The Amazon Frontier of Land-Use Change: Croplands and Consequences for Greenhouse Gas Emissions

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ABSTRACT: The Brazilian Amazon is one of the most rapidly developing agricultural frontiers in the world. The authors assess changes in cropland area and the intensification of cropping in the Brazilian agricultural frontier state of Mato Grosso using remote sensing and develop a greenhouse gas emissions budget. The most common type of intensification in this region is a shift from single- to double-cropping patterns and associated changes in management, including increased fertilization. Using the enhanced vegetation index (EVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, the authors created a green-leaf phenology for 2001–06 that was temporally smoothed with a wavelet filter. The wavelet-smoothed green-leaf phenology was analyzed to detect cropland areas and their cropping patterns. The authors document cropland extensification and double-cropping intensification validated with field data with 85% accuracy for detecting croplands and 64% and 89% accuracy for detecting single- and double-cropping patterns, respectively. The results show that croplands more than doubled from 2001 to 2006 to cover about 100 000 km^2 and that new double-cropping intensification occurred on over 20% of croplands. Variations are seen in the annual rates of extensification and double-cropping intensification. Greenhouse gas emissions are estimated for the period 2001–06 due to conversion of natural vegetation and pastures to row-crop agriculture in Mato Grosso averaged 179 Tg CO$_2$-e yr^{-1}, over half the typical fossil fuel emissions for the country in recent years.

KEYWORDS: Carbon; Deforestation; Remote sensing; Agricultural intensification; Soybean; Cerrado

1. Introduction

Today, agricultural land occupies almost 40% of Earth's land surface, with rapid growth in tropical regions (Foley et al. 2005; Hansen et al. 2008). Economic development and global markets have driven large-scale conversions of tropical ecosystems to agricultural use in recent decades (Nepstad et al. 2006). Local changes in land cover and land use in tropical regions have become increasingly linked to national and international demands, moving away from subsistence agriculture to large-scale, heavily mechanized agriculture. These shifts in land cover and land use can have large environmental impacts including the release of greenhouse gases through biomass burning and biogeochemical processes affected by clearing activities (Forster et al. 2007).

Detailed measurements of tropical land-clearing activities at high temporal and spatial resolution are essential for improving estimates of impacts on carbon emissions, biogeochemical cycles, climate, and biodiversity (Hansen et al. 2008). Land clearing is particularly evident in the Brazilian Amazon, where the deforestation rate reached a high of 27 772 km^2 yr^{-1} in 2004 (INPE 2008). Mato Grosso state (Figure 1) is a global hotspot of tropical deforestation and is a major contributor to the Brazilian Amazon ''arc of deforestation,'' because the state accounts for 38% of Amazon deforestation since 2000 (Hansen et al. 2008; INPE 2008). The clearing of forests to create pastures has been the dominant land-use transition in this region for decades. Initial clearings were government supported for colonization and border security, giving way to pasture development through various government aid programs. Today, pasture remains the largest land use in the Amazon, but its rate of growth is outpaced by the recent, rapid growth of row-crop agriculture, particularly in the southern Amazon state of Mato Grosso (Barona
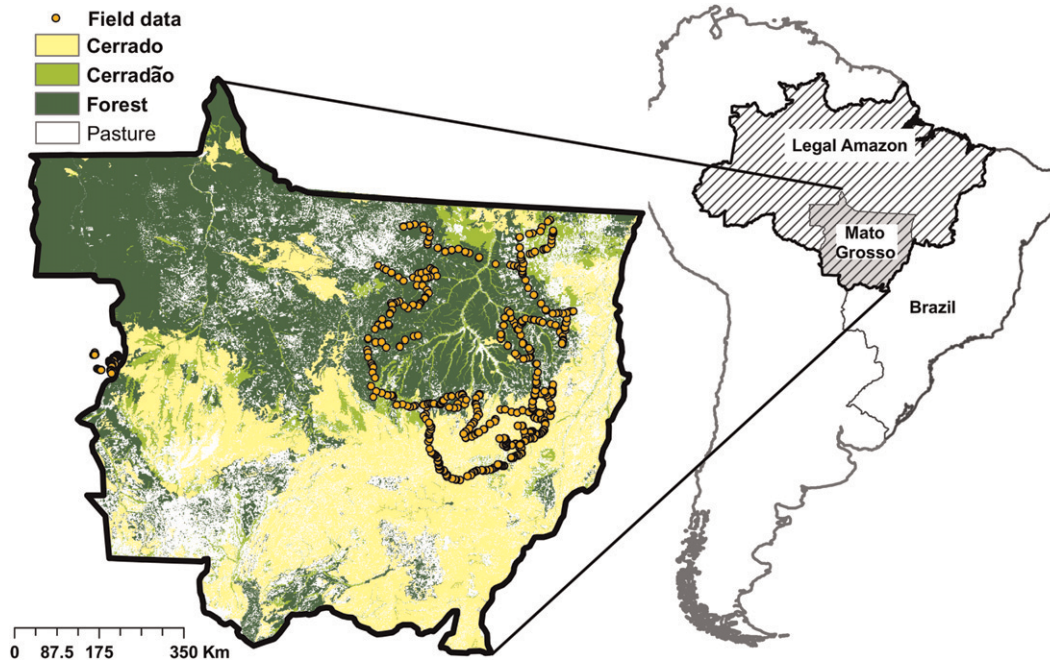
Figure 1. Mato Grosso state, the frontier of agricultural development in the Brazilian Amazon, is shown here in the context of the Brazilian legal Amazon and with potential natural vegetation (Mello 2007) and the extent of pastures in 2001 (Morton et al. 2006; Morton et al. 2009). Field data points used for validation are shown with orange dots.

2008; Brown et al. 2005; Nepstad et al. 2006). These cropland operations are very large. Over 75% of the mechanized soybean farms cultivate areas ranging from 500 to over 5000 ha (Fundação Agrisus 2006). The rapid growth in row-crop agriculture has been enabled by recent advances in mechanized farm technology, crop breeding, and crop engineering in response to global product demand and national development activities (Brown et al. 2007; Fearnside 2001; Nepstad et al. 2006). The result has been large-scale conversions of natural ecosystems or lower-production agricultural lands (e.g., pasture) to row-crop agriculture (Jepson et al. 2008). Large-scale deforestation continues with little transition back to forest (Rudel et al. 2005). In the agricultural frontier of the Brazilian Amazon, the major expansion of croplands with mechanized agriculture is emerging as a significant new dynamic that needs to be further examined (Morton et al. 2006).

The dynamics of land use in Mato Grosso are complex and represent a variety of pathways leading to cropland establishment (Figure 2). Desired increases in crop production may be met through clearing natural lands for additional agricultural production (extensification) or through increased production on existing agricultural lands (intensification; Boserup 1965). In Mato Grosso, cropland extensification involves land clearing through slash and burn and leaves no residual slash or woody debris that could hinder the mechanized tilling and planting. Intensification, or the increased production per unit area or per unit time by switching patterns of agricultural management, can be implemented in many different ways,
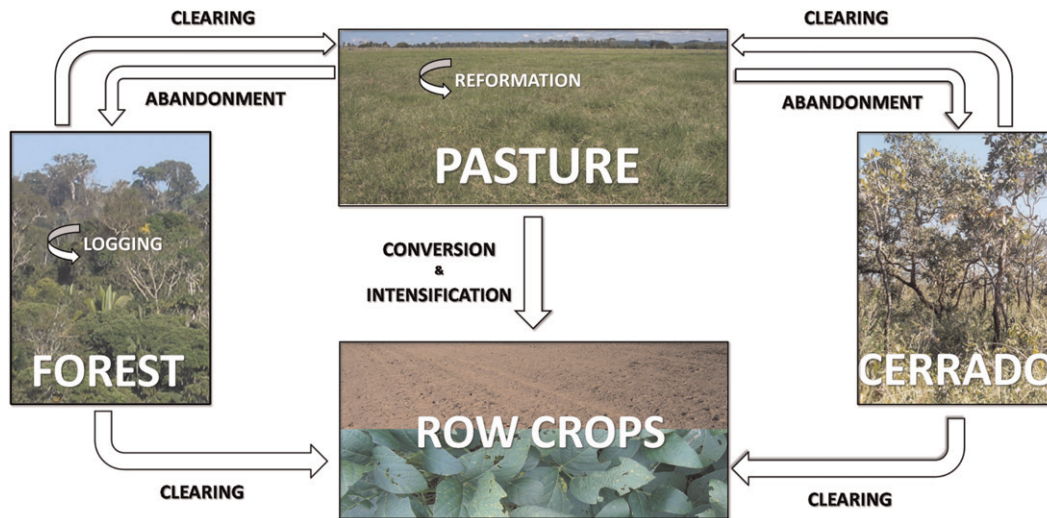
Figure 2. Dominant land-use trajectories for Mato Grosso. The foci of this paper are transitions to row-crop agriculture and intensification within existing croplands.

including shifting cropping patterns, transforming pastures to croplands, selecting new cultivars, controlling weedy growth and pests, using irrigation, and adding nutrients (Gregory et al. 2002; Keys and McConnell 2005). A change in cropping-pattern intensity, such as increased plantings of the same crop or a shift in cultivars, is a common type of intensification well documented in other parts of the world (Turner and Ali 1996). In Mato Grosso, increased production per area from intensification occurs by changing cropping patterns from single cropping (typically soybean) to double cropping (typically soybean followed by corn) in one growing season, enabled by the use of fertilizers in the double-cropping system (Fundação Agrisus 2006). Quantification of the space–time dynamics associated with expanding croplands and changing cropping patterns is critical for many areas of ecological assessment and agricultural sustainability, including improved estimates of greenhouse gas emissions, regional climate modeling, hydrological cycling, biodiversity monitoring, and agricultural soil fertility.

To document and understand land-cover and land-use change over broad spatial and temporal scales, we have come to rely on remote sensing, particularly in large areas such as the Amazon (Adams et al. 1995; Alves 2002; Skole and Tucker 1993). Since 1988, the Brazilian government has used remote sensing analyses to track deforestation for enforcement of forest protection laws, often with great success but also with some uncertainty because of relatively infrequent repeated measurements, the limitations of validation over such a large and remote area as the Amazon, and conservative detection techniques used to minimize false positives (INPE 2008). Today, we can reduce the error in these estimates using higher-frequency observations provided by the Moderate Resolution Imaging Spectroradiometer (MODIS; Justice 1998) and even distinguish among pasture, crops, and natural land cover (Anderson et al. 2005; Brown et al. 2005; Galford et al. 2008; Morton et al. 2005). Recent studies using remote sensing data have moved beyond

detection of deforestation to analyses of more complex land-use phenomena, such as fire frequency and transitions of natural areas and pastures to croplands (Galford et al. 2008; Morton et al. 2008).

The creation of croplands and evolution of cropping patterns are well-known land-use changes in this region (Fundação Agrisus 2006) but remain unquantified by previous remote sensing studies or by government records (surveys and census data). In this analysis, we quantitatively assess the rates of change associated with these processes using new observations from remotely sensed data, coupled with validation work. We also estimate the consequences of the land-use changes on regional greenhouse gas emissions, with a focus on carbon dioxide and methane emissions associated with cropland establishment and management and nitrous oxide emissions associated with crop fertilization.

2. Materials and methods

2.1. Study area

The state of Mato Grosso (Figure 1) is located in the southern part of the Amazon and has an area of 925 225 km^2. The region's natural vegetation includes forest, cerradão (savanna woodland), and cerrado (scrub savanna). The Amazon forest has long been recognized for its high biodiversity and role in the global climate as well as for threats to it from deforestation and logging (Dale et al. 1994; Shukla et al. 1990; Skole and Tucker 1993). The cerrado and cerradão of Brazil are less well known but are one of the world's biodiversity hot spots threatened by agricultural development. To date, two-thirds of the Brazilian cerrado and cerradão has been converted to agriculture (Klink and Machado 2005; Myers et al. 2000). Much of the remaining intact cerrado and cerradão are in Mato Grosso, but the threat of agricultural conversion creates a challenging juxtaposition of agricultural development and conservation priorities (Conservation International 2008; Klink and Machado 2005; Mello 2007).

2.2. Remote sensing of croplands

We used newly developed remote sensing techniques (Galford et al. 2008) to analyze MODIS data to detect croplands and the evolution of cropping patterns in Mato Grosso. We created a MODIS enhanced vegetation index (EVI; Huete et al. 2002) time series from 8-day composite surface reflectance data at a moderately coarse resolution of 500 m, appropriate for the size of croplands in Mato Grosso, where a majority of the farms are over 500 ha (Alves 2002; Fundação Agrisus 2006). For this MODIS product, the reflectance value of each pixel represents the best observation over the 8-day period, so there may be several different observation dates within one image. A time series can be skewed by assuming the file name, which corresponds to the first day of the 8-day period, is the actual observation date for a given pixel. To create a more accurate time series, the actual observation date of each pixel was extracted from the MODIS data product's ''date of observation flag'' instead of using a single date of observation for all pixels (Galford et al. 2008). We stacked the EVI observations into a time series of

remotely sensed green-leaf phenology. Because of the frequent anomalous observations (noise) in these data from clouds and other instrument and observation effects, we temporally smoothed the time series with a wavelet transform to distinguish true phenological peaks from noise. Croplands were detected from the wavelet-smoothed time series by their characteristically high annual standard deviation of green-leaf phenology, because crops have large annual phenological changes as they go from essentially bare soil to extremely uniform green cover. The results are grouped into classes of cropland with the cropland class divided into subclasses based on single- and double-cropping patterns from the number of phenological peaks in the wavelet-smoothed time series over the growing year. We have named the growing year for the year of harvest (e.g., August 2000–July 2001 would represent the 2001 growing year), which allows us to track the wet season growth peaks. Each year was analyzed independently of its class from the previous year. Galford et al. (Galford et al. 2008) discuss this methodology in detail.

Further phenological analyses of single- and double-cropping patterns were used to determine areas of extensification (new croplands) and double-cropping intensification (a shift from single to double cropping). We used the 2001 growing year as the baseline year for quantifying change. We classed "extensification" as any area that moved from "not cropland" in 2001 to "cropland" in any subsequent year and remained in cropland through 2006. We identified the source ecosystem cleared for the cropland using the potential natural vegetation map, or the extent of natural vegetation were there no land use, of Mello (Mello 2007) to calculate greenhouse gas emissions. Mello (Mello 2007) collected and compiled natural vegetation data from various state-level offices in Mato Grosso using a geographic information system (GIS).

Besides natural vegetation, croplands may also be derived from pastures. We combined our cropland classification scheme, the natural vegetation map (Mello 2007), and pasture maps generated elsewhere but covering almost the same study period (2001–05; Morton et al. 2009; Morton et al. 2006) to determine these land-use transitions. For 2006, new pasture areas were assumed to have a linear relationship based on the 2001–05 period, and their distribution was weighted by biome. Our approach allows us to identify where and when new croplands are developed directly from each natural ecosystem or from pastures. In the case of pastures, we can identify the natural ecosystem from which they have been derived. The pasture dataset is likely an overestimate of planted pasture in the cerrado region, because it includes natural (unmanaged) grasslands that may not be grazed. Despite these caveats, this is the best spatially explicit estimate of pasture lands available to us for the study period. Pasture-to-cropland transitions were identified where new croplands were detected in areas mapped as pasture in the previous growing season.

To create a spatially coherent product, we smoothed the cropping-pattern classes using a 3×3 pixel window to sieve outlying classes, designating them as unclassed (ITT 2008). Unclassed pixels were then clumped (ITT 2008) into the dominant class within the 3×3 pixel window. Cropping-pattern classes from the sieving and clumping procedure were then validated against field data (see section 2.3 for further discussion of validation). After validation, we restricted analysis to Mato Grosso.

Table 1. Description of field datasets used for accuracy assessment for the classes of cropland and cropping patterns detected with remote sensing.

Dataset	Methods	Spatial data	Year
Brown et al. 2007	Farm interviews and mapping for land-use history	Field mapping as polygons	2005
Galford 2010	Farm records and mapping for land-use history	Field mapping as polygons	2006
C. M. Stickler 2006, personal communication	Regional transect observations of land-cover and land-use changes	GPS point data	2006

2.3. Remote sensing validation

We used three new cropland datasets for validation (Table 1). Each dataset documents observed land uses at the time of field visits and/or reconstructed land uses from farm records and GIS maps generated by the researchers or provided by the farms. We included validation points from farms on the border of Mato Grosso, in the neighboring state of Rondônia, to increase the validation dataset. This is a soybean-growing region similar to the croplands in Mato Grosso, and the data from this area were treated the same as the other field data. Rondônia was not included in the final cropland analysis, because croplands are only a minor land use on the state scale. Each dataset had a slightly different spatial format, such as point observations or polygons of field areas.

We standardized the representation of the ground-truth observations to facilitate validation. First, all datasets were converted to point data (Figure 1) and matched to the corresponding pixels of the remote sensing classified images. Errant field points were identified in a cloud-free 2005 MODIS reflectance image and removed by hand if they met one of the following criteria: 1) points occur on mixed pixels (e.g., forest edges as recorded in the field notes); 2) two points recording the same land use occur in one pixel that would cause double counting; or 3) two points reporting different land uses occur in one pixel, because we cannot say which use makes up the majority of the pixel. The points in these datasets are not randomly stratified across the classes, because they were collected for purposes other than this validation exercise. They may overrepresent forested areas and double-cropping patterns, but these are the best available field data at the scale and detail required for validation.

For further validation, we used Instituto Brasileiro de Geografia e Estatística (IBGE; IBGE 2009) annual estimates of croplands to compare with the remote sensing results. We assessed the accuracy of our aggregate statewide cropland area detection by direct comparison to the statewide numbers reported by IBGE (IBGE 2009). Annual production records are aggregated by IBGE from monthly data under the direction of the Coordenador Estadual de Pesquisas Agropecuárias (state coordinator of agricultural research) with the aid of the IBGE data collection network; other local government offices; and the producers at "município" (equivalent to a U.S. county), regional, and state levels (IBGE 2002). We used the state-level data because of uncertainties in the finer-scale records related to how data are collected and reported. For example, data are collected for each município, but the total cropland area in one município may be larger than the total area in the

Table 2. Biomass estimates (above ground + below ground) used to calculate carbon savings and losses.

Land cover or land use	Carbon (10^6 g ha^{-1})	Reference(s)
Forest	130[a]	Saatchi et al. 2007; Saatchi et al. 2009
	130	Houghton et al. 2001
Cerradão	98[a]	Nogueira et al. 2008
	113[b]	Saatchi et al. 2007
	195[c]	Saatchi et al. 2007
Cerrado	13[a]	Castro and Kauffman 1998
	33[b]	Ministry of Science and Technology 2006
	45[c]	Saatchi et al. 2009
Pasture (well managed)	10	Buschbacher et al. 1988

[a] The low estimate used.
[b] The estimate used here.
[c] The high estimate used.

município, because a single farm may straddle two municípios and the cropland area will be reported in the município housing the farm headquarters. Comparing remote sensing results to the government estimates on a larger, aggregated level removed some of these smaller-scale artifacts.

2.4. Estimating greenhouse gas emissions

We used a bookkeeping model to calculate greenhouse gas emissions from the carbon losses associated with land-cover and land-use change as well as the nitrous oxide losses associated with nitrogen fertilizers applied in croplands. We focused on greenhouse gas emissions from the formation and fertilization of croplands. These components of the regional greenhouse gas budget have not been well studied to this point and compliment other well-studied components of the regional budget (e.g., DeFries et al. 2008; Steudler et al. 1996).

2.4.1. Carbon emissions from land-cover and land-use change

We estimated the biomass lost during land-use conversions to croplands by accounting for the area affected as determined from remote sensing inputs and for biomass per unit area for each of the major biome types using median values from the literature (Table 2). We assumed constant biomass values across each biome. In Mato Grosso, abandonment of croplands is rare (Rudel et al. 2005), so vegetation regrowth is not considered.

We assumed all natural biomass was completely lost by burning during land conversion because cultivation practices, such as plowing and harvesting with large machinery, require fields to be free of roots, stumps, and other forest remnants that could damage farm equipment. Unlike clearing for pastures, where some trees are left standing and many stumps and logs persist for decades, croplands are devoid of any signs of the former land cover.

Greenhouse gas emissions due to the loss of biomass in land-use transitions were calculated separately for forests and nonforest ecosystems. For forest clearing, carbon is released from biomass burning predominantly as carbon dioxide with a minor component released as methane (Andreae and Warneck 1994; Cofer et al.

1996; Hao and Ward 1993). For the Amazon forest, we assumed a CH_4-C/CO_2-C emission ratio of 1.1% (Longo et al. 2009; Steudler et al. 1996). No release of methane is assumed to occur during the conversion of nonforest (pasture, cerrado, and cerradão) ecosystems to croplands. These carbon greenhouse gas emissions (GHG_{CARBON}), reported in grams CO_2-equivalents (CO_2-e), were estimated as follows:

$$GHG_{CARBON} = GHG_{NON\text{-}FOREST} + GHG_{FOREST}, \tag{1a}$$

$$\begin{aligned} GHG_{NON\text{-}FOREST} = &\ C_{BIOMASS} \times (Area) \\ &\times (44\ g\ CO_2/12\ g\ C) \times (GWP_{CO2}), \quad \text{and} \end{aligned} \tag{1b}$$

$$\begin{aligned} GHG_{FOREST} = &\ [(0.989) \times (C_{BIOMASS}) \times (Area) \times (44\ g\ CO_2/12\ g\ C) \\ &\times (GWP_{CO2})] + [(0.011) \times (C_{BIOMASS}) \times (Area) \\ &\times (16\ g\ CH_4/12\ g\ C) \times (GWP_{CH4})], \end{aligned} \tag{1c}$$

where $C_{BIOMASS}$ is the carbon content of the biomass (g C ha^{-1}) of pasture or natural land cover (Table 2), area is the land area (ha) converted to crops, GWP_{CO2} is the 100-yr global warming potential (GWP) of carbon dioxide (1), and GWP_{CH4} is the 100-yr GWP of methane (25; Forster et al. 2007).

2.4.2. Fertilizer nitrous oxide emissions

We estimated total fertilizer use as a function of area by cropping pattern. We assumed that single crops are soybean, as is typical in the region (Fundação Agrisus 2006), with a fertilizer input of 10 kg N ha^{-1}. Soybean agriculture typically does not require nitrogen additions, but most farmers in the region add this modest amount as "insurance." Double-cropping systems may require fertilizer applications when the second crop (corn) is planted, in which case no additional fertilizer is applied to the first crop.

To estimate the mean amount N fertilizer applied for corn planted in a double-cropping pattern, we combined farm records of fertilizer use and field trial fertilization rates needed to produce the mean corn yields in Mato Grosso. Studies show that corn may require up to 120 kg N ha^{-1} to reach optimal productivity (Mar et al. 2003; Rezende Pereira et al. 2009), but the total N fertilizer added may be somewhat reduced by the N fixed by the soybean grown as the first crop. Data from government surveys show that Mato Grosso corn crops have an average yield of 3.71 metric tons ha^{-1} (IBGE 2009). Field trials in the Amazon forest and cerrado regions achieve these productivity levels with fertilizer doses ranging from 0 to 77 kg N ha^{-1} (Cruz et al. 2005; de Carvalho et al. 2008; Mar et al. 2003; Souza and Sorrato 2006). Recommended fertilizer doses range from 34 to 120 kg N ha^{-1} (Broch and Pedroso 2008; Broch and Pedroso 2009; de Carvalho et al. 2008). Farm records from the Amazon show a comparatively low dose of N fertilizer is typically used, with a mean of 23 kg N ha^{-1} (range from 0 to 70 kg N ha^{-1}; Cerri et al. 2007; Edgar 2007; Galford 2010). From these sources, the average N fertilization

Table 3. Validation results (pixel counts) for remotely sensed classes of cropping patterns compared to the collective pool of all field datasets. Overall accuracy was 85.6%.

Remotely sensed classes	Field data			Row total	User's accuracy
	Single cropping	Double cropping	Noncropland		
Single cropping	47	16	50	113	41.6%
Double cropping	26	163	4	193	84.5%
Not row crop	0	4	383	387	99.0%
Column total	73	183	437	693	
Producer's accuracy	64.4%	89.1%	87.7%		

for corn as a secondary crop is 34.3 kg N ha^{-1} (Broch and Pedroso 2008; Broch and Pedroso 2009; Cerri et al. 2007; Cruz et al. 2005; Edgar 2007; de Carvalho et al. 2008; Galford 2010; Mar et al. 2003; Souza and Sorrato 2006). For this work, we used the average fertilizer rate (34 kg N ha^{-1}) for second crops and included a high (75 kg N ha^{-1}) and low range (0 kg N ha^{-1}) in our sensitivity analysis. We then used the area in single and double crops to estimate greenhouse gas emissions (in CO_2-e) associated with fertilizer N_2O losses (GHG_{N2O}),

$$GHG_{N2O} = 0.03 \text{ Fertilizer Area } (44 \text{ g } N_2O/28 \text{ g N}) \text{ } GWP_{N2O}, \quad (2)$$

where 3% of the applied N fertilizer is lost as N_2O (Crutzen et al. 2008; Scanlon and Kiely 2003), fertilizer is the N fertilizer dose in g N ha^{-1} (10 000 g N ha^{-1} for single crop and 34 000 g ha^{-1} for double crop), area is the land area (ha) being fertilized, and GWP_{N2O} is the 100-yr GWP of nitrous oxide (300; Forster et al. 2007).

3. Results

3.1. Remote sensing accuracy

We assessed our accuracy in remote sensing analyses with the comparison of field data using overall accuracy, producer's and user's accuracy, and KAPPA K_{hat} metrics (Table 3). We find that our overall accuracy is 86%. Further accuracy assessments were conducted to better represent the nature of the dataset. The producer's accuracy is a measure of omission by using column totals, and the user's accuracy is a measure of commission using row totals. The KAPPA K_{hat} statistic assesses accuracy while accounting for the off-trace elements from the error matrix. A K_{hat} value close to one is much better than a random classification, zero is random, and negative numbers are worse than random (Jenson 2005). Croplands were detected with producer's accuracy of 98% and user's accuracy of 82%. The K_{hat} for the cropland and noncropland classes was 0.82. For the detection of mechanized agriculture single- and double-cropping land use, producer's and user's accuracies were 64% and 42% for single crops and 89% and 84% for double crops, respectively. The K_{hat} statistic for noncroplands and single- and double-crop classes was 0.74. The field data underrepresent single crops (Table 3), because many of the field sites had no recorded single crops and were not representative of the region, so this may be a bias that causes the validation to suggest that the remote sensing may systematically underestimate the presence of single crops.
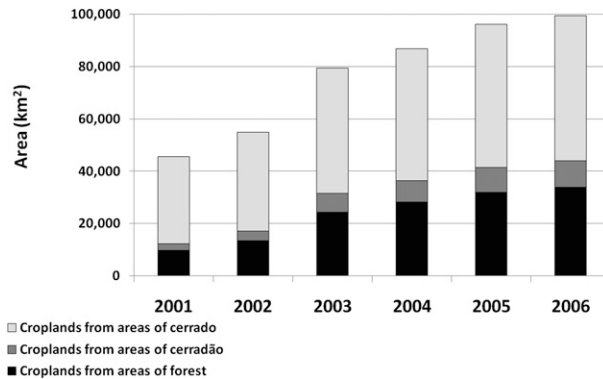
Figure 3. Total cropland area (km^2) in Mato Grosso by natural ecosystem of origin.

Our statewide estimates of cropland area (see section 3.2.1) generally agree with government estimates (IBGE 2009). The remote sensing estimates tend to under-represent the cropland area. On average across the study period, the remote sensing data detects 65% of the cropland estimated in IBGE 2009. Looking at individual years, the lowest agreement between these datasets is 40% in year 2001 and the highest is 82% in year 2003.

3.2. Changes in croplands

3.2.1. Cropland extensification

Total cropland area in Mato Grosso more than doubled from 2001 to 2006, increasing from 45 497 to 99 488 km^2 (Figure 3). We document an average annual rate of increase for agricultural extensification of 0.47%. By 2006, Mato Grosso croplands covered 11% of the state (Figure 4).

We see different cropland extensification rates for the different natural biomes (Figure 4). When weighted by area of potential natural vegetation type, the cerrado supplied the largest relative amount of land for croplands, with croplands accounting for 18% of the cerrado's potential area as estimated by Mello (Mello 2007). Over 22 000 km^2 of new croplands emerged in the cerrado biome, a 10% increase in cropland area for Mato Grosso's cerrado region (Figure 4). Spatially, we see that new extensification occurs around areas of previously existing croplands, giving a "clumping" effect to the cropland distribution (Figure 5).

Rates of conversion to cropland vary by land-cover and land-use sources and exhibit interannual variability. On average, over 60% of conversions in the cerrado region were two-phase transitions: cerrado to pasture and then pasture to cropland Figure 6). In the cerradão regions, 70% of new croplands followed such a two-phase transition. The sequence of forest-to-pasture and then pasture-to-cropland conversions accounted for over 60% of the forest land-use transitions, and total cropland area in this region increased 24 200 km^2 over the study period. The rates of pasture-to-cropland transitions show high interannual variability, particularly in areas of former cerrado (Table 4).
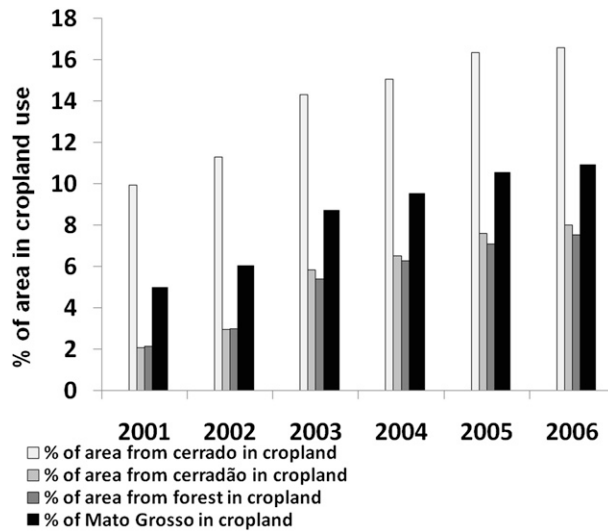
Figure 4. The percentage of land in cropland use in each originating biome and for the entire state.

3.2.2. Double-cropping intensification

Double cropping increased significantly over the period 2001–06, occurring on less than 2% (15 991 km^2) of Mato Grosso in 2001 and 4.25% (39 359 km^2) of the state by 2006. Averaged over the study period, double cropping accounts for 40% of all croplands but is not uniformly distributed across the natural ecosystems (Figure 7).

Rates of conversion to double cropping vary by source land cover and land use (Figure 8). By biome, cerrado has the largest overall level of double-cropping intensification, with double-cropping patterns at almost 50% of all croplands (Figure 8). Double-cropping patterns account for an annual average of 47% of cerrado croplands, increasing their share of the cerrado land cover from 4% to 8% over the study period. Cerradão and forest both have double-cropping patterns in less than half the cropland area. In the cerradão system, double-cropping rates as a percentage of all cropland area in cerradão ranged from a low of 18% in 2003 to a high of 30% in 2004. Double cropping increased over threefold during the study period in the forested region, ending with 3% double-cropping land use.

3.3. Estimated greenhouse gas emissions

We estimate an annual average of 179 Tg CO_2-e yr^{-1} emissions from cropland extensification in Mato Grosso (Figure 9), with forest-to-cropland transitions having the highest carbon emissions at 126 Tg yr^{-1} CO_2-e. In forest-to-cropland transitions, methane emissions average 12 Tg CO_2-e yr^{-1} from forest biomass burning. Cerrado-to-crop, cerradão-to-crop, and pasture-to-crop transitions have modest emissions (17, 16, and 21 Tg CO_2-e yr^{-1}, respectively). Emissions from
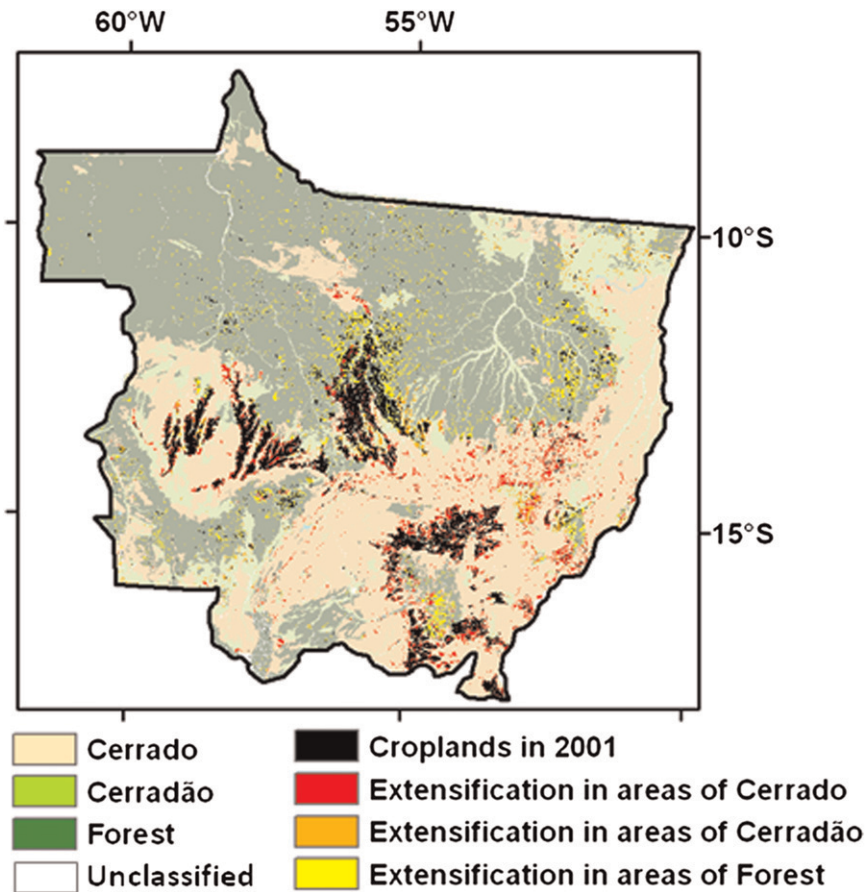
Figure 5. Agricultural cropland extensification (new areas of cropland from 2001 to 2006) mapped by natural ecosystem of origin, largely nucleating from existing croplands.

fertilizer additions are comparatively low at 0.4 Tg CO_2-e yr^{-1}, two-thirds of which we estimate from fertilizer applied in areas of double cropping.

By adding existing and nonredundant estimates, we developed a relatively complete greenhouse gas budget for Mato Grosso (Table 5). The combined estimates are 422.5 Tg CO_2-e yr^{-1}. It includes estimates of carbon losses from forest conversion to pasture and cropland, from natural ecosystem and pasture conversions to cropland, and from pasture maintenance fires and cattle emissions of methane (DeFries et al. 2008; after Steudler et al. 1996).

4. Discussion

4.1. Land-use change

A growing human population along with dietary changes is expanding the global area of agriculture, with the southern Amazon being one of the most rapidly
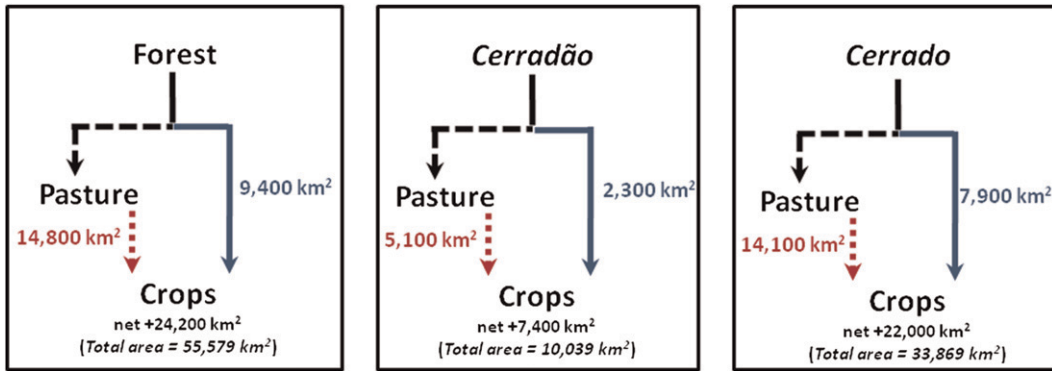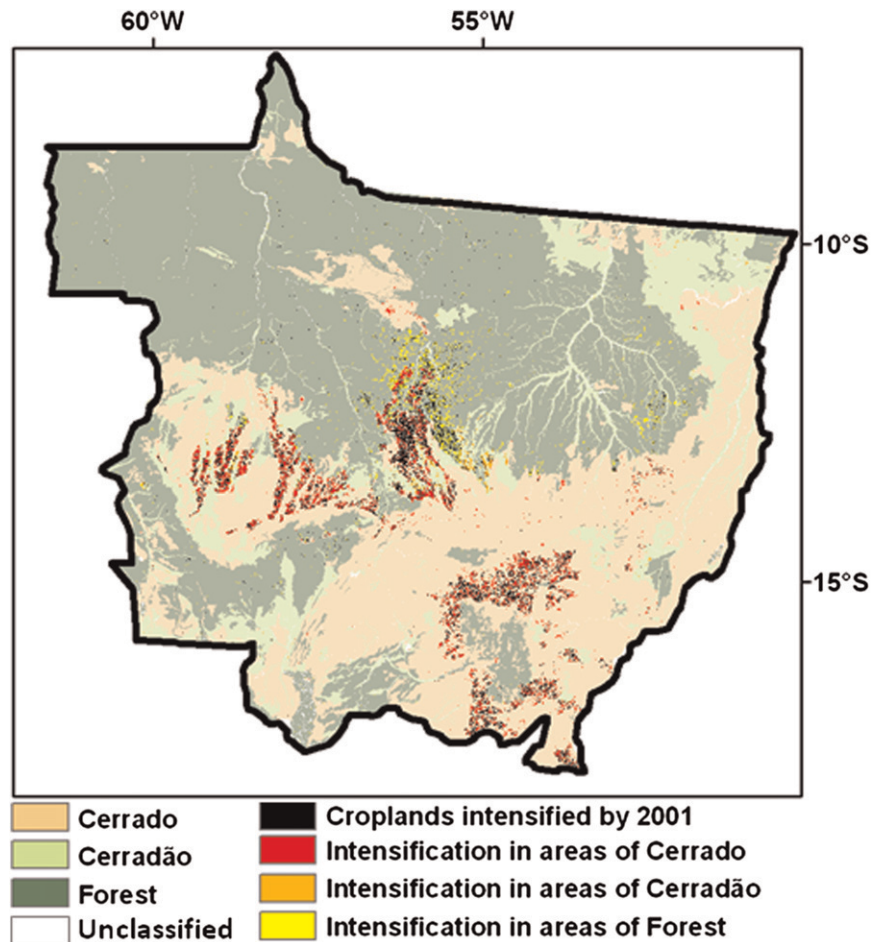
Figure 6. Transitions to croplands detected with remote sensing from 2001 to 2006. The two primary cropland development paths analyzed in this paper (transitions of natural ecosystem directly to cropland or pasture to cropland) are illustrated for each of the natural ecosystems of origin. The net cropland is total increase in cropland area from either land-use trajectory. The total area is the cropland area in 2006 that came from either trajectory. Also, see Table 4 for annual transition rates.

growing agricultural regions in the world. This and previous studies in the Amazon frontier have documented rapid land-use change for pastures and croplands and point out the differing land-use trajectories within the region (Brown et al. 2007; Galford et al. 2008; Morton et al. 2006). Here, we show that remote sensing techniques track landscape-level processes of cropland extensification and double-cropping intensification with temporal and spatial detail not provided by census or agricultural surveys. We document that the average annual rate of agricultural extensification (0.47% increase each year) doubled from the 1990–96 annual rate (0.24%) reported in the agricultural census data (IBGE 2009). We estimate slightly higher rates of forest conversion to cropland (average >1500 km^2 yr^{-1}) as compared to previous studies (average 1350 km^2 yr^{-1}; Morton et al. 2006). This could

Table 4. The relative importance of pasture-to-cropland transitions as a percentage of all transition in each of the three major biomes in Mato Grosso. The year of conversion is the year prior to the first crop harvest. For example, an area converted in 2005 would first be harvested in 2006, so only conversions between 2001 and 2006 are reported here. See Figure 4 for net (area) transitions along each land-use trajectory.

Year of conversion	Pasture-to-cropland transitions (percent of all cropland transitions)		
Natural ecosystem of origin	Cerrado	Cerradão	Forest
2002	60	67	64
2003	66	65	60
2004	82	78	68
2005	42	67	53
Annual avg	63	69	61
Std dev	17	6	6

Figure 7. Agricultural cropland intensification is mapped by natural ecosystem of origin, where intensification is the transition from noncroplands or single-cropping patterns to double-cropping patterns between 2001 and 2006.

be for several reasons; our remote sensing algorithm is more specifically tuned for crop detection, we use different land-cover datasets to define the forest biomes, and the years included in the study are slightly different. Our analysis confirms that most lands moved into croplands do not revert to pasture or natural vegetation; in fact, as suggested by Rudel et al. (Rudel et al. 2005), croplands show little reversal to natural vegetation at least over the period studied in this region.

We observe high interannual variability in intensification and extensification rates within each biome. Extensification was particularly high between the years 2002 and 2003 and occurred mainly in cerrado areas. The cerrado is favorable for extensification for two reasons. First, it has some of the oldest croplands in the state, and existing croplands serve as nucleation centers for new cropland because infrastructure is already in place and farm equipment is easily moved between fields. Second, it is easier to clear cerrado than it is to clear cerradão or forest,
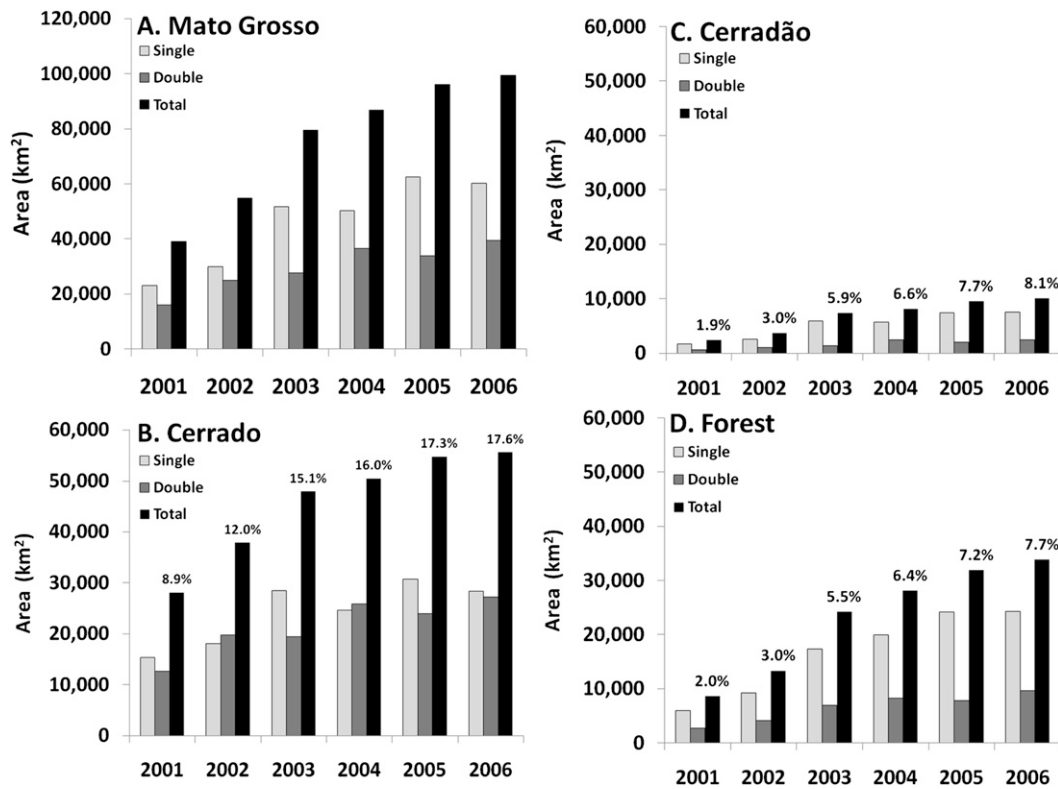
Figure 8. Cropland area and single- and double-cropping patterns from 2001 to 2006 for (a) Mato Grosso and each natural ecosystem of origin: (b) cerrado, (c) cerradão, and (d) forest.

because cerrado has lower above-ground biomass and smaller root structures, which make it easier to clear for croplands.

Extensification rates for cerrado-to-cropland transitions slow in 2005 and 2006, whereas double-cropping intensification continues to increase. The increased double cropping in cerrado may be due to a shift in the relative profits from Brazilian soybeans dropping with the falling Brazilian currency in 2004 (Nepstad et al. 2006), which likely made intensification more cost effective than extensification at that time. Further, double cropping is more widespread in the cerrado than in other biomes, because double-cropping intensification generally occurs a few years after extensification and there is a longer history of extensification in the cerrado (primarily southern Mato Grosso). For croplands from areas of forest and cerradão, extensification continues steadily, whereas intensification rates remain low. Existing croplands from the forest and cerradão biomes represent a potential target for intensification that follows environmentally sound production guidelines.

The process of cropland development is dynamic and the land-cover and land-use change story does not stop at land clearing. Suitable areas for mechanized croplands need to be large and amenable to large-scale mechanized agriculture: for
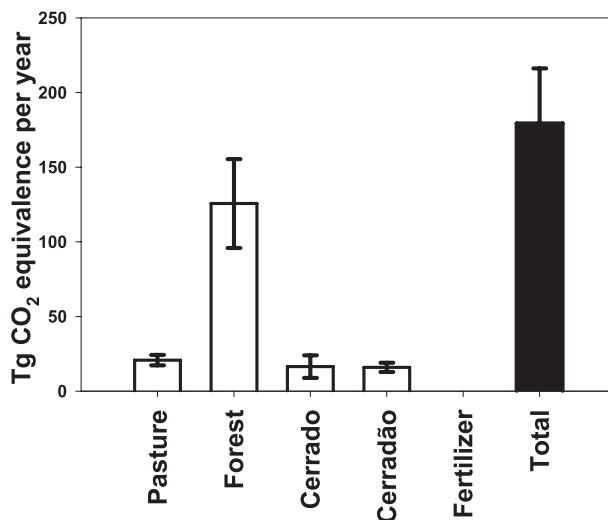
Figure 9. Greenhouse gas emissions from biomass loss and fertilizer additions. Pasture represents cropland extensification into areas of pasture that were previously created from areas of native vegetation. The range of emissions comes from a low, mid-, and high range of biomass estimates (Table 4).

example, fairly level topography (Jasinski et al. 2005). Lands are cleared through slash and burn until there are no roots or slash to foul machinery. To prepare for planting crops, soils may be amended with lime to reduce the aluminotoxicity; fertilized with nitrogen, phosphorus, and potassium; and often planted for 1–2 years with upland rice (Barbosa Filho and Yamada 2002; Fundação Agrisus 2006; Sanchez et al. 1982). The large-scale nature of croplands in the Amazon frontier is coupled both to scale dependence of profitable farming and the investors who will encourage that scale. From our observations, extensification of new single crops largely proceeds by expanding into adjacent lands rather than leaping to new

Table 5. Total annual greenhouse gas budget (CO_2-e emissions yr^{-1}) for Mato Grosso accounting for conversions to pasture and cropland, pasture maintenance, and methane emissions from cattle. This budget accounts for cattle emissions using a mean emission rate of 55 kg methane per head (Steudler et al. 1996) and a cattle herd of 19 600 000 for Mato Grosso (IBGE 2009).

Emissions estimate		Tg CO_2-e yr^{-1}
DeFries et al. 2008	Conversion of forest to pasture (CO_2, CH_4)	199.7
Galford et al. (this paper)	Conversion of pasture and natural ecosystems to cropland (CO_2, CH_4)	178.9
DeFries et al. 2008	Pasture maintenance (fire; CO_2)	22.0
After Steudler et al. 1996	Cattle herd (CH_4)	21.5
Galford et al. (this paper)	Cropland fertilization (N_2O)	0.4
Total		422.5

Table 6. Comparison of select major components of the carbon cycle in Brazil.

Region	Greenhouse gas source	Tg C yr^{-1}	Year of estimate	Reference
Brazil	Fossil fuels	89	2005	Boden et al. 2008
Amazon	Forest clearing	116	2006	Ministry of Science and Technology 2006
	Cerrado clearing	52	2006	Ministry of Science and Technology 2006
	Ecosystem dynamics driven by remotely sensed phenology	70, 130	2000, 2002	Potter et al. 2009
	Amazon fire emissions, including deforestation	200–500	2003	Van der Werf et al. 2003
	Deforestation	100	1989–98	Houghton et al. 2000
Mato Grosso	Cropland extensification	46	2000–06	—

development distant from the previous cropland activity centers. This spatial clumping is highly evident in the cerrado region, where most croplands have been concentrated. We see that double cropping is commonly carried out in the densest regions of mechanized croplands, not outlying regions that are newly established. Double-cropping patterns (soy–corn) typically emerge after several years of single cropping (soy). The time lag of extensification explains why the highest rates of double cropping are found in the cerrado, because this is the oldest cropland region in the state and holds the greatest amount of cropland by bioregion.

4.2. Greenhouse gas consequences

Land-use changes across the globe have contributed 35% of anthropogenic CO_2 emissions over the last 150 years (Foley et al. 2005). In the global context, Mato Grosso accounts for over 2% of the contemporary global greenhouse gas emissions from land-cover and land-use changes (Denman et al. 2007) while comprising less than 1% of the Earth's land surface. Annual greenhouse gas emissions from land-use extensification in Mato Grosso are equivalent to over half the Brazilian carbon emissions from fossil fuel burning and over 25% of all carbon emissions from Amazonian deforestation and from cerrado clearing (Table 6). Mato Grosso cropland extensification alone contributes at least half of the estimated CO_2 losses from all biomass burning throughout Southern Hemisphere South America (Van der Werf et al. 2006). Our estimates show that methane emissions from biomass burning are small but account for roughly 10% of the greenhouse gas forcing of carbon emissions. Pasture is still the dominant land use in the Amazon and Mato Grosso, but this work shows new clearing for cropland extensification accounts for almost half of Mato Grosso's total greenhouse gas budget (Table 5). If current trends in land-use change continue, cropland extensification may become the largest regional source of greenhouse gas emissions.

Greenhouse gas emissions in Mato Grosso related from N fertilizer in croplands are quite small today, totaling just 0.4 Tg CO_2-e yr^{-1}. Depending on shifting crop types, fertilizer prices, and management strategies that affect soil fertility and/or nitrogen-use efficiency, there is potential for these emissions to grow substantially. Regional field trials show diminishing returns on increasing fertilizer application

(Mar et al. 2003; Souza and Sorrato 2006), suggesting increasing N fertilization in this region may lead to increased N_2O emissions without a proportional increase in crop productivity. We lack information on N_2O production from soybean fields and how this changes over time (e.g., years planted in soy).

Remaining uncertainties in the total greenhouse gas budget could be clarified through total cost accounting that includes emissions from termite mounds; other animal sources; and postclearing soil biogeochemistry dynamics of based on management, such as the impacts of tillage practices on soil carbon storage (Cerri et al. 2004).

4.3. Ecosystems consequences

This work provides information on the mosaic of landscape heterogeneity, land-cover types, and length of crop cover as it changes with single and double cropping that may be useful in future climate modeling efforts. These large-scale changes in land cover in the Amazon have distant teleconnections in the global climate system (e.g., increased precipitation in the U.S. Midwest; Avissar and Werth 2005). Climate research in the Amazon shows that, locally, cleared lands adjacent to natural ecosystems can alter convection patterns, leading to increased dry season cloud cover, increased high energy storms, and stronger storm clouds (Ramos da Silva et al. 2008; Baidya Roy and Avissar 2002). Croplands may have negative feedbacks to their own microclimate, as models show low stature vegetation becomes drier and warmer than the original natural ecosystems (Costa et al. 2007).

Land-use changes also affect the bidirectional relationship between biodiversity and ecosystem function. Here, we document the rate of disappearance of natural ecosystems and provide information on changes in cropland area that may be used to estimate impacts on biodiversity, while adding richness in understanding trade-offs between agricultural development and natural ecosystem conservation. Species gains and losses related to changing habitats may alter ecosystem function. There are several ecosystems characteristics related to biodiversity that could be assessed with remote sensing methods. It is imperative to note that conservation of these uniquely diverse ecosystems and their associated species biodiversity is important in its own right and that ecosystem function and climate regulation are only a few of many additional reasons for conservation.

The agricultural mosaic of land use and the dynamic nature of croplands affect environmental and agricultural sustainability. The landscape configuration can have cascading affects on surrounding intact ecosystems. Information on land-use configurations in the matrix of natural land covers can be applied in conservation work to reduce environmental impacts, such as in protecting waterways and wildlife corridors (Green et al. 2005). The agricultural dynamics we observe suggest that cropland extensification and intensification will likely continue in this region through the coming decades. Thus, conservation priorities must focus on 1) increasing double cropping over new extensification to reduce the regional carbon emissions and preserve other ecosystem services while responding to global product demand and 2) understanding and communicating best management practices for croplands that synergistically reduce the environmental impact of croplands and increase farm production.

5. Conclusions

As suggested by Morton et al. (Morton et al. 2006), new land clearing for croplands is an emerging force that is rapidly increasing in the Brazilian agricultural frontier. We have verified this trend using a new set of detection algorithms, while enhancing the story of cropland dynamics, by tracking single crops maturing to double-cropping patterns. Intensification through double cropping is emerging as a new and major component of regional land uses, with rapid increases along with extensification. Information from remote sensing on the location and extent of cropping patterns is a useful addition to other datasets, such as deforestation detections and crop surveys conducted by the Brazilian government. There are a wide range of applications and implications from these cropland dynamics. Here, we estimate the greenhouse gas implications of cropland extensification and intensification; however, to assess the environmental impacts more comprehensively, we need to consider the consequences of these cropland changes for local and regional climate, hydrology, and biodiversity.

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