Global Environmental Change 53 (2018) 233–243

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Intensification in agriculture-forest frontiers: Land use responses to development and conservation policies in Brazil

R.D. Garrett[a,b,*], I. Koh[a], E.F. Lambin[c,d], Y. le Polain de Waroux[e], J.H. Kastens[f], J.C. Brown[g]

[a] Department of Earth and Environment, Boston University, 685 Commonwealth Ave., Boston, MA, 02215, USA
[b] Global Development Policy Center, Boston University, Boston, MA, 02215, USA
[c] School of Earth, Energy, and Environmental Sciences, Stanford University, Stanford, CA, 94305, USA
[d] Georges Lemaître Centre for Earth and Climate Research, Earth and Life Institute, Université Catholique de Louvain, 1348, Louvain-la-Neuve, Belgium
[e] Institute for the Study of International Development and Geography Department, McGill University, Canada
[f] Kansas Biological Survey, University of Kansas, Lawrence, KS, 66047, USA
[g] Office of the Provost and Department of Geography and Atmospheric Science, University of Kansas, Lawrence, KS, 66045, USA

ARTICLE INFO

Keywords:
Double cropping
Pasture management
Soy
Cattle
Amazon
Cerrado
Deforestation
Sustainability
Corporate commitments
Public regulations

ABSTRACT

Deforestation associated with agricultural expansion, particularly that of extensive cattle ranching, remains a pressing challenge for sustainable development and climate mitigation efforts in South America. In response to these challenges, national and local governments, as well as private and non-governmental actors, have developed new forest conservation governance mechanisms. In addition to reducing deforestation for agricultural expansion, it is hoped that these policies may lead to the intensification of existing agricultural regions, thereby contributing to global food availability and continued rural development. The objective of this study is to understand the timing and spatial patterns of crop and pasture intensification in agriculture-forest frontiers in the context of changing conservation policies and rural development. We focus on Mato Grosso, the largest soy and cattle producing state in Brazil, which spans the Cerrado and Amazon biomes and has experienced among the highest levels of deforestation for agricultural expansion globally. Using econometric analysis of remotely sensed and agricultural survey data, we find that cropland and pasture intensification are both linked to increasing forest conservation restrictions and broader supply chain development. However, the effect of conservation restrictions on intensification is lower in regions where there is more forest remaining. While crop and pasture area dynamics are often coupled in agriculture-forest frontiers, crop intensification does not appear to have contributed to pasture intensification through animal feed production. Intensification of crop and pasture areas was associated with temporary, immediate reductions in local deforestation, but crop intensification was associated with increased deforestation over longer time periods. These results suggest that targeted investments in supply chain infrastructure in the Amazon frontier could promote intensification and relieve pressure to clear forests, but must be coupled with substantial, long-term negative incentives for deforestation, including more effective public forest governance and private zero-deforestation commitments.

1. Introduction

Population growth, rising affluence, and changing dietary preferences are increasing global demand for livestock products and livestock feed, while globalization is shifting supply of these products away from temperate producers toward tropical regions (Foley et al., 2005; Kastner et al., 2012; Weinzettel et al., 2013). As a consequence of these global economic changes, the Brazilian tropical savanna (Cerrado), Brazilian and Bolivian moist tropical forest (Amazon), and seasonally dry forests of Argentina, Paraguay, and Bolivia (Chaco and Chiquitano) have become the new global hotspots for soybean and corn production, while continuing to support a substantial proportion of the world's beef production (le Polain de Waroux, Garrett et al., 2017; Nolte et al., 2017). The expansion of agricultural activities in South America has resulted in the loss of native vegetation in these biomes, leading to high carbon emissions, biodiversity loss, and the disruption of local and regional hydrological cycles (Barlow et al., 2016; Baumann et al., 2017; Coe et al., 2013; De Sy et al., 2015; Silvério et al., 2015).

In response to accelerated deforestation for agricultural expansion in the early 2000s, new forest conservation governance mechanisms

* Corresponding author at: Department of Earth and Environment, Boston University, 685 Commonwealth Ave., Boston, MA, 02215, USA.
E-mail address: rgarr@bu.edu (R.D. Garrett).

https://doi.org/10.1016/j.gloenvcha.2018.09.011
Received 30 October 2017; Received in revised form 17 September 2018; Accepted 23 September 2018
Available online 21 October 2018

have emerged in South America. In Argentina, a temporary moratorium on deforestation was declared by some provincial governments in the Gran Chaco region, followed by the enactment of a national law requiring provinces to develop new conservation and agricultural zoning policies (le Polain de Waroux, Garrett, et al., 2017). In Paraguay, a zero-deforestation law was enacted for the Atlantic forest (Nolte et al., 2017). In Brazil, protected areas were increased and existing forest conservation policies were strengthened, particularly for the Amazon region, via the introduction of credit restrictions and real time monitoring and enforcement of deforestation policies. Alongside these public initiatives, private companies in the soy and beef cattle sectors adopted voluntary commitments (the Soy Moratorium in 2006 and the G4 Cattle Agreements in 2009) to not source commodities produced on areas that were deforested after July of the year in which the agreements were signed, though the Soy Moratorium cut-off was later pushed back to 2008 (see le Polain de Waroux, Garrett et al., 2017; Gibbs et al., 2016; Alix-Garcia and Gibbs, 2017). Other regions, including the Bolivian Chaco and Chiquitano and the Brazilian Cerrado, maintained comparatively lax conservation restrictions and enforcement (le Polain de Waroux et al., 2017; Garrett et al., 2016; Spera, 2017).

Two important questions for understanding the effectiveness of these emerging deforestation policies and their broader impacts on development and food security are: i) whether restricting land use on large tracts of forest lands has resulted in intensification on existing agricultural areas, and ii) whether such intensification has led to additional forest conservation in later periods. Agricultural *intensification* generally refers to an increase in the amount of output (food, fuel, or fiber) produced per unit of land through improved management practices and technologies or increased inputs (Tilman et al., 2011). Here we focus on two intensification processes that rely on increasing non-land inputs to achieve greater food production: i) on croplands, switching from single to double cropping; and ii) on pasture, raising more cattle per unit of pasture.

Increasing food production on existing agricultural areas has the potential to help spare land for carbon storage and biodiversity (i.e. "land sparing"), particularly in light of increasing global food demand (Phalan et al., 2011). Intensification could also help reduce the displacement of agricultural expansion and deforestation to new forest frontiers. When this displacement is the result of increases in conservation restrictions in existing production regions it is known as "leakage" (le Polain de Waroux et al., 2017; Garrett et al., 2017; Meyfroidt et al., 2013). More specifically, intensification in Brazil's Amazonian humid forest may help spare the relatively less protected Cerrado savanna and Chaco dry forest biomes of South America (Spera, 2017). Intensification could also stimulate rural economic growth, contributing to higher local wages and better access to health and education services (VanWey et al., 2013). Planting a double crop of corn after the soybean harvest has also been shown to mitigate disruptions to regional hydrologic cycles by increasing total evapotranspiration rates (Spera et al., 2016). Yet, if intensification leads to an increase in local incomes or global consumption, it could increase deforestation in the region that experienced intensification (i.e. "a rebound effect", which refers to a response of agents to new technologies introduced to reduce resource use), thereby offsetting any land sparing effect (Erb, 2012; Lambin and Meyfroidt, 2011). Intensification via greater agrochemical use may also result in increased water and air pollution and health risks compared to lower input practices (Tilman et al., 2002). Despite a proliferation of studies on patterns of agricultural expansion and intensification in South America (Arima et al., 2011; Galford et al., 2008; Gasparri and Grau, 2009; Graesser et al., 2015; Grau and Aide, 2008; Kastens et al., 2017; Macedo et al., 2012; Spera et al., 2014), few studies have sought to understand the mechanisms underlying agricultural intensification (Richards et al., 2015; VanWey et al., 2013). Moreover, there has been little empirical analysis of the impacts of changes in conservation policy on agricultural intensification, the relationship between crop and pasture intensification, or feedbacks on conservation at the local scale.

The literature suggests three potential pathways by which intensification could occur: (i) a "land scarcity" pathway, whereby land becomes more expensive relative to non-land inputs, which induces intensification (Lambin et al., 2001; Turner and Ali, 1996; Villoria et al., 2013); (ii) an "agglomeration economies" pathway, whereby agricultural area expansion spurs the growth of agricultural supply chain infrastructure, increasing profitability of agriculture and incentives to invest in both agricultural expansion and intensification in a snowball process (Garrett et al., 2013a; Porter, 2000; Richards, 2017); and (iii) a "livestock industrialization" pathway, whereby increasing availability of grain from agriculture causes livestock to become decoupled from the land base due to the substitution of grain for pasture (Herath et al., 2005; Hinrichs and Welsh, 2003; Naylor et al., 2005). These three potential pathways, described in further detail below, are not mutually exclusive. Indeed, where they co-occur, they may be reinforcing, leading to rapid development of agriculture while potentially sparing land. They may also play out differently across crop and cattle systems.

Here we use a newly assembled dataset that includes spatially and temporally explicit information on land use change, including agricultural production and area, supply chain infrastructure, and conservation policies to answer the following questions: (Q1) How have changes in conservation policies and supply chain development influenced patterns of agricultural intensification? (Q2) Is crop intensification having positive spillovers on pasture intensification? (Q3) Is crop and pasture intensification contributing to greater forest conservation?

We investigate the processes and outcomes of intensification using the case study of Mato Grosso, Brazil, which spans the Amazon and Cerrado ecological biomes. Due to its large share in global deforestation and soy, corn, and beef production, land change processes in Mato Grosso are of global relevance (Cohn et al., 2016b, 2014; Macedo et al., 2012; Morton et al., 2006; Richards and VanWey, 2016). Between 2000 and 2011, the 65,394 km^2 of deforestation that occurred in Mato Grosso (INPE, 2016) accounted for 12% of South American deforestation and 3% globally (Hansen et al., 2013). During the same period Mato Grosso accounted for 16% of South American soy production (7% globally) and 6% of South American beef production (1% globally), making it the single largest soy and beef producing state in Brazil (IBGE, 2013).

2. Background and theory

2.1. Influence of forest conservation policies on land use

Forest conservation policies take many forms and differ substantially between public and private actors. In South America, most public forest conservation policies are either based on public land allocation for conservation or focus on providing disincentives for deforestation on private lands via the applications of fines, seizure of property, and in some cases imprisonment (le Polain de Waroux, Garrett, et al., 2017). Many new private forest conservation policies (i.e. "zero deforestation agreements") rely on market exclusion and credit restrictions to discourage deforestation or on voluntary sustainable production standards (Börner et al., 2015b; Lambin et al., 2018; Rueda et al., 2017). Few organizations provide positive incentives for forest conservation (e.g., preferential market access or payments for environmental services) in South America, though some tools do exist (Börner et al., 2015b; Börner and Wunder, 2012; Garrett et al., 2016). For example, in 2010 the Brazilian government launched the Low-Carbon Agricultural Plan ("ABC Plan") which provides loans with subsidized interest rates to farms that adopt low-carbon agricultural practices, including restoration of degraded pastures, integrated crop and livestock systems, no-till farming, and commercial forest plantations (MAPA, 2011).

Disincentive-oriented conservation policies theoretically impose high costs for producers who deforest illegally. However, producers who comply with anti-deforestation regulations also incur costs. First, the opportunity costs of foregone production may be substantial (Börner and Wunder, 2012; Stickler et al., 2013). Secondly, there are transaction costs associated with maintaining and verifying compliance, such as land mapping and registration, and protection from fires or squatters. Finally, by restricting forestland availability for agricultural expansion, regulations may lead to higher agricultural land prices (Hertel, 2012). Whether and when these deforestation disincentives result in reduced agricultural expansion compensated by agricultural intensification, or result in other outcomes such as rebound effects or outmigration and land use leakage, remains poorly understood. Net land use outcomes depend on the available intensification options, consumption patterns, and technological changes, the costs of non-land inputs that enable intensification, the suitability of nearby alternative areas for farming, and the ease at which producers can relocate, among other factors (Angelsen, 2010; Erb, 2012; le Polain de Waroux, Garrett et al., 2017).

There is evidence that existing conservation restrictions are rearranging agricultural expansion patterns, for example by reducing deforestation directly for cropland expansion as occurred in the Brazilian Amazon (Gibbs et al., 2015; Kastens et al., 2017; Macedo et al., 2012), or by leading larger ranching operations to seek out less regulated regions for new investments as occurred in the Chaco (le Polain de Waroux et al., 2016). On the other hand, outside of the Brazilian Amazon, pasture and crop expansion does not appear to have slowed in response to changing forest conservation policies (le Polain de Waroux, Garrett et al., 2017). Amidst these diverging land use responses in different regions, it remains unclear whether farmers who intensified did so in response to forest conservation policies or to other economic incentives. For example, it is well known that double cropping increased in the Legal Amazon region of Brazil throughout the 2000s, but no one has examined whether these processes are statistically related to changes in protected areas, deforestation policy enforcement, and new zero-deforestation commitments, or if they occurred independently of these changes. Field interviews suggest that perceived land scarcity from increased enforcement of forest conservation policies is increasing incentives for cattle ranchers to intensify production (Garrett et al., 2017b). However, opportunities to evade deforestation regulations still exist for both crop and cattle producers (Gibbs et al., 2016; Rausch and Gibbs, 2016; Richards et al., 2017).

2.2. Influence of supply chain development on land use

The presence of a supportive agribusiness environment can be critically important for land use activities due to its effects on prices, technology, and information flows among farmers (Garrett et al., 2013a, 2013b). In agriculture-forest frontiers, the emergence of clusters of agribusinesses is essential to promote a competitive environment and economies of scale. Together with land availability, the agglomeration economies (i.e., positive spillovers) produced by agribusiness clusters can outweigh the disadvantages of being located very far from consumption markets, leading to rapid agricultural expansion (Garrett et al., 2013a; Porter, 1998; Richards, 2017). There is some evidence that agglomeration economies also influence land use intensity, not just land area (Neumann et al., 2010). In the state of Mato Grosso, previous research found that double cropping increased in areas where mechanized agriculture had already been widely adopted, federal highways were present, and GDP per capita was high (VanWey et al., 2013). These findings suggest that regional economic development is an important predictor of intensification, but they do not lend insight to the precise influence of agribusiness infrastructure on land use intensity. Notably, VanWey et al. (2013) did not examine how economic development affected pasture intensification or control for simultaneous changes in conservation policies.

2.3. Influence of crop intensification on livestock

Links between grain production and livestock industrialization have been well documented in the United States and China (Herath et al., 2005; Hinrichs and Welsh, 2003; Naylor et al., 2005). Yet the relationship between grain availability and pasture intensification in South America remains poorly understood despite a proliferation of research on the potential ecological benefits of integrating crops into livestock systems (see Garrett et al., 2017b, c; and references therein). Soy and corn can be used to supplement the nutrition that cattle obtain from pasture, particularly during the dry season, or to completely replace pasture in confinement systems. Though increasing in Brazil, these practices are likely still rare as a proportion of pasture area (Gil et al., 2016; Vincente, 2016). Additionally, the expansion of soy and corn agribusinesses can reduce the costs of improving pastures by improving access to soil amendments, such as lime and fertilizer. However, if most of the soy and corn produced in a region is exported or used for pig and poultry feed, which have a higher efficiency of weight gain with respect to grain consumption (Shepon et al., 2016), it is less likely to be used as a cattle feed and reduce the need for pasture expansion.

2.4. Effects of intensification on deforestation

Agricultural intensification is more likely to lead to local land sparing when it is driven by increases in the price of land relative to non-land inputs, when it does not decrease production costs (thereby increasing income), and where restrictions on converting forests are more stringent (Angelsen and Kaimowitz, 2010; Ceddia et al., 2014). Both cattle and crop intensification can increase production costs. However, there is substantial evidence that certain forms of pasture intensification in Brazil, including rotational grazing and the use of crop rotations in an integrated crop and cattle system, would greatly increase profitability, which could spur further expansion (de Oliveira et al., 2015; Gil et al., 2018; Martha et al., 2011). At a global level, feedbacks of intensification on forest conservation depend on how integrated that region is with global markets and whether or not demand for that product is elastic (Byerlee et al., 2014). When demand is elastic (i.e., it changes significantly in response to price, as is thought to be the case with meat and bioenergy crops), then regional increases in production that lead to global price decreases may be offset by additional demand.

3. Methods

To investigate processes and outcomes of intensification in Mato Grosso, we develop a statistical model that regresses indicators of environmental regulations and supply chain conditions, along with a series of control variables, against measures of agricultural intensification. We then examine the correlation between deforestation and our agricultural intensification measures in prior years. We first describe these variables and then detail the models used in our analysis.

3.1. Characterizing changes in land use, supply chains, and forest availability

Our units of analysis are the 141 municipalities of Mato Grosso, from 2001 to 2013. The municipal scale was chosen because it is the minimum scale at which all data were available. All data are described in Table S1 and some data are illustrated in Fig. 1.

3.1.1. Land use and land cover

The land use/land cover (LULC) data employed in this study are described in Kastens et al. (2017). They used a spatially extensive, nine-year ground reference dataset and remotely sensed, normalized difference vegetation index (NDVI) time-series data from the Moderate

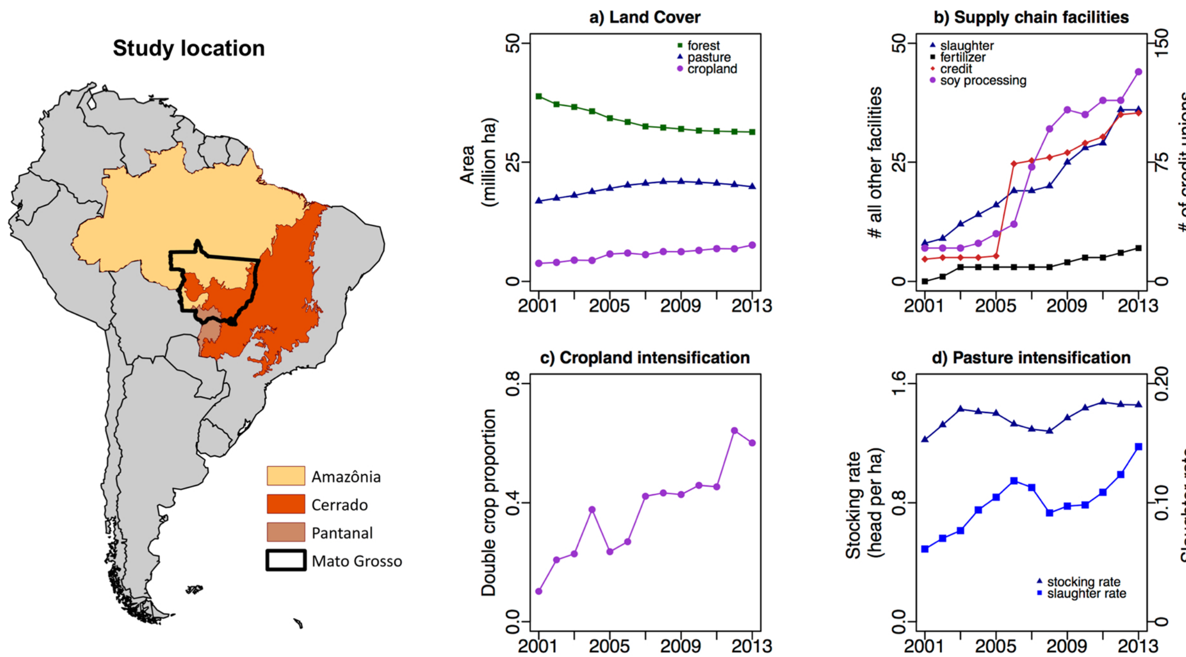

Fig. 1. Annual trends in land cover change, supply chain development, and agricultural intensification in Mato Grosso (2001–2013). Lines represent the sum of the values for all counties for all of the variables except for land intensity where lines present the mean value for all counties. For Fig. 1d, "slaughter rate" refers to the number of cattle slaughtered in the state per unit of pasture. Both stocking rate and slaughter rate use the MapBiomas pasture area. Data sources explained in Table S1.

Resolution Imaging Spectroradiometer (MODIS) to develop annual Mato Grosso land cover maps for the 2001–2014 crop years (a crop year consists of an annual crop production cycle that ends with July of the nominal year; for our purposes we associate the LULC data directly with calendar year data). The raster LULC maps have a resolution of 240 m (5.76 ha/pixel) and are included in the supporting information provided online with Kastens et al. (2017). The class structure consists of forest, pasture/Cerrado, three soybean classes, cotton, sugarcane, and static urban and water classes. The latter four classes, which collectively account for just 1% of total Mato Grosso area on average during 2001–2013, were not used in this study. Soybean classes include soy single crop; soy-commercial double crop, where the commercial crop is predominantly corn and excludes cotton; and soy-cotton double crop. Reported accuracy for the LULC maps was 79–85% (Kappa 0.71-0.78) using cross validation (lower values) and an independent roadside dataset consisting of more than 3000 observations spread across three years (higher values). Statewide mapped soy area during our 2001–2013 study period accounted for 94% of estimated soy crop area reported in federal crop statistics (www.sidra.ibge.gov.br). As documented by Kastens et al. (2017), double-cropped soy area increased tenfold throughout the study period from 340,000 ha in 2001 to more than 4.3 million hectares in 2013. Single crop soy area fluctuated around 3 million hectares throughout the study period.

Since Kastens et al. (2017) do not distinguish between pasture and Cerrado we obtained refined estimates of pasture area from Project MapBiomas - Collection 3 of Brazilian Land Cover & Use Map Series, which distinguishes between native forest, savanna and grassland and agricultural pastures using a biome specific classification tree based on various spectral indices. The methods used by Project MapBiomas for each biome are described at www.mapbiomas.org/pages/methodology. We refer to these data as "MapBiomas" pasture area and the other data source as the "Kastens" pasture area. Results for the latter provide a systematic overestimate of pasture area and are included in the Table S6 for reference.

Intensification is measured in two ways. The first metric, *Double Crop Rate*, represents crop intensification and includes both the soy-corn and soy-cotton double crop areas identified in the LULC dataset as a proportion of total soy area. During the study period, the soy-corn class comprises 93% of the total soy-double crop area (Kastens et al., 2017). During the study period, double cropped area increased from 10% to 60% of the total soy area in the state (Fig. 1c).

The second metric, cattle *Stocking Rate*, represents pasture intensification and is the number of cattle present in a municipality divided by the MapBiomas pasture area (in the SM we present stocking rate results for the number of cattle divided by the Kastens pasture area). As shown in Fig. 1d, pasture areas intensified significantly in Mato Grosso during the study period in terms of the number of live cattle per unit of pasture (from 1.2 to 1.5 live cattle per hectare). The number of cattle slaughtered per unit of pasture area increased even more substantially (from 0.12 to 0.29 cattle slaughtered per hectare). Ideally we would also examine fertilizer usage and labor inputs as measures of intensification. However, such data are lacking over space and time.

3.1.2. Supply chains

We collected spatially explicit time-series data on the locations of soy processing facilities, biodiesel plants, fertilizer plants, commercial grain storage facilities, chicken and pork production facilities, and cattle slaughterhouses (Fig. 1b) and snapshots of the distribution of trader offices. After analyzing the correlations between different supply chain infrastructure variables (Table S2), we concluded that the location of soy processing and biodiesel facilities were the best indicators of the presence of a well-developed soy cluster because they were significantly correlated with other soy supply chain variables. The location of cattle slaughterhouses was the only indicator available to represent the presence of cattle supply chain infrastructure. It was weakly positively correlated with many of the soy supply chain variables (Table S2), likely due to a positive time trend for all infrastructure variables.

To assess how proximity to the soy and cattle supply chain infrastructure influenced land use outcomes, we developed travel cost and distance estimates for the centroid of each municipality to the nearest (in terms of cost distance) soy processing or biodiesel facility (*Soy Chain*

Distance), cattle slaughterhouse (*Cattle Chain Distance*), and export terminal (*Port Distance*) in each year based on road infrastructure in 2016[1], with differentiation between primary and secondary paved surfaces and unpaved tertiary or access roads.

We also derived state-level demand for soy and corn based on chicken and pork slaughter rates in Mato Grosso *(Feed Demand)*. We estimated that each unit of pork produced in Mato Grosso required 2.5 units of soy meal and 2 units of corn meal and each unit of chicken required 1.25 units of soy meal and 1 unit of corn meal, given the assumptions that: i) in a confined system each unit of pork production requires at least 4 units of feed; ii) each unit of chicken production requires at least 2 units of feed (Brown, 2006); iii) only 80% of each soybean can be used as soy meal, while 100% of the corn harvest can be used as meal; and iv) each animal gets an equal portion of soy and corn in their feed. This results in a demand of 4.5 or 2.25 units of a mixed soy and corn feed per unit pork or chicken produced, respectively. While chicken and pork production rely almost exclusively on soy and corn for nutrition in Mato Grosso, the use of crops to supplement cattle remains rare. According to the 2006 Agricultural Census, only 16% of ranchers supplemented their cattle with grains or rations (IBGE, 2006).

3.1.3. Forest conservation policy

Forest *Regulations* are measured as the percentage of the forestland within each municipality that is theoretically protected according to existing public regulations. This includes the proportion of each property that must be kept as a “Legal Reserve” according to the Forest Code (Law 2012/12,651) and the presence of Protected Areas. It does not include the amount of area that would theoretically be protected by “Areas of Permanent Preservation”. Since public forest conservation requirements remained largely unchanged in the study region during the 2001–2013 study period, the *Regulations* variable picks up variations in conservation requirements between the Amazon and Cerrado and changes in protected areas, including indigenous reserves, across all regions over time. To assess the influence of changes in monitoring and enforcement of private conservation policies – the Soy Moratorium and G4 Cattle Agreement – we created a governance index variable ranging from 0 to 1. This index is a function of categorical estimates of deforestation *Penalties* (i.e. the level of fines), *Monitoring* capacity (i.e. ability to track forest loss in near real time), and *Enforcement* mechanisms (e.g. credit restrictions and market exclusion) that are specific to each commodity (i.e. *Soy Governance* and *Cattle Governance*) (le Polain de Waroux, Garrett, et al., 2017). By taking the average of *Regulations* and its product with this index variable we obtain a new forest governance variable for soy (*Regulations’ Soy*) and cattle (*Regulations’ Cattle*):

$$Regulations'_{i,t} = Regulations_{i,t} \times (0.5 + Governance_{i,t} \times 0.5) \quad (1)$$

where:

$$Governance_{i,t} = Penalties_{i,t} \times Monitoring_{i,t} \times Enforcement_{i,t} \quad (2)$$

where i is the municipality and t is the year. Additional details on these variables are provided in the SM.

3.1.4. Prices

Since cropping and livestock rearing are primarily land use substitutes (even integrated systems rely on land rotations), decisions to invest in either land use should be influenced by the relative price of crops vis-à-vis beef. However, no panel data were available for local crop and beef prices in the study region for all counties and years. Since local soy price data were available for 12 counties and 5 years (2008–2013) (see Table S1), we used these data to assess whether or not our supply chain travel distance and cost calculations were a good proxy for price variations. We found that distance to ports was moderately negatively correlated with soy prices for the counties for which there were data (Pearson’s R = -0.45, p= < 0.001), indicating that this variable is a reasonable substitute for local soy prices in the double cropping regressions. Distance to soy facilities was not correlated with prices. There were no spatially explicit data available for beef to test for correlation with distance to ports or slaughterhouses.

3.2. Assessing the relationship between supply chains, forest policies and intensification

We use an ordinary least squares model with time fixed effects to assess the influence of supply chain conditions and forest policies on *Double Crop Rate* and *Stocking Rate*. We limited the sample for the *Double Crop Rate* model to the 106 (out of 141) counties where there was at least some double cropping by the end of the study period (2013). This yielded 1264 observations. The *Stocking Rate* model was run for the entire sample except two counties that did not have cattle throughout the study period. This resulted in 1668 observations. Both models used an ordinary least squares estimation via the plm package in R. All explanatory variables included in the model except for *Governance*, which included all zeros in some years, are mean scaled.

$$\begin{aligned} \mathrm{DoubleCropRate}_{i,t} &= \alpha + \beta_1 \mathrm{SingleCropArea}_{i,t-1} + \beta_2 \mathrm{CornYield}_{i,t-1} \\ &+ \beta_3 \mathrm{PastureProportion}_{i,t-1} + \beta_4 \mathrm{SoyChainDistance}_{i,t-1} + \beta_5 \mathrm{CattleChainDistance}_{i,t-1} \\ &+ \beta_6 \mathrm{PortDistance}_{i,t-1} + \beta_7 \mathrm{FeedDemand}_{i,t-1} \\ &+ \beta_8 \mathrm{Regulations}_{i,t-1} \times \beta_9 \mathrm{ForestAvailability}_{i,t-1} + \delta_t + \varepsilon_{i,t} \end{aligned} \quad (3)$$

and

$$\begin{aligned} StockingRate_{i,t} &= \alpha + \beta_1 SingleCropArea_{i,t-1} + \beta_2 DoubleCropProportion_{i,t-1} \\ &+ \beta_3 DoubleCropProportionNeighbor_{i,t-1} + \beta_4 PastureProportion_{i,t-1} \\ &+ \beta_5 SoyChainDistance_{i,t-1} + \beta_6 CattleChainDistance_{i,t-1} \\ &+ \beta_7 PortDistance_{i,t-1} + \beta_8 FeedDemand_{i,t-1} \\ &+ \beta_9 Regulations_{i,t-1} \times \beta_{10} ForestAvailability_{i,t-1} + \delta_t + \varepsilon_{i,t} \end{aligned} \quad (4)$$

where δ_t represents the time fixed effect and $\varepsilon_{i,t}$ is the error term.

The two models largely contain the same variables. *Double Crop Rate* includes *Corn Yield* as an additional predictor. Corn yields increased rapidly over the study period (Kastens et al., 2017), which may lead to higher profitability from double cropping, encouraging adoption. The variable *Single Crop Area* is included because the *Double Crop Rate* may increase more quickly in counties that have a very large single cropped area, due to economies of scale (Richards, 2017). *Pasture Proportion* is included because expansion of single cropped soy into pasture may be an alternative to intensification in the context of increased native vegetation scarcity (due to increased conversion restrictions). *Stocking Rate* contains *Double Crop Proportion* (double crop area as a proportion of total area) in the same county and *Double Crop Proportion Neighbor* for the average double crop area in adjacent counties, since having more soy and corn available as a feed source could influence farmers’ ability to increase their herd per unit of pasture.

We include results for three different models with each variant of the conservation policy variable (Model I-*Regulations*, Model II-*Governance*, and Model III-*Regulations’*). The impact of conservation policies on intensification may be influenced by forest scarcity, so we use an interaction term between the conservation policy variable and *Forest Availability* (forest area a % of total area in each municipality). There was no evidence of multicollinearity in the model. Variance Inflation Factor of each variable was less than 2.4.

[1] A continuous dataset of road areas was not available for every year. However, annual changes in supply chain infrastructure indirectly capture changes in road infrastructure. All variables vary over time because supply chain infrastructure and ports continued to expand during the study period.

3.3. Assessing the relationship between intensification and deforestation

Having examined the underlying determinants of crop and pasture intensification, we then used Pearson product-moment correlation coefficient tests to assess whether municipalities with higher rates of crop or pasture intensification in previous years experienced significantly lower forest loss later years. We examine these relationships at the municipal level using current data and one to four year lags in the intensification variable (e.g., cor(Deforestation$_t$, ΔStockingRate$_t$) for current intensification and cor(Deforestation$_t$, ΔStockingRate$_{t-4}$) for a four year lag in the intensification variable). The number of lags we included was limited by the size of the sample. We also examined the impacts of crop and pasture intensification on forest loss in neighboring counties, where forest area of the neighboring county was defined as the weighted average of forest loss among the counties that border the county experiencing intensification. Since likelihood of deforestation should change with legal forest availability, we assess this relationship using three samples: a) all counties, regardless of forest area; b) counties with more than 30% forest cover remaining in 2006 (as used in previous studies; e.g., Gollnow and Lakes, 2014); and c) counties with forest stocks exceeding the conservation requirement defined by the *Regulations* variable.

4. Results

(Q1) How have changes in conservation policies and supply chain development influenced patterns of agricultural intensification?

Double cropping and stocking rates were both significantly higher in regions where forest conservation policies were more stringent, but the effect of conservation policies on double cropping was reduced where forest availability was high (Tables 1 and 2). Governance improvements (penalties, monitoring, and enforcement), such as those associated with corporate zero-deforestation commitments, had a large positive effect on crop intensification and mixed effects on stocking rates. Improved governance for beef supply chains was weakly negatively associated with had no significant effect on stocking rates where forest availability was low, but positively associated with stocking rates where forest availability was high.

Crop intensification occurred more rapidly in regions with smaller distances to soy processing facilities (Fig. 2). These regions were largely located in the Cerrado portion of the state, but some occurred in the Amazon biome. Stocking rates were higher in regions with smaller distances to slaughterhouses. Double cropping and stocking rates were both higher in regions with higher demand for pig and poultry feed. The amount of pasture remaining had a negative effect on crop intensification.

Table 1
Double crop regression results.

	I	II	III
Soy Area$_{t-1}$	0.05	0.04	0.05
Pasture Proportion$_{t-1}$	-0.23***	-0.25***	-0.24***
Corn Yield$_{t-1}$	0.18***	0.15***	0.19***
Soy Chain Distance$_{t-1}$	-0.16***	-0.15***	-0.17***
Cattle Chain Distance$_{t-1}$	0.001	0.02	0.003
Port Distance$_{t-1}$	-0.06*	-0.06*	-0.07*
Feed Demand$_{t-1}$	0.11***	0.11***	0.11***
Regulations$_{t-1}$	0.10*	0.90**	0.15***
Forest availability$_{t-1}$	-0.04	-0.02	-0.06
Regulations$_{t-1}$ × Forest availability$_{t-1}$	-0.06†	-0.38**	-0.08*
Conservation policy variable	Regulations	Governance	Regulations'
Adjusted R^2	0.18	0.18	0.18

Notes: † indicates significance at the 90% confidence level, * = 95%, ** = 99%, and *** = 99.9%. n = 1264. Model I uses *Regulations* as the conservation policy variable, which includes only variations in the proportion of forest land protected by public regulations, including the Forest Code and designation as Protected Areas. Model II uses *Governance*, which includes only changes in monitoring and enforcement. Model III uses *Regulations'*, which includes the combined effects of changes in proportion of forest area protected and changes in governance..

Table 2
Log(Stocking rate) regression results.

	I	II	III
Double Crop Proportion$_{t-1}$	0.01	0.01	0.01
Double Crop Proportion Neighbor$_{t-1}$	0.004	0.003	0.004
Pasture Proportion$_{t-1}$	0.03***	0.04***	0.03***
Soy Chain Distance$_{t-1}$	-0.004	-0.005	-0.003
Cattle Chain Distance$_{t-1}$	-0.11***	-0.12***	-0.12***
Port Distance$_{t-1}$	0.08***	0.09***	0.09***
Feed Demand$_{t-1}$	0.02*	0.02	0.02
Regulations$_{t-1}$	0.03*	0.08	0.02*
Forest availability$_{t-1}$	-0.01	0.02	-0.01
Regulations$_{t-1}$ × Forest availability$_{t-1}$	-0.02†	0.08	-0.02†
Pasture variable	MapBiomas	MapBiomas	MapBiomas
Conservation policy variable	Regulations	Governance	Regulations'
Adjusted R^2	0.19	0.19	0.19

Notes: † indicates significance at the 90% confidence level, * = 95%, ** = 99%, and *** = 99.9%. n = 1668. Model I uses *Regulations* as the conservation policy variable, which includes only variations in the proportion of forest land protected by public regulations, including the Forest Code and designation as Protected Areas. Model II uses *Governance*, which includes only changes in monitoring and enforcement. Model III uses *Regulations'*, which includes the combined effects of changes in proportion of forest area protected and changes in governance.

(Q2) Is crop intensification having positive spillovers for the intensification of cattle systems?

We did not find evidence that crop intensification is promoting pasture intensification in the same or neighboring counties. Stocking rates were unrelated to rates of double cropping in the same or neighboring counties.

(Q3) Is crop and pasture intensification contributing to greater forest conservation in subsequent years?

Change in forest area was weakly positively correlated with change in the double crop area one to two years prior, and weakly negatively correlated with change in the double crop area three to four years prior (Table 3). There is no clear relationship between change in forest area and change in stocking rate in prior years in the same county, but current pasture intensification had a positive relationship with forest area in neighboring counties. The latter outcome was particularly strong in counties where forest was more abundant.

5. Discussion

5.1. Effects of conservation policies and supply chain development on agricultural intensification

Our results support the agglomeration economy pathway to agricultural intensification, and to a lesser extent the land scarcity pathway, which here is centered on the scarcity of forest area rather than on the scarcity of total non-cultivated arable land. Crop intensification occurred most rapidly in the non-forest Cerrado regions of Mato Grosso, near existing cropping supply chain infrastructure and international ports, and where large areas of single crop soy production were already present by 2001 (Fig. 2). The rapid development of cropping supply chains in the region likely resulted in improved access to inputs and technology, which decreased the cost associated with double cropping, and increased capital availability to make these investments (Garrett et al., 2013a; Richards, 2017; VanWey et al., 2013). Rates of crop intensification were positively associated with the growth of pig and poultry production in the region, which increased the internal demand for soy and corn for livestock feed by more than 2000%, likely contributing to higher soy and corn prices. This internal demand for feed was also moderately correlated with total cropland expansion (Pearson

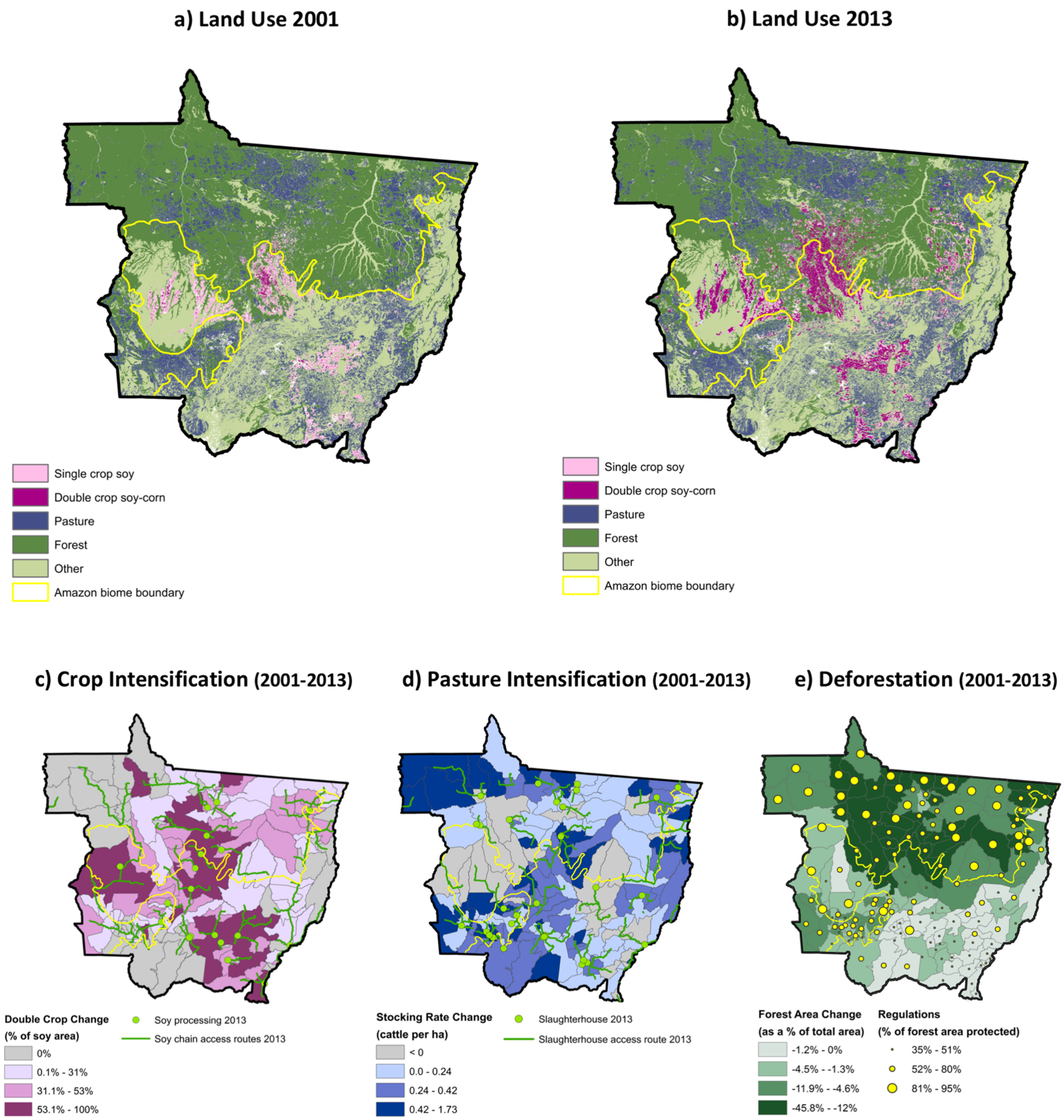

Fig. 2. Locations of agricultural intensification, deforestation, and supply chain development in Mato Grosso. (a) and (b) show a massive expansion in the double cropped soy-corn area. (c), (d), and (e) show, respectively, changes in average double cropped soy-corn area as a proportion of soy area, average stocking rates in terms of cattle head per unit of pasture, and total deforestation by municipality normalized by the municipality area between 2001 to 2013. Many regions with high levels of intensification also experienced high levels of forest loss, despite high levels of forest protection. “Access routes” indicate the least-cost path used to get to the closest soybean processing facility or slaughterhouse location as of 2013, based on 2016 road maps.

correlation coefficient = 0.39, $p < 0.0001$).

Pasture intensification was similarly supported by proximity to federally inspected slaughterhouses, which tend to offer better terms of payment and higher carcass weights than municipal or state slaughterhouses, and may offer price premiums for higher quality meat (Conexão JBS, 2017). This result supports previous work indicating that the uptake of integrated crop and livestock practices is higher near federally inspected slaughterhouses (Gil et al., 2016). Pasture intensification was likely further stimulated during the study period through the provision of low interest government loans to promote pasture restoration and productivity. Farmers located closer to existing pasture areas and federally inspected slaughterhouses may have had increased access to these loans. Pasture intensification was likely lower in areas that were closer to international ports because cattle ranching is more influenced by domestic markets, and all else equal, regions with better access to international markets favor soy production.

The land scarcity pathway is supported by the positive relationship between increasing deforestation regulation stringency and rates of intensification. Since all of the explanatory variables (except the governance variable) are mean scaled, we can see that the magnitude of the effect of regulations on double cropping is slightly smaller than that of other drivers of intensification. In contrast, the magnitude of the effect of regulations on stocking rates is the same or larger than other drivers of intensification, particularly when changes in governance (penalties, monitoring, and enforcement) are also accounted for. The effects of regulations and governance on intensification appear to be dependent

Table 3
Relationship between annual change in double crop area and annual change in forest area.

	Annual Δ in forest area in same municipality (2005–2013)		
Lag in Δ double crop area	Group 1	Group 2	Group 3
None (2005–2013)	–	–	–
1 year (2004–2012)	0.09**	–	–
2 years (2003–2011)	0.07†	0.10†	0.60***
3 years (2002–2010)	−0.06†	−0.11*	–
4 years (2001–2009)	−0.07*	−0.09†	−0.43†
	Annual Δ forest area in neighboring municipalities (2005–2013)		
Lag in Δ double crop area	Group 1	Group 2	Group 3
None (2005–2013)	–	–	–
1 year (2004–2012)	0.15***	0.18***	–
2 years (2003–2011)	–	–	0.56***
3 years (2002–2010)	−0.08*	−0.11*	–
4 years (2001–2009)	−0.06†	–	–
	Annual Δ in forest area in same municipality (2005–2013)		
Lag in Δ stocking rate	Group 1	Group 2	Group 3
None (2005–2013)	–	–	–
1 year (2004–2012)	–	–	–
2 years (2003–2011)	–	0.10†	–
3 years (2002–2010)	–	–	–
4 years (2001–2009)	−0.05†	–	–
	Annual Δ forest area in neighboring municipalities (2005–2013)		
Lag in Δ stocking rate	Group 1	Group 2	Group 3
None (2005–2013)	0.05†	0.12*	0.45***
1 year (2004–2012)	–	–	–
2 years (2003–2011)	–	0.09†	–
3 years (2002–2010)	–	–	–
4 years (2001–2009)	–	–	–

Notes: For the double cropping correlation tests, Group 1 (n = 848) includes all municipalities that had double cropping by 2013 (the same as the double crop regressions), Group 2 (n = 376) includes municipalities that had double cropping by 2013 and more than 30% of their forest remaining, and Group 3 (n = 16) includes municipalities that had double cropping by 2013 and forest area as a % of total area that exceeded what is required by federal regulations and protected areas. For the stocking rate correlation tests, Group 1 (n = 1228) includes all municipalities that had any cattle by 2013 (the same as the stocking rate regressions), Group 2 (n = 408) includes municipalities that had more than 30% of their forest remaining, and Group 3 (n = 40) includes municipalities that had double cropping by 2013 and forest area as a % of total area that exceeded what is required by federal regulations and protected areas. Values are Pearson product-moment correlation coefficients. † indicates significance at the 90% confidence level, * = 95%, ** = 99%, and *** = 99.9%. "–" indicates result was not significant.

on the amount of forest available. Regulations had larger positive effect on crop and pasture intensification in areas where forest availability was low. This outcome suggests that even if deforestation regulations increase the cost of land relative to other inputs, this increased cost is not enough to offset very low land prices in places where forest is still highly abundant. Thus regulations have an important impact in regions where the agricultural area is more consolidated and land prices are higher (and where supply chain infrastructure is more developed). By contrast, regulations have a lower impact in frontier regions where there may still be land that can be cleared legally and where monitoring and enforcement of illegally clearing may be more challenging (Börner et al., 2015a).

Similarly, changes in soy governance due to enhanced deforestation monitoring capacity and the Soy Moratorium had a larger positive impact on crop intensification where forest availability was low. In contrast, improved cattle governance, such as increases in deforestation monitoring and enforcement via public credit restrictions and G4 Cattle Agreement, had no significant impact on pasture intensification. This is likely due to the greater number of loopholes in deforestation monitoring in cattle supply chains (Alix-Garcia and Gibbs, 2017).

5.2. Spillovers between crop and cattle systems

Even though pasture intensification could theoretically benefit from the increased availability of soy and corn as a nutritional supplement or replacement for pasture, we found no evidence for a local "livestock industrialization" pathway. This may be because double cropping increases the opportunity costs of doing any form of cattle management relative to cropping, such that ranchers located near intensive cropping systems often sell or rent their land to crop farmers rather than intensifying production (Cohn et al., 2016a). Additionally, even as the use of supplemental feeding has become more common among a handful of capitalized farms in these regions, many ranchers remain resistant to incorporating supplementary feeding into their management practices, no matter how cheap it is, due to concerns over adding risk, complexity, and managerial intensity (Gil et al., 2016; Latawiec et al., 2017).

5.3. Impacts of intensification on land sparing

Crop and pasture intensification are both linked to lower deforestation in the short run, if not in the same county, then in neighboring counties (for pasture intensification). However, crop intensification in past years (3+ years) is linked to greater deforestation in the current period. These results suggest that agricultural intensification is helping to draw capital away from deforestation in the short run, but contributing to a rebound effect in the long-run through higher income. The reason for the difference in land sparing outcomes between crop and pasture intensification over the long run is unclear. One possibility is that pasture intensification has higher upfront costs and a longer payback period than switching from single to double cropping. If this is true, then in the short run ranchers that invest in intensification do not have funds available to invest in new land purchases and deforestation, while farmers that switch from single to double cropping have funding available more immediately. Another possibility is that demand for beef, which is primarily based on the domestic market, is less elastic than that of soy, which has a strong growing international market. Or, rebound effects may be lower for pasture intensification because cattle ranching decisions are less influenced by income motivations than long term speculative and non-monetary concerns (Garrett et al., 2017a; Piquer-Rodríguez et al., 2018) or because cattle and soy operators have different access to financing for new land investments. More research is needed to confirm the correlational relationships identified here and to explore the mechanisms underlying potential rebound effects.

5.4. Implications for policy

A combined effort to direct agribusiness development away from forest regions via targeted incentives could help promote intensification and short-term land sparing. Yet, intensification could result in additional local deforestation if it is applied in forest regions without stringent conservation requirements. The importance of crop and livestock delivery points such as trading, handling and processing facilities for crop and pasture land use activities underscores their centrality toward the development of effective conservation planning. Conservation restrictions can encourage farmers to intensify their existing land area by making new land inputs more expensive relative to other factors of production. However, intensification cannot occur if farmers lack access to sufficient inputs and technologies to achieve increased production through higher crop yields, implementation of double cropping systems, or improved livestock weight gain. This access could be improved by offering tax credits to fertilizer and input providers to locate in particular regions, in addition to offering subsidized credit for intensification as already occurs through the Low Carbon Agriculture Program (MAPA, 2011). However, intensification via double cropping will not be possible in all regions due to soil and climate limitations. Critically, these incentives for agribusiness development should take effect at the same time or immediately following the strengthening of conservation restrictions, rather than prior to such activities to avoid further deforestation (Kaimowitz and Angelsen, 2008; Merry and Soares-Filho, 2017). If intensification increases the profitability of agricultural activities in or close to forested areas and strong conservation restrictions are not in place, then farmers may have greater incentives to clear land for cropland or pasture expansion.

Loopholes for deforestation under existing private conservation policies must be fixed to avoid rebound effects from intensification. Loopholes in the current design of the Soy Moratorium and G4 Cattle Agreement allow some farmers to continue to deforest while their products still find their way to domestic and international supply chains (Alix-Garcia and Gibbs, 2017; Gollnow et al., 2018; Klingler et al., 2018; Rausch and Gibbs, 2016). As previous authors have noted, to improve the effectiveness of zero-deforestation agreements, it will be necessary include the entire supply chain in the commitment (e.g., cow/calf producers that sell to stocking and finishing operations) by tracking all cattle through their entire lifecycle (e.g., via registration of individual cows) (Alix-Garcia and Gibbs, 2017; Lambin et al., 2018). Getting smaller, non-federally inspected slaughterhouses to adopt these commitments is also critical so that leakage does not occur to domestic markets (le Polain de Waroux, Garrett et al., 2017).

Agribusinesses should consider intensification as a critical mechanism to reduce deforestation risk within supply chains, since it can help reduce undesirable deforestation leakage. Agribusiness companies are critical partners in the development of zero-deforestation policies in South America, yet currently most efforts aimed at engaging these companies in conservation are focused on helping them develop guidelines for avoiding products associated with deforestation. Since intensification on the existing land area is a key step in helping to minimize unanticipated leakage effects to other regions, actors, and commodities (le Polain de Waroux, Garrett et al., 2017), these agribusinesses should also be engaged in providing support for intensification, particularly within cattle production systems. Given the low intensity and high level of environmental degradation associated with existing cattle production practices in the region (Strassburg et al., 2014), there are numerous opportunities for “sustainable” or “ecological” intensification, whereby food production increases are achieved alongside better nutrient use efficiency and soil health improvements (Garnett et al., 2013; Tittonell et al., 2016). Mechanisms for promoting the sustainable intensification of cattle production include technical and financial support for integrated crop, livestock, and forestry systems and cattle nutrition and welfare, as well as price premiums for the outcomes associated with more environmentally responsible management (e.g., higher quality beef) (Garrett et al., 2017b, 2017c). As our results suggest, however, access to these programs is likely to be limited in areas located further from federally inspected slaughterhouses. Government programs should aim to fill this gap with additional research, demonstration units, and improved extension.

6. Conclusion

In the agriculture-forest frontiers of South America, conservation policies are rapidly changing in response to high conversion of natural ecosystems to crop and pastureland. The way these changes in policy and concurrent developments in infrastructure are influencing farmers' incentives to expand and/or intensify their agricultural area remains poorly understood. In this paper we analyzed interactions between land use intensity, supply chain development, and conservation policy through the globally relevant case study of Mato Grosso to better understand the factors leading to intensification and their outcomes on land sparing. Such an analysis is critical for understanding how to minimize tradeoffs between food production, development, and conservation and reduce potential for leakage from zero-deforestation policies.

We find that both crop and pasture intensification are partially driven by increased conservation restrictions where forest is already relatively scarce, and this intensification appears to have helped spare forests locally in the short run. Yet in the longer run crop intensification may be linked to greater deforestation. Both intensification processes rely on broader crop supply chain development. Crop and pasture intensification processes do not appear to be mutually reinforcing; pasture intensification was not higher in regions where corn and soy production was more abundant. These results imply that forest conservation restrictions are critical for promoting intensification, but not sufficient for ensuring that a greater amount of forest is conserved in the long run. To promote intensification and local land sparing while reducing leakage to other regions, financing and technical support toward this end needs to be coupled with improved zero-deforestation policies.

Acknowledgements

This work was supported by the Gordon and Betty Moore Foundation [grant GBMF #426]. We are grateful to the two reviewers for their constructive comments and to Laerte Ferreira and Leandro Parente for sharing MapBiomas Collection 3 data with us for this analysis.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gloenvcha.2018.09.011.

References

Alix-Garcia, J., Gibbs, H.K., 2017. Forest conservation effects of Brazil's zero deforestation agreements undermined by leakage. Glob. Environ. Change 207–217. https://doi.org/10.1016/j.gloenvcha.2017.08.009.
Angelsen, A., 2010. Policies for reduced deforestation and their impact on agricultural production. Proc. Natl. Acad. Sci. U. S. A. 107, 19639–19644. https://doi.org/10.1073/pnas.0912014107.
Angelsen, A., Kaimowitz, D., 2010. When does technological change in agriculture promote deforestation. Proc. Natl. Acad. Sci. 107, 19639–19644.
Arima, E.Y., Richards, P.D., Walker, R., Caldas, M.M., 2011. Statistical confirmation of indirect land use change in the Brazilian Amazon. Environ. Res. Lett. 6, 1–7. https://doi.org/10.1088/1748-9326/6/2/024010.
Barlow, J., Lennox, G.D., Ferreira, J., Berenguer, E., Lees, A.C., Mac Nally, R., Thomson, J.R., de Barros Ferraz, S.F., Louzada, J., Oliveira, V.H.F., 2016. Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. Nature 535, 144–147.
Baumann, M., Gasparri, I., Piquer-Rodríguez, M., Gavier Pizarro, G., Griffiths, P., Hostert, P., Kuemmerle, T., 2017. Carbon emissions from agricultural expansion and intensification in the Chaco. Glob. Change Biol. Bioenergy 23, 1902–1916.
Börner, J., Wunder, S., 2012. The scope for reducing emissions from forestry and agriculture in the Brazilian Amazon. Forests 3, 546–572.
Börner, J., Kis-Katos, K., Hargrave, J., König, K., 2015a. Post-crackdown effectiveness of field-based forest law enforcement in the Brazilian Amazon. PLoS One 10, e0121544.
Börner, J., Marinho, E., Wunder, S., 2015b. Mixing carrots and sticks to conserve forests in the Brazilian Amazon: a spatial probabilistic modeling approach. PLoS One 10, e0116846. https://doi.org/10.1371/journal.pone.0116846.
Byerlee, D., Stevenson, J., Villoria, N., 2014. Does intensification slow crop land expansion or encourage deforestation? Glob. Food Secur. 3, 92–98.
Ceddia, M.G., Bardsley, N.O., Gomez-y-Paloma, S., Sedlacek, S., 2014. Governance, agricultural intensification, and land sparing in tropical South America. Proc. Natl. Acad. Sci. 111, 7242–7247. https://doi.org/10.1073/pnas.1317967111.
Coe, M.T., Marthews, T.R., Costa, M.H., Galbraith, D.R., Greenglass, N.L., Imbuzeiro, H.M.A., Levine, N.M., Malhi, Y., Moorcroft, P.R., Muza, M.N., Powell, T.L., Saleska, S.R., Solorzano, L.A., Wang, J., 2013. Deforestation and climate feedbacks threaten the ecological integrity of south-southeastern Amazonia. Philos. Trans. R. Soc. B Biol. Sci. 368, 20120155. https://doi.org/10.1098/rstb.2012.0155.
Cohn, A.S., Mosnier, A., Havlík, P., Valin, H., Herrero, M., Schmidt, E., O'Hare, M., Obersteiner, M., 2014. Cattle ranching intensification in Brazil can reduce global

greenhouse gas emissions by sparing land from deforestation. Proc. Natl. Acad. Sci. 111, 7236–7241.
Cohn, A.S., Gil, J., Berger, T., Pellegrina, H., Toledo, C., 2016a. Patterns and processes of pasture to crop conversion in Brazil: evidence from Mato Grosso State. Land Use Policy 55, 108–120.
Cohn, A.S., VanWey, L.K., Spera, S.A., Mustard, J.F., 2016b. Cropping frequency and area response to climate variability can exceed yield response. Nat. Clim. Change 6, 601.
Conexão JBS, 2017. Farol da qualidade. Conexão JBS.
de Oliveira, A.M., Rocha, E.C., de Mattos Barretto, V.C., Pelá, A., da Silva, A., 2015. Evaluation and comparison of soil under integrated crop-livestock-forest system in the southeast of Gois, Brazil. Afr. J. Agric. Res. 10, 4461–4468.
De Sy, V., Herold, M., Achard, F., Beuchle, R., Clevers, J., Lindquist, E., Verchot, L., 2015. Land use patterns and related carbon losses following deforestation in South America. Environ. Res. Lett. 10, 124004.
Erb, K.-H., 2012. How a socio-ecological metabolism approach can help to advance our understanding of changes in land-use intensity. Ecol. Econ. 76, 8–14. https://doi.org/10.1016/j.ecolecon.2012.02.005.
Foley, J.Ja, DeFries, R., Asner, G.G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, Ea, Kucharik, C.J., Monfreda, C., Patz, Ja, Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570–574. https://doi.org/10.1126/science.1111772.
Galford, G.L., Mustard, J.F., Melillo, J., Gendrin, A., Cerri, C.C., 2008. Wavelet analysis of MODIS time series to detect expansion and intensification of row-crop agriculture in Brazil. Remote Sens. Environ. 112, 576–587. https://doi.org/10.1016/j.rse.2007.05.017.
Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., 2013. Sustainable intensification in agriculture: premises and policies. Science 341, 33–34.
Garrett, R.D., Lambin, E.F., Naylor, R.L., 2013a. The new economic geography of land use change: supply chain configurations and land use in the Brazilian Amazon. Land Use Policy 34, 265–275. https://doi.org/10.1016/j.landusepol.2013.03.011.
Garrett, R.D., Lambin, E.F., Naylor, R.L., 2013b. Land institutions and supply chain configurations as determinants of soybean planted area and yields in Brazil. Land Use Policy 31, 385–396.
Garrett, R.D., Carlson, K.M., Rueda, X., Noojipady, P., 2016. Assessing the potential additionality of certification by the Round Table on Responsible Soybeans and the Roundtable on Sustainable Palm Oil. Environ. Res. Lett. 11, 045003. https://doi.org/10.1088/1748-9326/11/4/045003.
Garrett, R.D., Gardner, T., Fonseca, T., Marchand, S., Barlow, J., de Blas, D.E., Ferreira, J., Lees, A.C., Parry, L., 2017a. Explaining the persistence of low income and environmentally degrading land uses in the Brazilian Amazon. Ecol. Soc. 22. https://doi.org/10.5751/ES-09364-220327.
Garrett, R.D., Niles, M., Gil, J.D.B., Dy, P., Reis, J., Valentim, J.F., 2017b. Policies for reintegrating crop and livestock systems: a comparative analysis. Sustainability 9, 473. https://doi.org/10.3390/su9030473.
Garrett, R.D., Niles, M.T., Gil, J.D.B., Gaudin, A., Chaplin-Kramer, R., Assmann, A., Assmann, T., Brewer, K., de Faccio Carvalho, P., Cortner, O., 2017c. Social and ecological analysis of commercial integrated crop livestock systems: current knowledge and remaining uncertainty. Agric. Syst. 155, 136–146. https://doi.org/10.1016/j.agsy.2017.05.003.
Gasparri, I.N., Grau, R.H., 2009. Deforestation and fragmentation of Chaco dry forest in NW Argentina (1972–2007). For. Ecol. Manag. 258, 913–921. https://doi.org/10.1016/j.foreco.2009.02.024.
Gibbs, H.K., Rausch, L., Munger, J., Schelly, I., Morton, D.C., Noojipady, P., Soares-Filho, B., Barreto, P., Micol, L., Walker, N.F., 2015. Brazil's Soy Moratorium. Science 347, 377–378.
Gibbs, H.K., Munger, J., L'Roe, J., Barreto, P., Pereira, R., Christie, M., Amaral, T., Walker, N.F., 2016. Did ranchers and slaughterhouses respond to zero-deforestation agreements in the Brazilian Amazon? Conserv. Lett. 9, 32–42. https://doi.org/10.1111/conl.12175.
Gil, J.D.B., Garrett, R.D., Berger, T., 2016. Determinants of crop-livestock integration in Brazil: evidence from the household and regional levels. Land Use Policy 59, 557–568.
Gil, J.D.B., Garrett, R., Rotz, A., Daioglou, V., Valentim, J., Costa, M.H., Pires, G.F., Reis, J., Lopes, L., 2018. Tradeoffs in the quest for climate smart agricultural intensification in Mato Grosso, Brazil. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aac4d1.
Gollnow, F., Lakes, T., 2014. Policy change, land use, and agriculture: the case of soy production and cattle ranching in Brazil, 2001–2012. Appl. Geogr. 55, 203–211. https://doi.org/10.1016/j.apgeog.2014.09.003.
Gollnow, F., Hissa, L., de, B.V., Rufin, P., Lakes, T., 2018. Property-level direct and indirect deforestation for soybean production in the Amazon region of Mato Grosso, Brazil. Land Use Policy 78, 377–385. https://doi.org/10.1016/j.landusepol.2018.07.010.
Graesser, J., Aide, T.M., Grau, H.R., Ramankutty, N., 2015. Cropland/pastureland dynamics and the slowdown of deforestation in Latin America. Environ. Res. Lett. 10, 34017.
Grau, H., Aide, M., 2008. Globalization and land-use transitions in Latin America. Ecol. Soc. 13. https://doi.org/10.5751/ES-02559-130216.
Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853. https://doi.org/10.1126/science.1244693.
Herath, D.P., Weersink, A.J., Carpentier, C.L., 2005. Spatial and temporal changes in the US hog, dairy, and fed-cattle sectors, 1975–2000. Rev. Agric. Econ. 27, 49–69.
Hertel, T.W., Implications of agricultural productivity for global cropland use and GHG emissions: Borlaug vs. Jevons. GTAP Working Paper 69, 2012, https://ideas.repec.org/p/gta/workpp/4020.html.
Hinrichs, C.C., Welsh, R., 2003. The effects of the industrialization of US livestock agriculture on promoting sustainable production practices. Agric. Hum. Values 20, 125–141.
IBGE, 2006. Agriculture and Livestock Census. Instituto Brasileiro de Geografia e Estatística.
IBGE, 2013. Municipal Agricultural Production Survey [WWW Document]. Braz. Inst. Geogr. Stat. http://sidra.ibge.gov.br.
INPE, 2016. Projeto PRODES: Monitoramento da floresta Amazônica Brasileira por satélite.
Kaimowitz, D., Angelsen, A., 2008. Will livestock intensification help save latin America's tropical forests? J. Sustain. For. 27, 6–24. https://doi.org/10.1080/10549810802225168.
Kastens, J.H., Brown, J.C., Coutinho, A.C., Bishop, C.R., Esquerdo, J.C.D.M., 2017. Soy moratorium impacts on soybean and deforestation dynamics in Mato Grosso, Brazil. PLoS One 12. https://doi.org/10.1371/journal.pone.0176168.
Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S., 2012. Global changes in diets and the consequences for land requirements for food. Proc. Natl. Acad. Sci. U. S. A. 109, 6868–6872. https://doi.org/10.1073/pnas.1117054109.
Klingler, M., Richards, P.D., Ossner, R., 2018. Cattle vaccination records question the impact of recent zero-deforestation agreements in the Amazon. Reg. Environ. Change 18, 33–46.
Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. U. S. A. 108, 3465–3472. https://doi.org/10.1073/pnas.1100480108.
Lambin, E.F., Turner, B.L., Geist, H.J., Agbola, S.B., Angelsen, A., Bruce, J.W., Coomes, O.T., Dirzo, R., Fischer, G., Folke, C., 2001. The causes of land-use and land-cover change: moving beyond the myths. Glob. Environ. Change 11, 261–269.
Lambin, E.F., Gibbs, H.K., Heilmayr, R., Carlson, K.M., Fleck, L.C., Garrett, R.D., de Waroux, Y., le, P., McDermott, C.L., McLaughlin, D., Newton, P., Nolte, C., Pacheco, P., Rausch, L.L., Streck, C., Thorlakson, T., Walker, N., 2018. The role of supply-chain initiatives in reducing deforestation. Nat. Clim. Change 8, 109–116.
Latawiec, A.E., Strassburg, B.B.N., Silva, D., Alves-Pinto, H.N., Feltran-Barbieri, R., Castro, A., Iribarrem, A., Rangel, M.C., Kalif, K.A.B., Gardner, T., Beduschi, F., 2017. Improving land management in Brazil: a perspective from producers. Agric. Ecosyst. Environ. 240, 276–286. https://doi.org/10.1016/j.agee.2017.01.043.
le Polain de Waroux, Y., Garrett, R.D., Heilmayr, R., Lambin, E.F., 2016. Land-use policies and corporate investments in agriculture in the Gran Chaco and Chiquitano. Proc. Natl. Acad. Sci. 113, 4021–4026. https://doi.org/10.1073/pnas.1602646113.
le Polain de Waroux, Y., Garrett, R., Lambin, E., Graesser, J., Nolte, C., 2017. The restructuring of South American soy and beef production and trade under changing environmental regulations. World Dev. https://doi.org/10.1016/j.worlddev.2017.05.034.
Macedo, M.N., Defries, R.S., Morton, D.C., Stickler, C.M., Galford, G.L., Shimabukuro, Y.E., 2012. Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. Proc. Natl. Acad. Sci. U. S. A. 109, 1341–1346. https://doi.org/10.1073/pnas.1111374109.
MAPA, 2011. Plano setorial de mitigação e de adaptação às mudanças climáticas para a consolidação de uma economia de baixa emissão de carbono na agricultura [Sectoral plan for climate mitigation and adaptation and the consolidation of a low carbon economy in agriculture]. MAPA/ACS, Brasilia.
Martha Jr, G.B., Alves, E., Contini, E., 2011. Dimensão econômica de sistemas de integração lavoura-pecuária (Economic dimension of integrated crop-livestock systems). Pesqui. Agropecuria Bras. 46, 1117–1126.
Merry, F., Soares-Filho, B., 2017. Will intensification of beef production deliver conservation outcomes in the Brazilian Amazon? Elem Sci Anth 5.
Meyfroidt, P., Lambin, E.F., Erb, K.-H., Hertel, T.W., 2013. Globalization of land use: distant drivers of land change and geographic displacement of land use. Curr. Opin. Environ. Sustain. 5, 438–444.
Morton, D.C., DeFries, R.S., Shimabukuro, Y.E., Anderson, L.O., Arai, E., del Bon Espirito-Santo, F., Freitas, R., Morisette, J., 2006. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. Proc. Natl. Acad. Sci. 103, 14637–14641. https://doi.org/10.1073/pnas.0606377103.
Naylor, R., Steinfeld, H., Falcon, W., Galloway, J., Smil, V., Bradford, E., Alder, J., Mooney, H., 2005. Losing the links between livestock and land. Science 310, 1621. https://doi.org/10.1126/science.1117856.
Neumann, K., Verburg, P.H., Stehfest, E., Müller, C., 2010. The yield gap of global grain production: a spatial analysis. Agric. Syst. 103, 316–326.
Nolte, C., le Polain de Waroux, Y., Munger, J., Reis, T.N.P., Lambin, E.F., 2017. Conditions influencing the adoption of effective anti-deforestation policies in South America's commodity frontiers. Glob. Environ. Change 43, 1–14. https://doi.org/10.1016/j.gloenvcha.2017.01.001.
Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333 (6047), 1289–1291.
Piquer-Rodríguez, M., Butsic, V., Gärtner, P., Macchi, L., Baumann, M., Gavier Pizarro, G., Volante, J.N., Gasparri, I.N., Kuemmerle, T., 2018. Drivers of agricultural land-use change in the Argentine Pampas and Chaco regions. Appl. Geogr. 91, 111–122. https://doi.org/10.1016/j.apgeog.2018.01.004.
Porter, M.E., 1998. Clusters and the new economics of competition. Harv. Bus. Rev. 77–90.
Porter, M.E., 2000. Location, competition, and economic development: local clusters in a global economy. Econ. Dev. Q. 14, 15–34. https://doi.org/10.1177/

089124240001400105.
Rausch, L.L., Gibbs, H.K., 2016. Property arrangements and Soy governance in the Brazilian state of Mato Grosso: implications for deforestation-free production. Land 5, 7.
Richards, P., 2017. It's not just where you farm; it's whether your neighbor does too. How agglomeration economies are shaping new agricultural landscapes. J. Econ. Geogr. 18, 87–110.
Richards, P.D., VanWey, L., 2016. Farm-scale distribution of deforestation and remaining forest cover in Mato Grosso. Nat. Clim. Change 6, 418–425.
Richards, P., Pellegrina, H., VanWey, L., Spera, S., 2015. Soybean development: the impact of a decade of agricultural change on urban and economic growth in Mato Grosso, Brazil. PLoS One 10, e0122510. https://doi.org/10.1371/journal.pone.0122510.
Richards, P., Arima, E., VanWey, L., Cohn, A., Bhattarai, N., 2017. Are Brazil's deforesters avoiding detection? Conserv. Lett. 10, 470–476.
Rueda, X., Garrett, R.D., Lambin, E.F., 2017. Corporate investments in supply chain sustainability: selecting instruments in the agri-food industry. J. Clean. Prod. 142, 2480–2492.
Shepon, A., Eshel, G., Noor, E., Milo, R., 2016. Energy and protein feed-to-food conversion efficiencies in the US and potential food security gains from dietary changes. Environ. Res. Lett. 11, 105002.
Silvério, D.V., Brando, P.M., Macedo, M.N., Beck, P.S.A., Bustamante, M., Coe, M.T., 2015. Agricultural expansion dominates climate changes in southeastern Amazonia: the overlooked non-GHG forcing. Environ. Res. Lett. 10, 104015. https://doi.org/10.1088/1748-9326/10/10/104015.
Spera, S., 2017. Agricultural intensification can preserve the Brazilian Cerrado: applying lessons from Mato Grosso and Goiás to Brazil's last agricultural frontier. Trop. Conserv. Sci. 10, 1940082917720662. https://doi.org/10.1177/1940082917720662.
Spera, S.A., Cohn, A.S., VanWey, L.K., Mustard, J.F., Rudorff, B.F., Risso, J., Adami, Marcos, 2014. Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics. Environ. Res. Lett. 9, 064010. https://doi.org/10.1088/1748-9326/9/6/064010.
Spera, S.A., Galford, G.L., Coe, M.T., Macedo, M.N., Mustard, J.F., 2016. Land-use change affects water recycling in Brazil's last agricultural frontier. Glob. Change Biol. Bioenergy 22, 3405–3413.
Stickler, C.M., Nepstad, D.C., Azevedo, A.A., McGrath, D.G., 2013. Defending public interests in private lands: compliance, costs and potential environmental consequences of the Brazilian Forest Code in Mato Grosso. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 368, 20120160. https://doi.org/10.1098/rstb.2012.0160.
Strassburg, B.B.N., Latawiec, A.E., Barioni, L.G., Nobre, C.A., da Silva, V.P., Valentim, J.F., Vianna, M., Assad, E.D., 2014. When enough should be enough: improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. Glob. Environ. Change 28, 84–97. https://doi.org/10.1016/j.gloenvcha.2014.06.001.
Tilman, D., Cassman, K.G., Matson, P.a, Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677. https://doi.org/10.1038/nature01014.
Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. 108, 20260–20264.
Tittonell, P., Klerkx, L., Baudron, F., Félix, G.F., Ruggia, A., van Apeldoorn, D., Dogliotti, S., Mapfumo, P., Rossing, W.A., 2016. Ecological intensification: local innovation to address global challenges. Sustainable Agriculture Reviews. Springer, pp. 1–34.
Turner, B.L., Ali, A.S., 1996. Induced intensification: agricultural change in Bangladesh with implications for Malthus and Boserup. Proc. Natl. Acad. Sci. 93, 14984–14991.
VanWey, L.K., Spera, S., de Sa, R., Mahr, D., Mustard, J.F., Sa, R., 2013. Socioeconomic development and agricultural intensification in Mato Grosso. Philos. Trans. R. Soc. B Biol. Sci. 368, 20120168. https://doi.org/10.1098/rstb.2012.0168.
Villoria, N.B., Byerlee, D., Stevenson, J., 2013. The effects of agricultural technological progress on deforestation: what do we really know? Appl. Econ. Perspect. Policy 36, 211–237.
Vincente, M., 2016. Adoção de ILPF chega a 11,5 milhões de hectares (Adoption of ILPF arrives at 11.5 million hectares). Embrapa.
Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A., 2013. Affluence drives the global displacement of land use. Glob. Environ. Change 23, 433–438. https://doi.org/10.1016/j.gloenvcha.2012.12.010.