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LETTER

Forest carbon emissions from cropland expansion in the Brazilian Cerrado biome

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Abstract

Land use, land use change, and forestry accounted for two-thirds of Brazil's greenhouse gas emissions profile in 2005. Amazon deforestation has declined by more than 80% over the past decade, yet Brazil's forests extend beyond the Amazon biome. Rapid expansion of cropland in the neighboring Cerrado biome has the potential to undermine climate mitigation efforts if emissions from dry forest and woodland conversion negate some of the benefits of avoided Amazon deforestation. Here, we used satellite data on cropland expansion, forest cover, and vegetation carbon stocks to estimate annual gross forest carbon emissions from cropland expansion in the Cerrado biome. Nearly half of the Cerrado met Brazil's definition of forest cover in 2000 ($\geq$0.5 ha with $\geq$10% canopy cover). In areas of established crop production, conversion of both forest and non-forest Cerrado formations for cropland declined during 2003–2013. However, forest carbon emissions from cropland expansion increased over the past decade in Matopiba, a new frontier of agricultural production that includes portions of Maranhão, Tocantins, Piauí, and Bahia states. Gross carbon emissions from cropland expansion in the Cerrado averaged 16.28 Tg C yr^{-1} between 2003 and 2013, with forest-to-cropland conversion accounting for 29% of emissions. The fraction of forest carbon emissions from Matopiba was much higher; between 2010–2013, large-scale cropland conversion in Matopiba contributed 45% of total Cerrado forest carbon emissions. Carbon emissions from Cerrado-to-cropland transitions offset 5%–7% of the avoided emissions from reduced Amazon deforestation rates during 2011–2013. Comprehensive national estimates of forest carbon fluxes, including all biomes, are critical to detect cross-biome leakage within countries and achieve climate mitigation targets to reduce emissions from land use, land use change, and forestry.

Introduction

Deforestation is an important source of global greenhouse gas emissions from human activity (Van Der Werf *et al* 2009a, 2009b, Le Quéré *et al* 2015). For tropical forest countries such as Brazil, carbon emissions from deforestation account for a large proportion of total greenhouse gas emissions (42% of

CO_2 emissions in 2010, BRAZIL 2016). Efforts to Reduce Emissions from Deforestation and Forest Degradation (REDD+) are therefore a critical component of climate mitigation activities (UNFCCC 2015, Morton 2016). Over the past decade, deforestation in the Brazilian Amazon declined by 80% (BRAZIL 2014), highlighting the potential for government, industry, and non-governmental

organizations to achieve emissions reductions from forest regions (e.g. Soares-Filho *et al* 2014, Gibbs *et al* 2015). However, forest cover in Brazil extends beyond the Amazon biome, and rapid expansion of agricultural production in other forested regions may offset some of the climate benefits of recent reductions in Amazon deforestation. The success of REDD+ efforts therefore depends on complete national accounting of forest cover changes, including emissions from Cerrado forest conversion processes.

The Cerrado biome is a vast neotropical savanna ecosystem in South America covering more than 2 million km^2, second only to the Amazon in terms of size. A biodiversity hotspot, the Cerrado comprises a diverse mix of grasslands, shrublands, and woodlands (Felfili and Silva Júnior 2005, Klink and Machado 2005). Aboveground biomass varies by Cerrado physiognomy and fractional tree cover (Ottmar *et al* 2001, Saatchi *et al* 2011, De Miranda *et al* 2014). Large carbon stores are also found in belowground biomass and soil carbon because Cerrado vegetation allocates substantial resources to root production (De Miranda *et al* 2014). The combined above and belowground carbon stocks in Cerrado vegetation likely represent an important source term in Brazil's national greenhouse gas emissions. Yet, current reporting either excludes forest conversion in the Cerrado (BRAZIL 2014) or provides aggregated estimates for all cover types and land uses (Lapola *et al* 2014, BRAZIL 2016), complicating efforts to track regional dynamics with satellite observations of land use change or greenhouse gas emissions.

Nearly half of the Cerrado has been converted to pasture (29.5%) or cropland (11.7%) (MMA 2015), and only a small portion (8.2%) of the biome is formally protected by parks or indigenous reserves (BRAZIL 2016). Since 1990, the Cerrado region has emerged as the leading producer of major export crops, and by 2014 it accounted for the majority of Brazil's planted area in soy (61%), maize (61%), and cotton (99%) (IBGE 2013). As in the Brazilian Amazon (Morton *et al* 2006, Macedo *et al* 2012), soy production is an important driver of deforestation in the Cerrado (Gibbs *et al* 2015, Morton *et al* 2016), motivated primarily by international market demand for animal ration (Nepstad *et al* 2011, Lambin and Meyfroidt 2011, Garrett *et al* 2013, Lathuillière *et al* 2014, Godar *et al* 2015). From 2008–2012, annual deforestation rates in the Cerrado were more than double that of the Brazilian Amazon (Lambin *et al* 2013). Recent expansion has been concentrated in new agricultural frontiers, including the Matopiba region that encompasses portions of Maranhão, Tocantins, Piauí, and Bahia states (BRAZIL 2016, Gibbs *et al* 2015, MMA 2015, Spera *et al* 2016). The Brazilian government's Matopiba Development Plan outlines a strategy for continued agricultural expansion in the region as part of a broader initiative on low-carbon agriculture.

Recent cropland expansion in the Cerrado region also reflects important changes in environmental legislation and industry efforts to reduce Amazon deforestation. The Forest Code (FC) is a key component of Brazil's environmental legislation (Soares-Filho *et al* 2014), with specific guidelines for legal reserves of natural vegetation on private properties in the Amazon (80%) and Cerrado (35% within the Legal Amazon, 20% for Cerrado outside the Legal Amazon). Changes to the FC legislation in 2012 removed permanent protection of 'hill top' areas, opening large areas of the Matopiba region for potential land use (Soares-Filho *et al* 2014, Hunke *et al* 2015). The Soy Moratorium (SoyM), an industry-led effort to reduce Amazon deforestation for soy production, contributed to marked reductions in Amazon deforestation (Macedo *et al* 2012, Gibbs *et al* 2015), but did not address forest conversion in the neighboring Cerrado biome.

Together, the SoyM and the new FC legislation altered the dynamics of soy expansion in the Brazilian Amazon and incentivized production in other regions (i.e. 'cross-biome leakage'), including the Cerrado, where the SoyM is not implemented and the FC allows a larger fraction of individual properties to be converted for agriculture. The Brazilian government has also instituted new policies for Cerrado protection. The Action Plan for Prevention and Control of Deforestation and Burning in the Cerrado (PPCerrado; MMA 2011, 2014) has a goal to reduce Cerrado deforestation by 40% by 2020 compared to mean deforestation during 1999–2008 (15,702 km^2), based on targeted programs to promote sustainable practices and forest restoration in accordance with the FC. In addition to these legal constraints, older frontiers of soy expansion (e.g. Mato Grosso) have few remaining flat lands suitable for large-scale grain production (Morton *et al* 2016), driving soy producers to alternative frontiers.

Here, we combined satellite remote sensing data on recent cropland expansion and vegetation carbon stocks to estimate gross forest carbon emissions from cropland expansion in the Cerrado. Our work addresses three primary questions in the context of complete carbon accounting for REDD+ (Bustamante *et al* 2016, Morton *et al* 2011) and global carbon emissions from land use change (Le Quéré *et al* 2015): (1) Is cropland expansion an important driver of forest conversion in the Cerrado? (2) What are the carbon emissions associated with forest and non-forest conversion for cropland? (3) To what extent do carbon emissions from forest conversion in the Cerrado offset emissions reductions from declining Amazon deforestation? Satellite-based estimates of annual cropland expansion provide critical insights into the spatial and temporal dynamics of land use emissions in the Cerrado. Expanding estimates of tropical forest carbon emissions beyond the Amazon biome is a critical step to improve regional and global carbon budgets, as Cerrado emissions contribute directly to fire carbon losses observed by regional

atmospheric inversion studies (Gatti *et al* 2014, Alden *et al* 2016) and global observing networks (e.g. Keppel-Aleks *et al* 2014).

Materials and methods

Cropland expansion 2003–2013

Annual estimates of cropland expansion in the Cerrado were developed using time series of Moderate Resolution Imaging Spectroradiometer (MODIS) data at 250 m resolution from NASA's Terra satellite (Gibbs *et al* 2015, Morton *et al* 2016). Although soy is an important driver of recent agricultural expansion in the Cerrado (IBGE 2013), mapped cropland in this study included all mechanized agriculture based on phenology metrics associated with planting and harvesting row crops, similar to previous studies of cropland dynamics in Brazil (Morton *et al* 2006, Galford *et al* 2008, Rudorff *et al* 2011, Macedo *et al* 2012). Time series of MODIS data capture the year-to-year changes in cropland extent—changes that cannot be estimated using land cover classification data from a single year. A 2-year temporal filter for consecutive cropland classification was used to minimize false detection of cropland cover types; cropland classification accuracy ranged from 76% (TerraClass-2010 field photos) to 94% (INPE air photos). A detailed description of the land cover change analysis can be found in Gibbs *et al* (2015).

Cropland expansion and carbon emissions

We combined annual estimates of cropland expansion with data on percent tree cover and vegetation carbon stocks to estimate gross carbon emissions. Forest and non-forest emissions were separated using fractional tree cover data (Hansen *et al* 2013). For reporting purposes, Brazil defines 'forest' as land spanning more than 0.5 hectares, with trees higher than 5 meters and a canopy cover of more than 10 percent (BRAZIL 2014). Based on this definition, we used a threshold of 10% canopy cover to separate forests and other wooded land areas (>10%) from non-forest areas (≤10%) in the Cerrado using Landsat-based estimates of fractional tree cover from Hansen *et al* (2013). Passive optical satellite data have little sensitivity to vegetation height; Landsat or MODIS-based estimates of fractional tree cover may therefore differ from forest areas identified using field or lidar-based estimates of tree heights ≥5 m.

Carbon emissions from cropland expansion were estimated using two approaches. In the first approach (hereafter 'satellite'), vegetation carbon stocks for Cerrado vegetation were estimated using a satellite data product from Saatchi *et al* (2011) in areas of cropland expansion. Saatchi *et al* (2011) used satellite data to model pantropical vegetation carbon stocks through 2005, including radar data with specific sensitivity to lower aboveground carbon stocks in

savanna and woodland cover types. For cropland expansion after 2005, we calculated emissions using spatially-explicit estimates of vegetation carbon stocks from Saatchi *et al* (2011) in areas of cropland expansion. For cropland expansion prior to 2005, we used the relationship between 2000 Landsat fractional tree cover estimates (Hansen *et al* 2013) and Saatchi *et al* (2011) biomass estimates for remaining areas of natural Cerrado vegetation (MMA 2015) to estimate pre-conversion vegetation carbon stocks based on fractional tree cover in 2000. We propagated uncertainties in vegetation carbon stocks (Saatchi *et al* 2011) into carbon loss estimates, scaling the total emissions estimates using the annual average carbon stock uncertainty from cropland expansion pixels each year.
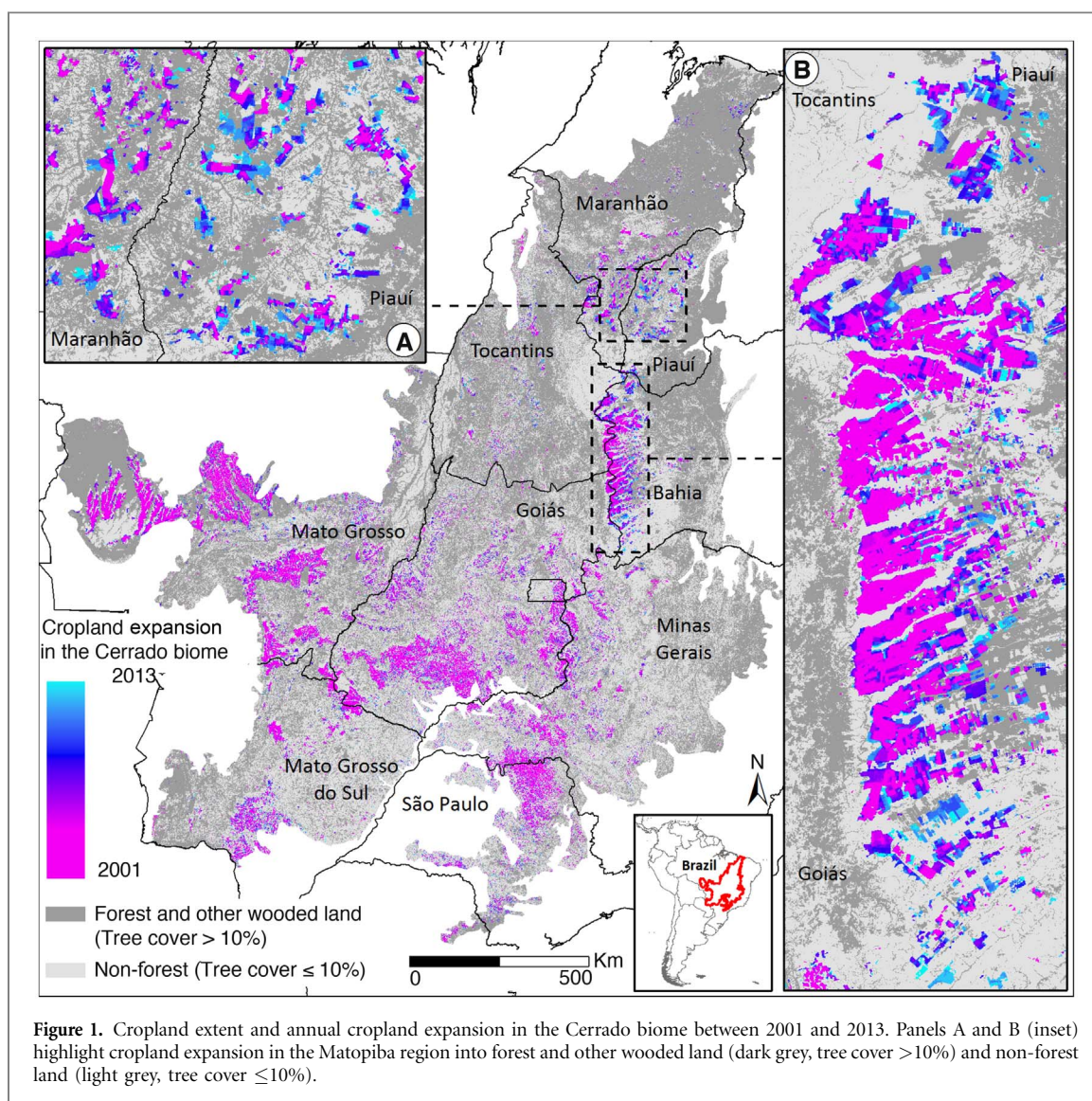
We compared carbon stock estimates from Saatchi *et al* (2011) to field measurements for each tree cover interval. Satellite-based estimates of aboveground biomass compared favorably to field estimates from Ottmar *et al* (2001), binned by fractional tree cover (figure S1). Saatchi *et al* (2011) used a root:shoot ratio that scales with aboveground biomass (AGB) to estimate belowground biomass (BGB) and total vegetation carbon stocks:

$$BGB = 0.489AGB^{0.89}$$

For low-biomass cover types (1–5 Mg ha^{-1}), this relationship yields a root:shoot ratio over 40%, while the root:shoot ratio ranges from 25%–30% for high-biomass cover types (75–300 Mg ha^{-1}). A recent synthesis of Cerrado field data suggests that average root:shoot ratios could be much higher for grasslands (334%) and shrublands (166%) with intermediate tree cover (De Miranda *et al* 2014). Satellite-based estimates of total vegetation carbon stocks (i.e. combined above and below-ground biomass) are likely conservative, especially for shrubland and grassland Cerrado cover types.

The second approach (hereafter 'look-up table') to estimate gross carbon emissions from cropland expansion in the Cerrado used the look-up table based on aboveground biomass (Ottmar *et al* 2001) and root:shoot ratios (De Miranda *et al* 2014) for different fractional tree cover intervals (figure S1). Pre-conversion carbon stocks in areas of cropland expansion were based on fractional tree cover in 2000 and the associated look-up table estimate of vegetation carbon stocks. The look-up table approach preserves the influence of higher root:shoot ratios in field data for gross carbon emissions.

Estimated gross carbon emissions from cropland expansion included both above and belowground biomass. Mechanized crop production requires the complete removal of above and belowground woody biomass, typically through repeated burning of piled woody debris (Defries *et al* 2008, Morton *et al* 2008, Van Der Werf *et al* 2009a). Gross and net carbon

Figure 1. Cropland extent and annual cropland expansion in the Cerrado biome between 2001 and 2013. Panels A and B (inset) highlight cropland expansion in the Matopiba region into forest and other wooded land (dark grey, tree cover >10%) and non-forest land (light grey, tree cover ≤10%).

emissions from deforestation for cropland are therefore similar, as long-term carbon storage in annual crops is small (Defries *et al* 2008). Gross carbon emissions estimates excluded changes in soil carbon pools. Soil carbon stocks in Cerrado cover types are large, but recent studies suggest small net carbon losses following agricultural conversion (Cerri *et al* 2009, Batlle-Bayer *et al* 2010, Mello *et al* 2014, Bustamante *et al* 2012, 2016), in part due to the widespread practice of no-till agriculture.

To evaluate the impact of recent Cerrado land use changes on Brazil's carbon budget, we compared gross carbon emissions from cropland expansion in the Cerrado to gross carbon emissions from deforestation in the Brazilian Amazon. Estimated carbon losses for both biomes represent 'committed' emissions based on changes in vegetation carbon stocks, without accounting for time-dependent carbon releases from fire and decomposition. For 2003–2010, we used data from Brazil's forest reference emissions level (FREL) report to the United Nations Framework Convention on Climate Change (UNFFCCC; BRAZIL 2014). For 2011–2013, we estimated deforestation carbon emis-

sions using the average vegetation carbon stocks from deforestation in 2003–2010 (153 Mg ha^{-1}) and annual deforestation estimates from PRODES (table S1, BRAZIL 2014). In 2011-2013, forest carbon emissions from Amazon deforestation declined relative to the 2011–2015 baseline (247.63 Tg C yr^{-1}, BRAZIL 2014). To quantify how much gross carbon emissions from cropland expansion in the Cerrado offset these declines, we estimated the difference between deforestation carbon emissions and the 2011–2015 baseline.

Results

Cropland expansion

Cropland expansion in the Cerrado biome was widespread over the decade from 2003–2013, totaling more than 9 Mha, of which 1.73 Mha replaced forests and other wooded lands (table S1). In the first half of the decade, cropland expansion was concentrated in areas of established production in the south and west (figure 1). Since 2008, frontiers of cropland expansion
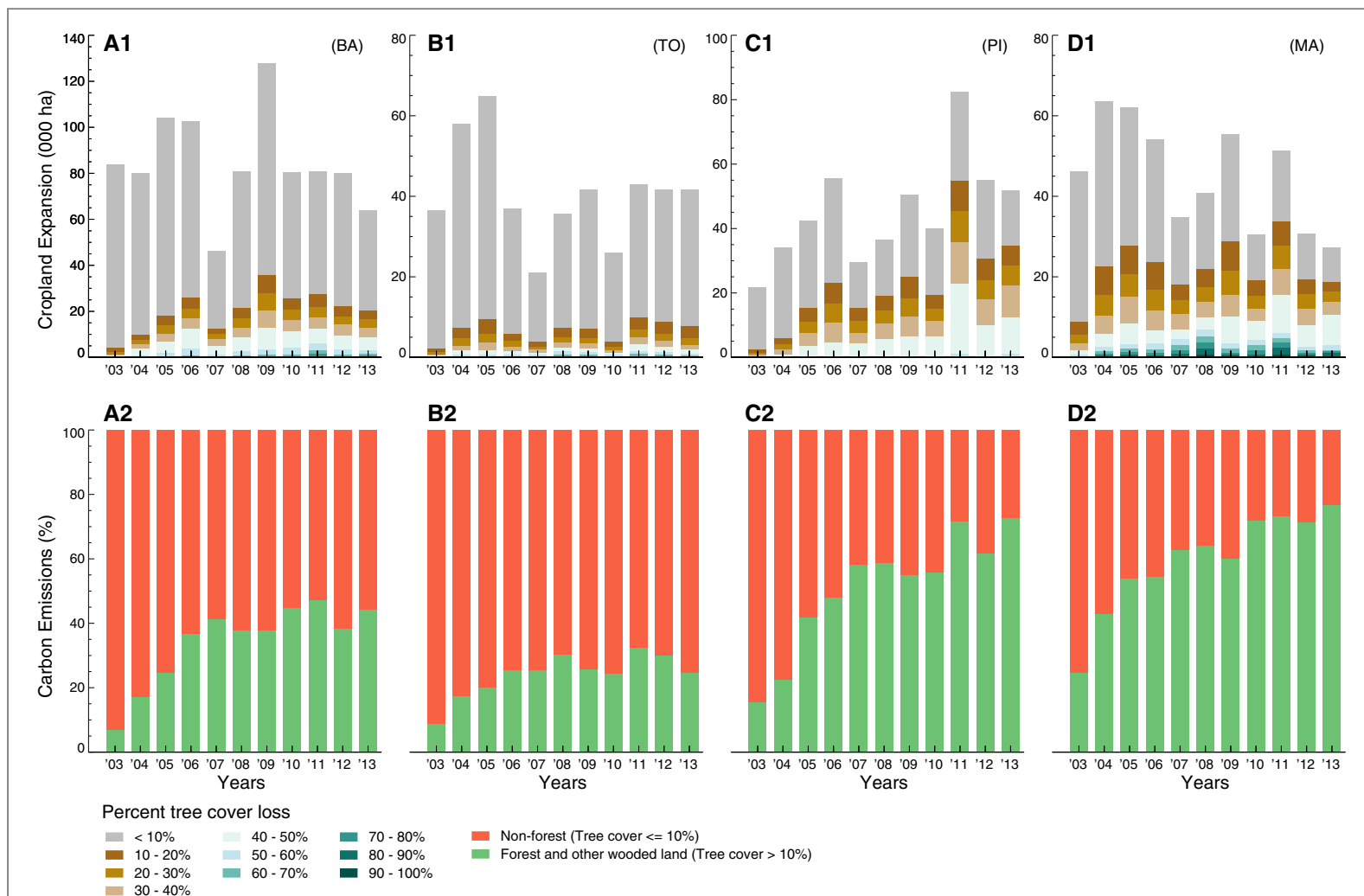
Figure 2. Cropland expansion and related carbon emissions in the Matopiba region between 2003–2013. A1–D1) Annual cropland expansion and associated fractional tree cover loss; A2–D2) Breakdown of estimated annual gross carbon emissions from cropland expansion into non-forest (tree cover ≤10%) and forest and other wooded land (tree cover >10%). States are labeled as Bahia (BA), Tocantins (TO), Piauí (PI), and Maranhão (MA).

shifted eastward to the Matopiba region, which accounted for 14% of all cropland expansion during the latter half of the decade, including 30% of cropland expansion into forest. MODIS-based estimates of total cropland area in 2013 were 15% lower than estimates from TerraClass, a Landsat-based land cover classification. These differences were attributable to the coarser spatial resolution of MODIS data (250 m versus 30 m) and conservative spatio-temporal filtering used in the MODIS approach (Gibbs *et al* 2015).

Overall, woody cover was not a strong barrier to cropland expansion in the Cerrado. On average, approximately 21% of the annual cropland expansion replaced forests and woodlands (table S1). In Matopiba, however, forest conversion accounted for a larger fraction of new cropland (figure 2), especially in the states of Maranhão (51%) and Piauí (46%). Annual rates of cropland expansion in Matopiba remained consistent during this period, with steady increases in forest conversion for cropland expansion even as cropland expansion declined in other Cerrado regions (figure S2).

Gross carbon emissions from cropland expansion

Conversion of forest and non-forest Cerrado formations for cropland expansion was an important source of carbon emissions during 2003–2013. In the satellite-based estimate, conversion of forests and other wooded lands accounted for 29% (52 Tg C) of estimated total carbon emissions from cropland expansion in the Cerrado biome, compared with 127 Tg C (71%) from conversion of non-forest Cerrado physiognomies during the study period. Annual emissions from forest and non-forest conversion averaged 16.3 Tg C yr^{-1}, with considerable interannual variability due to changes in the rates of cropland expansion and the proportion of forest cover types converted (table S1, figure 3). Average annual emissions from forest conversion for cropland were 4.69 Tg C yr^{-1} (table S2).

Emissions estimates using the look-up table approach (figure 3) were somewhat higher than using satellite data on vegetation carbon stocks from Saatchi *et al*. Field data suggest a greater allocation to belowground biomass by Cerrado vegetation than estimated by Saatchi *et al*, leading to higher vegetation carbon stocks for each fractional tree cover bin (figure S1). As a result, average carbon emissions estimates based on the look-up table approach were 1.09 Tg C yr^{-1} (18.9%) and 4.22 Tg C yr^{-1} (29.3%) higher for conversion of forest and non-forest Cerrado areas, respectively.

The Matopiba region accounted for 33% of forest carbon emissions from cropland expansion in the Cerrado during 2003–2013 (17 Tg C, table S2). Between 2010–2013, Matopiba accounted for a greater proportion of forest carbon emissions (45%), with the largest contributions from Maranhão (14.42%)—a
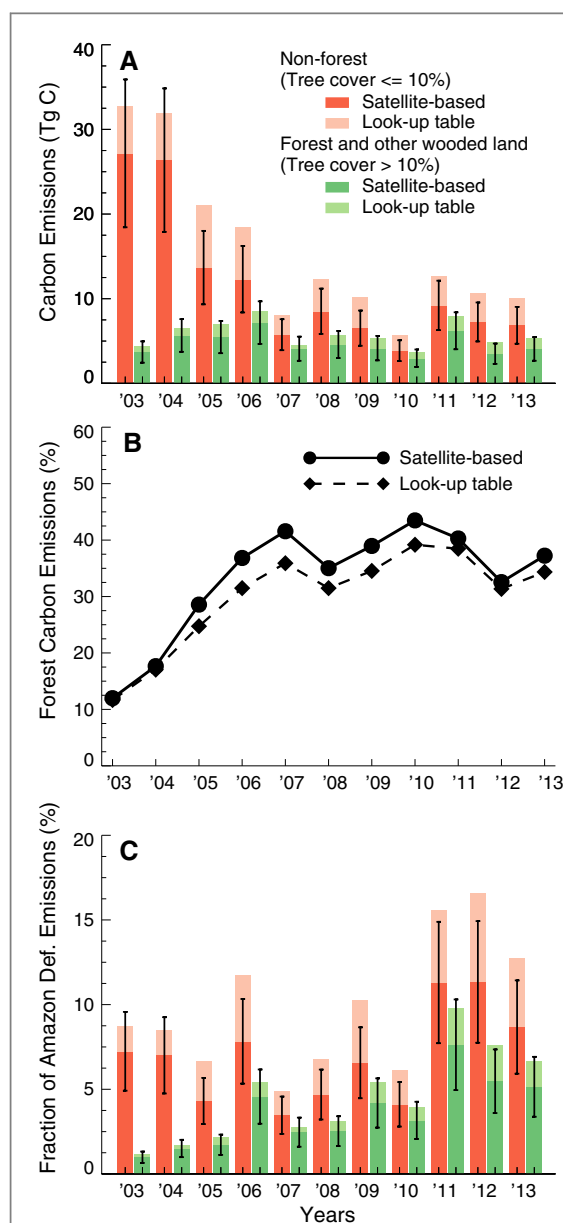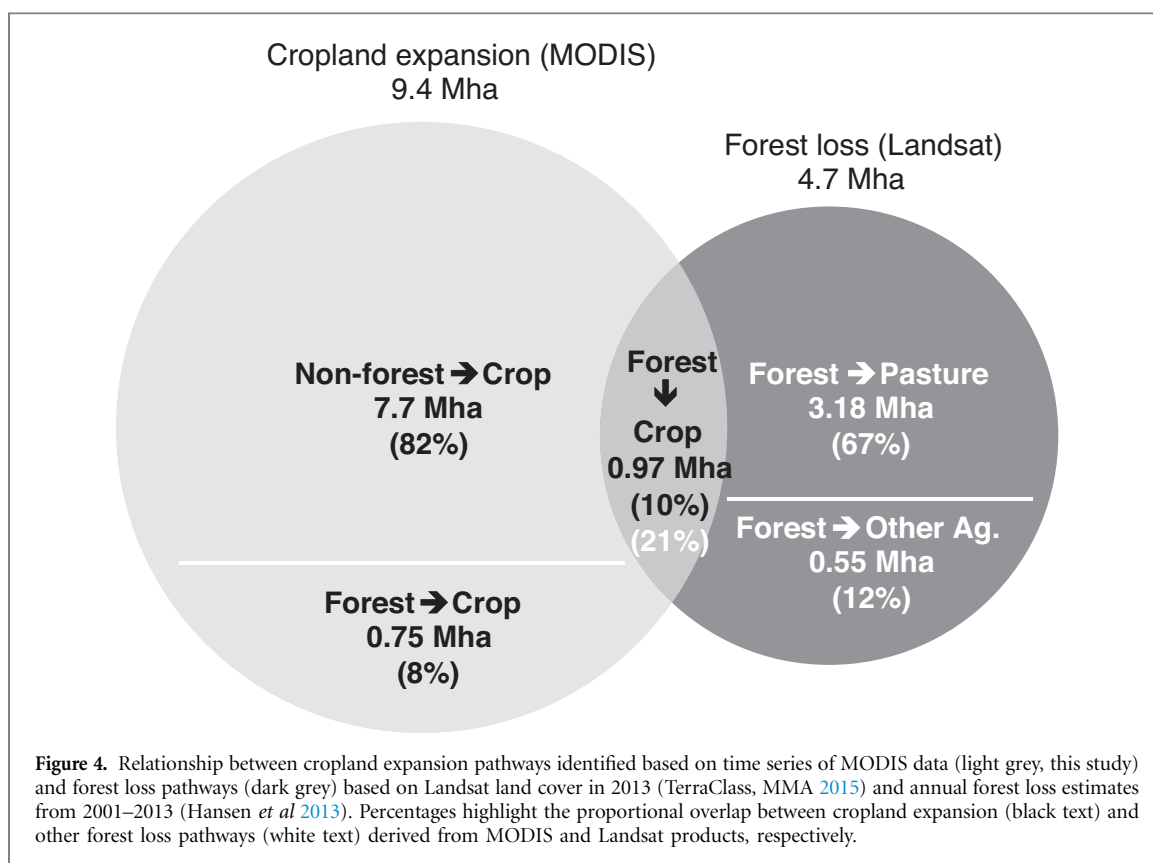

Figure 3. (*a*) Satellite-based and look-up table estimates of annual gross carbon emissions from cropland expansion into non-forest (orange) and forested (green) Cerrado cover types between 2003 and 2013. Error bars indicate ± average uncertainty in satellite-based vegetation carbon stocks within cropland expansion areas. (*b*) Fractional contribution of forest conversion to gross carbon emissions from cropland expansion in the Cerrado. (*c*) Comparison between gross carbon emissions from cropland expansion in the Cerrado and emissions from Amazon deforestation.

state with higher biomass at the transition between the Cerrado and Amazon biomes.

Forest-to-cropland transitions in the Cerrado biome partially offset reductions in Amazon deforestation emissions over the past decade. In a direct comparison of gross carbon emissions across biomes during 2011 to 2013, annual forest carbon emissions from cropland expansion in the Cerrado were more than 6% of estimated carbon emissions from Amazon deforestation (figure 3). Satellite and look-up table estimates of Cerrado forest carbon stocks, including uncertainty in above and belowground biomass

Figure 4. Relationship between cropland expansion pathways identified based on time series of MODIS data (light grey, this study) and forest loss pathways (dark grey) based on Landsat land cover in 2013 (TerraClass, MMA 2015) and annual forest loss estimates from 2001–2013 (Hansen *et al* 2013). Percentages highlight the proportional overlap between cropland expansion (black text) and other forest loss pathways (white text) derived from MODIS and Landsat products, respectively.

(figure S1), bound the emissions range for 2011–2013 at between 4% and 8.3% of carbon emissions from Amazon deforestation. Cropland expansion into Cerrado vegetation, including all forest and non-forest cover types, added 16% to 19% to estimated carbon emissions from Amazon deforestation since 2011, with higher estimates from the look-up table approach (see figure 3).

Gross carbon emissions from cropland expansion in the Cerrado can also be compared to recent reductions in emissions from declining Amazon deforestation, calculated based on performance against the reference level C of historic emissions. Compared to Brazil's baseline deforestation emissions for 2011–2015 (247.63 Tg yr^{-1}, BRAZIL 2014), declines in Amazon deforestation reduced gross carbon emissions in 2011–2013 by an average of 74.82 Tg C yr^{-1}. Forest carbon emissions from cropland expansion in the Cerrado offset 1.9% of these emissions reductions during 2011–2013, and combined emissions from all Cerrado-to-cropland transitions offset 5% of emissions reductions in the Brazilian Amazon in these years. Estimated emissions from the look-up table approach were slightly higher, with combined forest and non-forest transitions offsetting 7% of avoided Amazon deforestation carbon emissions.

Forest conversion for cropland is only one pathway of forest loss in the Cerrado biome. Estimated forest carbon emissions from cropland expansion between 2003–2013 (179 ± 58.6 Tg C) are therefore a substantial underestimate of total forest carbon emissions

from all agricultural expansion in the Cerrado. Cropland expansion in this study accounted for 21% of the total forest loss identified by Hansen *et al* (2013) (figure 4). Nearly two-thirds (67%) of forest loss was associated with pasture conversion and a small proportion (12%) was related to other agricultural activities. However, not all forest-to-cropland transitions from MODIS were mapped as forest loss by Hansen *et al*. Differences between cropland expansion and forest loss estimates may reflect limitations of the annual Landsat approach to detect phenology differences during the rapid change from forest to cropland. Some of the difference may also be attributable to the coarser spatial resolution of MODIS (250 m) relative to Landsat (30 m). Monitoring approaches to track forest conversion for pasture and other land uses will therefore be critical for 'full' carbon accounting of forest cover conversion in the Cerrado and other biomes in Brazil.

Discussion

Complete carbon accounting is essential for national reporting of greenhouse gas sources and sinks and global carbon cycle studies to support climate mitigation. The Amazon and other tropical rainforest regions have been the primary target for REDD+, given high carbon stocks in tropical forests (Saatchi *et al* 2011, Baccini *et al* 2012) and rapid deforestation for agricultural expansion in recent decades (Hansen *et al* 2013, Kim *et al* 2015, Morton *et al* 2016). Forest

conversion in other tropical biomes has received less national and international attention, despite growing evidence of concentrated cropland expansion in dry tropical forest regions (e.g. Aide *et al* 2013, Lambin *et al* 2013, Graesser *et al* 2015, Baumann *et al* 2016).

In the Cerrado, emissions from large-scale cropland expansion totaled 179 Tg C between 2003–2013. During the study period, the fraction of annual emissions from forest conversion increased from 12% to 37%, driven by a shift in cropland expansion to the Matopiba region and a steady increase in the proportion of forest conversion for cropland expansion. Over the same period, the fraction of annual emissions from forest conversion in the Matopiba region increased from 13% to 56%. Similar contributions from cropland expansion to forest carbon emissions have been documented for other dry forest regions, including the Chaco in Argentina, Paraguay, and Bolivia (Baumann *et al* 2016).

The decline in Amazon deforestation since 2005 underscores the importance of Cerrado emissions. Cerrado cropland expansion during 2011–2013 added an estimated 6% (forest) and 16% (combined forest and non-forest transitions) to total Amazon carbon emissions. As a result, Cerrado conversion for cropland offset 5%–7% of the estimated emissions reductions from avoided Amazon deforestation, calculated relative to the 2011–2015 baseline (reference emissions level). Given that cropland expansion only accounted for one-fifth of forest loss between 2003–2013, total forest carbon emissions from the Cerrado constitute a substantial and growing part of Brazil's national greenhouse gas budget and should be included in regional estimates of deforestation and fire emissions (e.g. Defries *et al* 2008, Van Der Werf *et al* 2009b, Gatti *et al* 2014, Alden *et al* 2016).

Emissions estimates in this study are similar to official reports in Brazil's Third National Communication to the UNFCCC (BRAZIL 2016), yet several issues prevent a direct comparison of the results. Brazil's Third National Communication suggests that net emissions from agricultural expansion in the Cerrado totaled 575.2 Tg CO_2 (156.9 Tg C) between 2002–2010, with the majority of net carbon emissions from forest conversion to cropland (82%, 129 Tg C). Estimated gross carbon emissions from cropland expansion in this study from 2003–2010 totaled 142 ± 46.41 Tg C (see figure 3), but with only 27% of emissions from forest conversion. Satellite data on fractional tree cover suggest a lower proportion of forest conversion for cropland expansion than Brazil's Third National Communication, potentially due to differences in land cover classifications or deforestation information.

Our analysis developed annual estimates of cropland expansion from satellite data, while the UNFCCC submission used periodic land cover information to generalize emissions over multi-year intervals. Ultimately, sub-annual information on the timing and magnitude of land use change emissions is critical to link bottom-up accounting with measurements of atmospheric trace gases from aircraft (e.g. Gatti *et al* 2014) or satellite observations (Edwards *et al* 2006, Van Der Laan-Luijkx *et al* 2015). In addition, we reported gross carbon fluxes (rather than net carbon emissions) and did not further disaggregate carbon emissions using information on fire emissions ratios (Van Leeuwen and Van Der Werf 2011) or combustion completeness (e.g. Van Der Werf *et al* 2009a). Accounting for non-carbon greenhouse gas emissions, including nitrous oxide from fertilizer use (Galford *et al* 2010), is also critical to capture the full range of impacts from cropland expansion.

To date, commodity industry commitments to zero deforestation have overlooked forest losses in dry forest regions such as the Cerrado. In Brazil, the government, civil society, and industry have primarily focused on reducing deforestation in the Amazon region (e.g. the SoyM). More recent efforts, including PPCerrado (MMA 2011, 2014) and Low Carbon Agriculture Program (ABC), have been implemented to reduce land use and agricultural emissions within the Cerrado. Time series of satellite data in this study suggest that total cropland expansion in the Cerrado declined between the baseline period for PPCerrado (2002–2008) and the end of our study period (2013, see table S1), consistent with the PPCerrado goal of a 40% decrease in deforestation from all sources by 2020. However, rates of forest conversion for cropland in the Cerrado remained nearly constant, as expansion shifted to new frontiers in Matopiba. Synergies between PPCerrado and existing legislation, including Brazil's FC, offers a mechanism to restrict Cerrado conversion in legal reserve areas with the full implementation of Brazil's Rural Environmental Registry (Cadastro Ambiental Rural; CAR) of private properties (Soares-Filho *et al* 2014, Gibbs *et al* 2015).

There are several barriers to effective monitoring and conservation in the Cerrado. First, the tools for effective satellite monitoring of private properties developed for the Amazon region (e.g. PRODES, DETER, and DEGRAD) are not operational for the Cerrado biome, with the notable exception of the recent TerraClass Cerrado product (MMA 2015). Monitoring is critical to ensure compliance with environmental legislation; in 2014, nearly half of the Amazon deforestation in the states of Pará and Mato Grosso occurred within designated legal reserve areas (Gibbs *et al* 2015). Policies such as PPCerrado are also counterbalanced by government efforts to promote agricultural development in the Matopiba region (Matopiba plan, BRAZIL 2016). Satellite monitoring offers an objective perspective in the search for balance between Brazil's goals to increase agricultural production, reduce greenhouse gas emissions, and adhere to commitments for forest restoration as part of the New York Declaration on Forests (UNCS 2014). Other

ecosystem services beyond carbon storage are also important to consider, such as biodiversity conservation, water recycling (Spera *et al* 2016), and regional climate impacts (Pongratz *et al* 2006, Loarie *et al* 2011). Efforts that focus on deforestation area (as opposed to carbon emissions), consistent with industry commitments to zero deforestation, could help balance land use pressures among biomes, regardless of carbon stocks.

Satellite-based estimates of annual cropland expansion and vegetation carbon stocks provide an important benchmark in support of complete national accounting of carbon emissions from land use change. Higher resolution data may help future studies improve upon these estimates. MODIS resolution is suitable for mapping and monitoring cropland expansion in the Cerrado region, but Landsat (30 m) data allows for more precise delineation of management areas and deforestation. Existing satellite products in Brazil, including TerraClass, PRODES, and MAPBIOMAS (MAPBIOMAS 2016), offer a blueprint for regular monitoring of land use changes in the Cerrado at Landsat resolution.

This study estimated gross carbon emissions from cropland expansion, since complete removal of above and belowground biomass for mechanized crop production simplified the emissions calculation. A comprehensive assessment of carbon emissions and uncertainty remains a challenge (Houghton *et al* 2012), in part due to the broad range of land management practices for establishment and maintenance of pastures and croplands in the Cerrado region (e.g. Van Der Werf *et al* 2009a). Second-generation biomass products, developed from upcoming lidar and radar satellite missions (Morton 2016), will map aboveground biomass at higher resolution, consistent with the spatial scales of vegetation heterogeneity and land management. Efforts to track the reduction in forest and shrub biomass from expansion of grazing lands will also benefit from new remote sensing data, particularly from radar sensors with the ability to map carbon stocks in low-biomass vegetation types. Field estimates of above and belowground carbon stocks in Cerrado vegetation remain critical for improving estimates of vegetation carbon stocks; differences between the satellite and look-up table estimates of emissions from conversion of non-forest cover types were nearly 30%.

Conclusions

This study presents the first estimate of annual forest carbon emissions from cropland expansion in the Cerrado biome. Forest conversion accounts for a growing proportion of recent cropland expansion in the Cerrado, particularly in newer agricultural frontiers such as the Matopiba region. Although soy and other mechanized crop production are not the major drivers of deforestation in the Amazon or Cerrado, cropland expansion has larger gross and net carbon emissions per unit area than pasture expansion, based on the need for complete removal of above and below-ground biomass (Van Der Werf *et al* 2009a). Cropland expansion partially offset recent declines in Amazon deforestation emissions, highlighting the critical need for national scale accounting for successful climate mitigation through REDD+.

Acknowledgments

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