Deforested Area (ha)	Tg C.eq	Relative Contribution (%)	Deforested Area (ha)	Tg C.eq	Relative Contribution (%)
Pasture	SOC [1]	20,736,682.0	67.3 ± 12.3	1.5	7,372,477.2	49.5 ± 10.3	12.3
	Aboveground biomass		2931.9 ± 1138.1	66.9		86.9 ± 59.9	21.6
	Belowground biomass		557.5 ± 387.4	12.7		102.1 ± 97.5	25.4
	Livestock [2]		195.1 ± 49.8	4.4		62.0 ± 15.8	15.4
Cropland	SOC	3,652,803.9	13.2 ± 2.2	0.3	3,042,495.5	13.7 ± 2.9	3.4
	N-Fertilizer (Urea) & Lime		4.74 ± 1.2	0.1		1.5 ± 0.4	0.4
	Aboveground biomass		511.5 ± 198.6	11.7		35.9 ± 24.7	8.9
	Belowground biomass		97.2 ± 67.6	2.2		42.2 ± 40.2	10.5
	Fossil fuel—NT		1.44 ± 0.4	0.03		2.25 ± 0.6	0.6
	Fossil fuel—CT		4.41 ± 1.1	0.1		6.77 ± 1.7	1.7
Total			4384.2 ± 1858.6			402.8 ± 254.1	

[1] SOC: soil organic carbon (data of SOC changes induced by land use changes used in this calculation were obtained from Maia et al. [28]); [2] Livestock includes the emissions from enteric fermentation and manure management. NT: no-tillage; CT: conventional tillage.
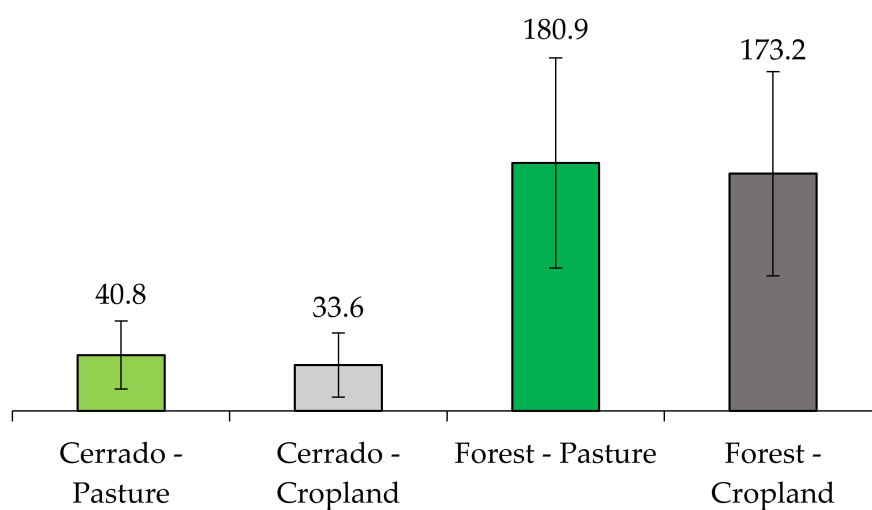
C emissions (Mg Ceq ha⁻¹)

Figure 2. C emissions (Mg Ceq ha^{-1}) for the period of 1970–2005 due to land use change and agroecosystem in the Cerrado and Amazon forest of the Rondônia and Mato Grosso states. Data of soil organic carbon (SOC) changes induced by land-use changes used for this calculation were obtained from Maia et al. [28]).

3.2. BMPs Scenarios

The data presented in this report also show that the adoption of BMPs on cleared lands can offset a part of the C emissions (Figure 3). However, to meet growing food demands and advance global food insecurity, it is necessary not only to increase agronomic productivity from the exiting agroecosystems but also to better understand how and in which biomes new land can be brought under agricultural production. Therefore, comparative scenarios of BMPs for the Amazon forest and Cerrado in Rondônia and Mato Grosso states were assessed (Table 3).

Figure 3. Examples of best management practices in Rondônia and Mato Grosso states, Brazil. (**A**) No-tillage (NT) system in commercial farm in Rondônia; (**B**) Integrated crop-livestock system in Mato Grosso with sorghum-*Brachiaria* grass intercropping.

The most promising option for the cleared Amazon forest area in Rondônia and Mato Grosso states is indicated by the restoration of the total area under degraded pastures (Scenario 2) that would sequester (maximum potential) 121 Tg of SOC in 20 years. Similarly, conversion of degraded to well-managed pastures in the Cerrado biome would sequester 89.3 Tg of SOC in 20 years (Table 3). While these data indicate vast potential of C sequestration, the amount is grossly insufficient to compensate the emissions associated with clearance and burning of vegetation in the Amazon forest and Cerrado in Rondônia and Mato Grosso (Table 2).

The study also estimated that 9% of the degraded pastures in Rondônia and Mato Grosso would be converted to well-managed pasture through the "Plano ABC" (i.e., scenario 1). This would sequester 10.6 Tg C in 20 years in the land converted from forest and 7.8 Tg C from the Cerrado (Table 3). This scenario 1 is more feasible to be implemented in the short to medium term than the scenario 2 discussed before which would require restoration of the entire converted land.

Another plausible scenario is the expansion of the areas under integrated crop-livestock (ICL) or crop-livestock-forestry (ICLF) systems, which is a sustainable agricultural production and increases the soil C stocks by adoption of NT farming. Integrated systems (ICL/ICLF) encompass diverse range of activities such as incorporating improved pastures in cropland, enhancing soil fertility under NT, and increasing soil C stocks. Thus, the scenario 3 would enhance SOC storage by 85.8 Tg C for the Amazon forest and 63.1 Tg C for Cerrado lands (Table 3) assuming that all degraded pasture land of Mato Grosso and Rondônia were to adopt the ICL system.

The scenario 7 that combines the conversion of all land under conventional tillage to NT and conversion of all area under NT to ICL would store 14.1 and 29.9 Tg C in 20 years for the Amazon forest and Cerrado areas, respectively. We also assessed the C sequestration potential of combining the conversion of the total area under NT and under conventional tillage to ICL. This scenario 8 would result in a SOC storage of 16.2 Tg and 33.5 Tg, respectively, for Amazon forest and Cerrado in Rondônia and Mato Grosso states (Table 3). The comparative analyses of data presented in Table 2 (C emissions) and Table 3 (SOC storage) indicate that agricultural expansion is feasible in the Cerrado (C emission of 102.29 Tg Ceq, and potential SOC storage of 122.8 Tg C in 20 years), and the Amazon forest in Rondônia and Mato Grosso states must be protected and restored for nature conservancy.

Table 3. SOC stock rates and storage from scenarios of best management practices in cleared Amazon forest and Cerrado areas in Rondônia and Mato Grosso states.

Land Use/Scenarios	Amazon Forest			Cerrado		
	Area (10^3 ha)	SOC Rate * (Mg C ha^{-1} year^{-1})	SOC Storage (Tg C in 20 year)	Area (10^3 ha)	SOC Rate (Mg C ha^{-1} year^{-1})	SOC Storage (Tg C in 20 year)
Total pasture	15,328.6	-	-	11,914.8	-	-
Degraded pasture	9125.4	-	-	6712.9	-	-
SC1	793.9	0.665	10.6	584.0	0.665	7.8
SC2	9125.4	0.665	121.4	6712.9	0.665	89.3
SC3	9125.4	0.470	85.8	6712.9	0.470	63.1
No tillage	1893.1	-	-	4271.9	-	
Conventional tillage	378.4	-	-	645.1	-	
SC4	378.4	0.477	3,6	645.1	0.477	6.2
SC5	1893.1	0.278	10.5	4271.9	0.278	23.8
SC6	378.4	0.755	5.7	645.1	0.755	9.7
SC7	2271.5		14.1	4917.0		29.9
SC8	2271.5		16.2	4917.0		33.5

SC1: Restoration of 9% of the degraded pastures, following the Brazil's Low-Carbon Agriculture plan (Plano ABC); SC2: Restoration of the total area (100%) under degraded pastures (i.e., maximum potential of C accumulation); SC3: Conversion of the total area under degraded pasture to integrated crop-livestock system; SC4: Conversion of the total area under conventional tillage to NT; SC5: Conversion of the total area under NT to integrated crop-livestock system; SC6: Conversion of the total area under conventional tillage to integrated crop-livestock system; SC7: SC4 + SC5; SC8: SC5 + SC6; * SOC rates were obtained from Maia et al. [41].

3.3. C Footprint of Grain and Beef

The data show the C footprint of 2.0 kg C kg^{-1} grain for Amazon forest and 0.32 kg C kg^{-1} grain for Cerrado (Table 4). The Cerrado biome also has a lower C footprint per kg of beef (23.2 kg C kg^{-1} beef) than that for the Amazon forest (102.9 kg C kg^{-1} beef) emphasizing the necessity of identifying suitable conditions for bringing new land under production. Data from IBGE [25] were collated to calculate an average value of 49.9 kg beef ha^{-1} year^{-1} for the Rondônia and Mato Grosso states. However, lower values (30 kg ha^{-1} year^{-1}) are also reported in the literature [49]. Therefore, the challenge for the beef production sectors for both Amazon forest and Cerrado in Rondônia and Mato Grosso is to provide credible research data to help producers create "low cost–high profit" cattle that yield a product desired by the consumer and manage resources in a sustainable manner with more profit per animal than per unit area.

Ranchers in Rondônia and Mato Grosso are eager to obtain a better knowledge of agribusiness and start to correctly plan the production processes [50]. In consequence, traditional extensive cattle breeding is one of the activities, which mostly loses competitiveness. The herds are being driven towards cheaper lands every day to maintain a small number of animals per unit area. The mean stocking of pastures in Brazil of 0.9 animal unit (AU) ha^{-1} [25] is too low and not sustainable. Therefore, increasing the stocking rate is a promising option for beef cattle production [51,52]. Beside genetic improvement to increase output, enhanced product quality and increased disease resistance of the livestock are among principal challenges.

The data presented herein indicate that establishing adoption of ICL is the most sustainable agroecosystem that takes into account C sequestration and food security aspects in Rondônia and Mato Grosso states (Table 3). The pasture restoration supports both components, and its intensification does not increase the C footprint. Indeed, less CH$_4$ is emitted by enteric fermentation per unit weight gain in areas that have adopted BMPs based on intensive grazing in fertilized pastures [52]. Increasing beef production by 25% in Brazil would increase CH$_4$ emission by only 2.9% [53]. Recently, Oliveira Silva et al. [51] reported reductions up to 10% of GHG emission by 2030 for a scenario of beef production intensification in Brazilian Cerrado to meet an increase of 30% of current beef consumption when decoupled from deforestation. Adoption of feedlot would be another feasible option to overcome dry periods of fodder scarcity when beef production is low but demand is high.

Avoided deforestation in Amazon forest and Cerrado due to adoption of BMPs were also estimated (Table 4). The largest area that would be avoided from clearing Amazon forest is related to the scenario of converting degraded pasture to ICL (18.25 Mha). The same scenario for the Cerrado would avoid deforestation of about 13 M ha. It confirms our hypothesis, in which adoption of BMPs, especially in pastureland should be strongly encouraged to partially offset the environment and socio-economic debits of agriculture expansion in Brazil. The areas of native vegetation spared by avoiding deforestation are of the same order of magnitude, but a difference of 3.5 times is observed for the avoided C emissions (1557 Tg Ceq for the forest against 434.5 Tg Ceq for the Cerrado).

Table 4. Carbon footprint and sequestration, additional people fed and avoided deforestation due to best management practices in cleared Amazon forest and Cerrado areas in Rondônia and Mato Grosso states, Brazil.

Agrosystem	Emissions	C Footprint		C Sequestration		People Feed		Avoided Deforested Area	Avoided Emission
	Mg C ha^{-1} year^{-1}	kg C kg^{-1} Grain	kg C kg^{-1} Beef	Scenario	Tg C in 20 year	Beef (Million)	Grain (Million)	Mha	Tg C
Amazon forest									
Pasture	5.14	-	102.9	SC1	10.55	0.96	-	0.79	135.1
Cropland	4.91	2.0	-	SC2	121.36	11.1	-	9.12	1553.2
				SC3	85.77	11.1	67.38	18.2	3106.4
				SC4	3.61	0.0	-	-	-
				SC5	10.52	2.30	-	1.89	322.9
				SC6	5.71	0.46	-	0.37	64.5
				SC7	14.13	2.30	-	1.89	322.9
				SC8	16.24	2.76	-	2.27	387.4
Cerrado									
Pasture	1.16	-	23.2	SC1	7.76	0.71	-	0.58	18.6
Cropland	0.95	0.32	-	SC2	89.28	8.17	-	6.71	214.2
				SC3	63.10	8.17	59.95	13.42	428.5
				SC4	6.15	0.0	-	-	-
				SC5	23.75	5.19	-	4.27	126.7
				SC6	9.74	0.78	-	0.64	19.1
				SC7	29.90	5.19	-	4.27	126.7
				SC8	33.49	5.98	-	4.91	145.8

SC1: Restoration of 9% of the degraded pastures, following the Brazil's Low-Carbon Agriculture plan ("Plano ABC); SC2: Restoration of the total area (100%) under degraded pastures (i.e., maximum potential of C accumulation); SC3: Conversion of the total area under degraded pasture to integrated crop-livestock system; SC4: Conversion of the total area under conventional tillage to NT; SC5: Conversion of the total area under NT to integrated crop-livestock system; SC6: Conversion of the total area under conventional tillage to integrated crop-livestock system; SC7: SC4 + SC5; SC8: SC5 + SC6.

3.4. Food Security

Dietary preferences are shifting towards livestock products and specifically beef consumption. Income growth, relative price changes, urbanization and shifts in consumer preferences have altered dietary patterns particularly in developing countries [54]. Global average per capita annual meat consumption increased from 34 kg to 43 kg between 1990 and 2010, especially, due to growing demand in Asia and to a lesser extent in Latin America [55]. Our scenario of conversion of the total area under degraded pasture to ILC, indicate that 19 million additional people could be fed (Amazon forest: 11 million and Cerrado: 8 million) with beef produced in Rondônia and Mato Grosso states (Table 4). Additionally, we estimate that the grain needs (332 kg person^{-1} year^{-1}) can be met for more than 120 million people by the ICL system that would yield not only beef but also soybean, corn and rice.

The data also show that grain needs in developing countries could be met for 160 million people from enhanced production in Rondônia and Mato Grosso; for 84 million people from the conversion of 9 M ha of degraded pasture to ICL in the forest and for 75 million people from the conversion of 6.7 M ha in the Cerrado. An additional 24 million people from developing countries would also benefit from beef production upon conversion of degraded pastures to ICL in Rondônia and Mato Grosso.

Reduction in the growth rates of world agricultural production and crop yields in recent years has raised fears that the world may not be able to grow enough food and other commodities for the present and projected population [54]. Global estimates indicate a population growth of 2.22 billion people for the next 35 years (7.55 billion in 2017 increased to 9.77 billion in 2050), an increase of 30% [56]. Nearly all of this population increase will occur in developing countries, where natural resources are already under great stress. Urbanization will continue at an accelerated pace, and about 70% of the world's population will be urban by 2050. Income levels will be many multiples of what they are now. Food production will have to be substantially increased in order to feed more urban and highly affluent population [54], becoming one of most challenging issue of the 21st century [57].

The data also show how the adoption of BMPs in Rondônia and Mato Grosso could contribute to the global food security. With the business as usual (i.e., none of the scenarios adopted), additional world population of 2.22 billion in 2050 [56] would need an area of 2164 M ha for beef production and 278 Mha for cereal production. However, from our scenario of converting degraded pasturelands to ICL, beef productivity would be 99.8 kg ha^{-1} year^{-1} and grain productivity would be 2965.3 kg ha^{-1} year^{-1}. This would result in a reduction of 56% of the area (1082 M ha from our ICL scenario against 2442 M ha without BMPs adoption) needed to meet the needs of 2.2 billion people for beef plus grain consumption in 2050.

Such results are of great interest since less new agricultural land will be cleared than in the past. At global level, there is adequate unused potential farmland. A comparison of soils, terrains and climates with the needs of major crops suggests that an extra 2.8 billion ha are suitable albeit at varying degrees for the rainfed production of grain and permanent crops. This is almost twice as much land as is currently farmed [58]. However, only a fraction of this extra land is realistically available for agricultural expansion in the near future, as much is needed to preserve forest cover and to support infrastructural development. Accessibility and other constraints also stand in the way of any substantial expansion. More than half the land that could be developed exist in just seven countries of tropical Latin America and sub-Saharan Africa, whereas other regions and countries face a shortage of suitable land [55]. In these regions, intensification through adoption of BMPs is the main, indeed virtually the only, option of increasing food production.

4. Conclusions

Land use changes to meet the demand for food, fiber and biofuels may continue to occur in Brazilian Amazon forest and the Cerrado biomes. Nevertheless, agricultural expansion in Rondônia and Mato Grosso states seems to be more environmentally feasible over Cerrado areas, whereas Amazon forest areas must be protected and restored for nature conservancy.

National and regional public policies to incentivize BMP adoption in already established pasture and croplands would bring important social and economic benefits. However, land conversions must be done carefully, and by adopting BMPs to reduce the environmental footprint for C, water, biodiversity, air quality, among others.

Agriculture will have to adapt to climate change, but it can also mitigate the climate change by offsetting anthropogenic emissions through C sequestration in soils and biota. The data presented also enhance the awareness of policy-makers and of the general society about the fragility of the global food system. However, the enhanced awareness must be translated into political will and an effective action plan. Now is the time to think beyond COP 21 and take concrete actions to address these issues of global significance.

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