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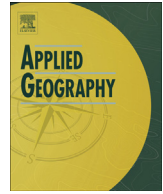
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Land use sustainability on the South-Eastern Amazon agricultural frontier: Recent progress and the challenges ahead



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ABSTRACT

The recent decoupling of deforestation and soybean production has raised optimistic expectations towards enhanced land use sustainability in the South-Eastern Amazon agricultural frontier. Nonetheless, assessing land use sustainability implies not only the consideration of how agricultural activities affect natural ecosystems but also how they impact on society and how society can cope with them. We review some of the forthcoming challenges that the agricultural sector should address to confirm its significant progress towards land use sustainability. Firstly, we assess the recent efforts to adopt environmentally friendly practices with regard to the ongoing intensification process mainly based on double cropping systems. Secondly, while rapid agricultural development has brought major social advances, we evidence a recent trend towards a decoupling of soy production and the Human Development Index at municipality level. We then put this result into perspective considering that the trend towards agricultural intensification based on the use of large amounts of agrochemicals could lead to major health concerns which are still too rarely considered. Finally, we discuss how the recent efficient policies to contain deforestation in the Amazon can cause indirect land use changes in the Brazilian Cerrados and in African Savannas, thus potentially leading to an “illusion of preservation” at global scale. We conclude that new indicators involving social sciences are necessary to better address the complexity of land use sustainability on the still very dynamic agricultural frontier in the South-Eastern Amazon.

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1. Introduction

The rapid expansion of cultivated areas in the South-Eastern Amazon has long been pointed out as a major threat to the environment (Dubreuil, 2002; Fearnside, 2001; Morton et al., 2006). This is especially true in the state of Mato Grosso where the area covered by soybean crops grew from 1.5 to 8.9 million hectares from 1990 to 2015 (IBGE, 2016) while 139,917 km² of forests were cleared between 1988 and 2015, i.e. 33.8% of total deforestation in the Legal Amazon (INPE, 2016). Nonetheless, the last decade has been marked by a decoupling of deforestation and soybean production (Macedo et al., 2012), since deforestation rates in Mato Grosso experienced a 90% decrease between 2004 and 2014 (from 11,814 to 1075 km²/year; INPE, 2016) whereas crop production continued to increase thanks to the adoption of intensive agricultural practices (from 14.5 to 26.5 million tons of soybean; IBGE, 2016).

Whereas a few studies suggest that this recent slowdown in deforestation in the South-Eastern Amazon may be partially due to the scarcity of available land suitable for agricultural development in Mato Grosso (Spera et al., 2014) or to the adaptation of land owners who clear forest in a way that cannot be detected by the remote sensing-based monitoring systems (Richards, Arima, VanWey, Cohn, & Bhattarai, 2016), most authors emphasize the importance of the implementation of effective environmental public policies (Arima, Barreto, Araújo, & Soares-Filho, 2014) and market-oriented agreements (Gibbs et al., 2015; Nepstad et al., 2014) involving well-designed public-private instruments (Lambin et al., 2014). Increased considerations for environmental governance to contain deforestation have led to initiatives promoted at i) international level (e.g. “Amazon Fund” with a Norwegian commitment; Nepstad et al., 2009), ii) federal level (e.g. Low Carbon Agriculture Plan (Ministerio da Agricultura, 2012); or the implementation of efficient monitoring and licensing systems (INPE, 2016; SFB, 2016)), iii) state level (e.g. Soy and Beef moratorium; Rudorff et al., 2011; Gibbs et al., 2015) and iv) local level (e.g. Lucas Legal and SorrisoVivo projects; Le Tourneau et al., 2013) to establish an improved environmental-friendly agricultural model.

Such evolution raised optimistic expectations towards enhanced land use sustainability (Galford, Soares-Filho, & Cerri, 2013; Hecht, 2012; Lapola et al., 2013; Martinelli, Naylor, Vitousek, & Moutinho, 2010; Nepstad et al., 2014). Nonetheless, land use sustainability in the Amazon is often approached from an environmental perspective, for example assessing how the adoption of new agricultural practices may contribute to maintain ecosystem services such as climate regulation through the reduction of greenhouse gas emissions (Galford et al., 2013). Yet, at a time when a new integrated governance model with complementary socio-economic and environmental policies is being promoted (Arvor, Daugeard, et al., 2016), other dimensions of sustainability deserve to be considered in order to get a better overview of the level of sustainability on the Amazon agricultural frontier. In this regard, a special attention must be paid to interrelated issues that embody both challenges and opportunities created by the development of frontier regions (Gardner, Godar, & Garrett, 2014). For instance, economic development through agricultural intensification may

both lead to improved living conditions and to the eviction of people from rural areas due to monoculture and land concentration, thus increasing inequality among local communities (Lapola et al., 2013; Tritsch & Le Tourneau, 2016).

Based on this assertion, the objective of this paper is to analyze recent land use changes in the South-Eastern Amazon agricultural frontier in order to raise underexplored questions about the forthcoming challenges that the Brazilian Amazon agricultural sector should address to confirm its recent progress towards land use sustainability.

In order to achieve this objective, we consider that sustainability deals with analyzing society–environment interactions with respect to the possibility of continuing the observed trajectories into the future (Haberl, Fischer-Kowalski, Krausmann, Weisz, & Winiwarter, 2004). In this regard, assessing land use sustainability of society–environment interactions implies not only the consideration of (1) how socio-economic activities affect natural ecosystems, i.e. which driving forces for which environmental impacts, but also (2) how these changes impact on society and (3) how society can cope with them (Haberl et al., 2004). To address these issues, we joined an interdisciplinary research team under the frame of the H2020 ODYSSEA European project (Observatory of the Dynamics of Interactions between Societies and Environment in the Amazon) in order to review papers about recent agricultural dynamics in the South-Eastern Amazon and also cross-reference agricultural, socio-economic and health data.

In the first section, we discuss the recent generalization of new agricultural practices in a context of global climate-change. In the second section, we consider how land use changes related to large scale agricultural activities have enabled social development in Mato Grosso but also raised new concerns about human health. Finally, in the third section, we put into perspective the recent decrease in deforestation, considering its potential implications for other biomes and countries elsewhere.

2. New agricultural practices: a sustainable pathway in a context of global change?

2.1. New agricultural practices towards sustainable intensification

While crop expansion has long been the main pillar of agricultural growth in the Amazon (Fig. 1), the adoption of new agricultural practices currently represents the main pathway to increase crop production with limited impacts on wildlands. In this regard, the Low Carbon Agriculture Plan (ABC Plan) launched by the Brazilian government in 2010 includes six programs to support the adoption of environmentally friendly practices (R\$10 billion of loans had already been allocated to farmers by February 2015; Ministerio da Agricultura, 2015). Amongst the main technologies promoted, no-tillage practices, nitrogen fixation, integrated crop-livestock-forestry systems and the restoration of degraded pastures are of particular importance.

The wide and rapid generalization of no-tillage practices in Brazil (31.811 million hectares in 2012; FEBRAPDP, 2015), especially in the Cerrado biome, is quite impressive. It consists in leaving the soil profile undisturbed, sowing successive crops in between the

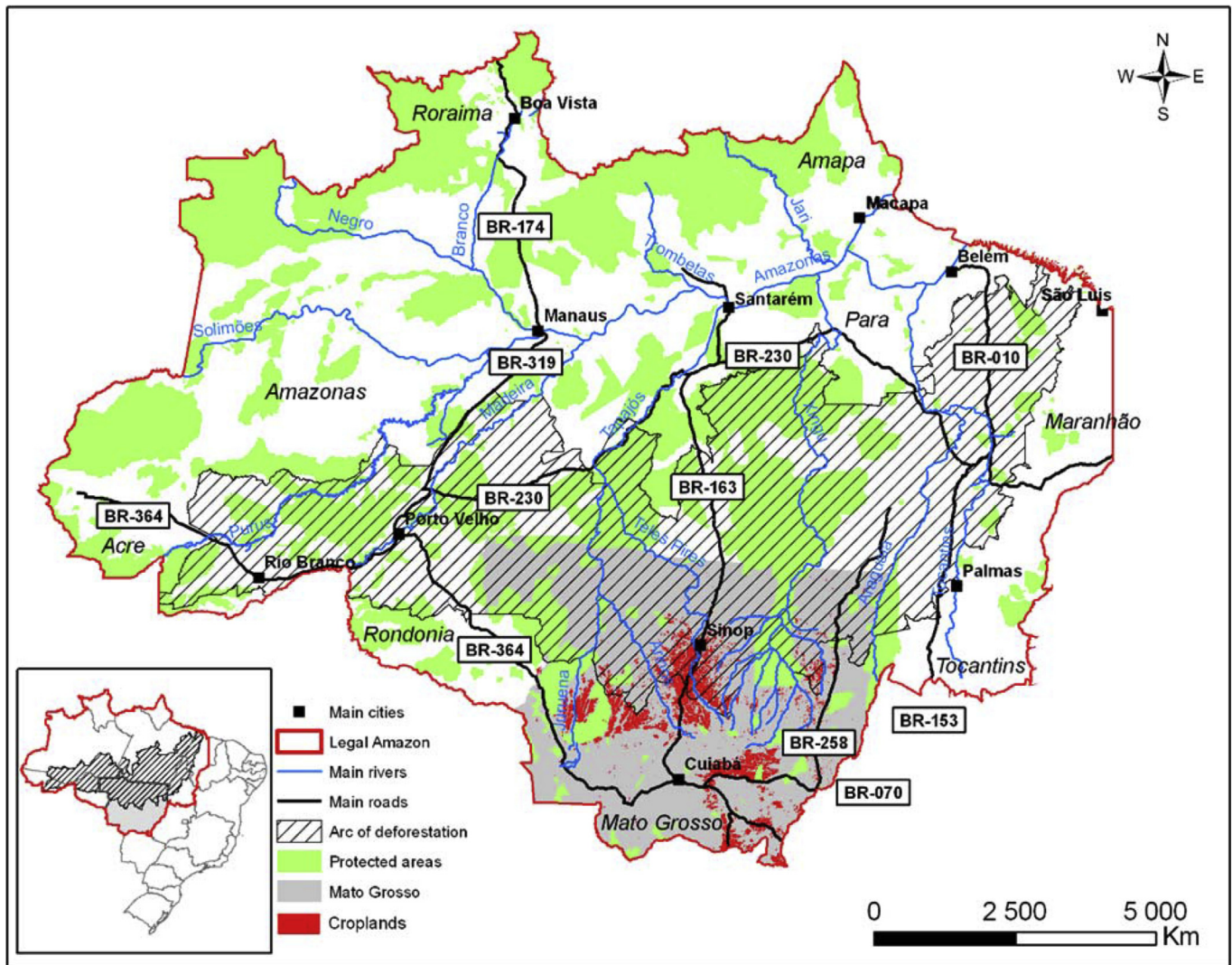


Fig. 1. Location of the State of Mato Grosso in the "Legal Amazon", showing the main roads, rivers, croplands, protected areas, and the arc of deforestation according to the Brazilian Institute of Environment (Portuguese acronym IBAMA).

stubble of the previous one. Thus, no-tillage is usually accompanied by the use of a second crop (usually maize, cotton, sorghum or millet) sown after the soybean harvest in order to improve the soil's quality by limiting the loss of chemical products (e.g. improving nitrogen fixation) and organic matter via erosion and by retaining water for a longer period (Landers, 2001; Scopel et al., 2005). In the main agricultural municipalities of Mato Grosso, such as Sorriso or Lucas do Rio Verde, the CONAB (Companhia Nacional de Abastecimento) estimates that 90% of the area planted with soybean is sown under no-tillage conditions.

More recently, integrated systems (IS) have been encouraged due to their environmental benefits (Lemaire, Franzluebbbers, Carvalho, de, & Dedieu, 2014; Salton et al., 2014). Four types of IS are usually defined: crop-livestock systems, livestock-forestry systems, crop-forestry systems and crop-livestock-forestry systems. At the Brazilian scale, the goal is to reach a total of 4 million ha cultivated with IS by 2020 (MAPA and MAPA, 2012), i.e. 6% of the total national cropped area of 66.4 million ha. According to Gil, Siebold, and Berger (2015), IS already cover about 500,000 ha in Mato Grosso, among which crop-livestock systems are largely dominant, accounting for 89% of the state's IS area. Integrated

systems based on an interannual rotation between pasture and crop are also part of a process to restore degraded pastures. IS thus represent important opportunities for sustainable intensification, as the restoration of degraded pastures is a major priority to improve the land use sustainability of the Amazon agricultural sector, especially with regards to greenhouse gas emissions and economic enhancement of degraded areas (Galford et al., 2013). Pastures currently represent the main land use in the Amazon and Cerrado biomes (Lapola et al., 2013), of which about 50% in the Cerrado biome and more than 60% in the Amazon biome are degraded pastures (Strassburg et al., 2014). The same authors indicated that both the conversion of part of these pastures to croplands and the increase in pasture productivity (from 32–34% to 49–52% of its potential at Brazilian scale) would enable demands for meat, crops, wood and biofuels to be met until 2040 without additional deforestation. This process of pasture conversion to croplands is already underway since it accounted for 49% of crop expansion in Mato grosso during the 2000–2013 (Cohn, Gil, Berger, Pellegrina, & Toledo, 2016), and even 91% for the 2006–2010 period (Macedo et al., 2012). Nonetheless, the conversion of pasture to crops seems to evolve slower than expected since only 1/7 of

pasture agronomically suitable for cultivation had been converted by 2013 (Cohn, Gil, et al., 2016).

2.2. The generalization of double cropping systems: a sustainable strategy in a context of climate change?

Despite the efforts to support the adoption of new environmentally friendly agricultural practices, the fact is that the main evolution observed during the last decade refers to the rapid generalization of intensive practices such as double cropping systems (from 35% to 62% of the net cropped area between 2000 and 2007; Arvor et al., 2012). Actually, even some environmental agricultural practices such as no-tillage were widely and rapidly adopted by farmers firstly because it facilitates the cultivation of two commercial crops per rainy season (especially soybean and maize or soybean and cotton). Whereas the generalization of double cropping systems may be considered as an effective strategy to reduce pressure on forests, it raises new important environmental issues that may counterbalance the benefits from deforestation reduction. First, the production of soybean, maize and cotton requires to use large amounts of agrochemical products which may affect Amazonian biodiversity (Schiesari, Waichman, Brock, Adams, & Grillitsch, 2013). At state level, the consumption of agrochemicals increased almost fivefold between 2000 and 2013, from 18,078 to 87,520 tons of active ingredient, i.e., 17% of total agrochemicals consumption in Brazil (IBAMA, 2014) (Fig. 2). This increase is primarily explained by the expansion of cropped areas but it is also the result of agricultural intensification. The mean use of agrochemicals increased from 3.8 to 6.7 kilograms of active ingredient per hectare to support a large increase in maize yields (from 3 to nearly 6 tons by hectare during the last decade) and the rapid expansion of cotton areas from 257 to 613 thousand hectares from 2000 to 2014 (IBGE, 2016). Indeed, nearly 80% of insecticides sold in Brazil is dedicated to cotton production (Pires, Caldas, & Recena, 2005) since farmers are used to apply up to 17 rounds of insecticides and

fungicides, using 41 different insecticides to cultivate cotton (Ofstehage, 2016). In an area dominated by single-cropped soybean with some fields double-cropped with maize, studies evidenced that concentrations of nitrate and phosphate in soils and groundwater of cultivated watersheds remain relatively low, similar to those observed in forest areas, and with low risk of losses to waterways (Neill et al., 2013; Riskin et al., 2013). However, these results should be considered carefully since results may vary significantly in areas where cotton is widely cultivated. Indeed, the authors warn about the long term capacity of soils to adsorb fertilizers on the long term in a context of increased erosion due to soil compaction and overall increased use of agrochemicals, as it is the case for cotton (Neill et al., 2013).

Second, many pivot irrigation systems were installed and numerous artificial ponds were created on river networks to ensure water supply for maize and cotton crops, which are harvested in June and July at the beginning of the dry season. In the municipality of Sorriso (9345 km², most important soybean producer in Mato Grosso), Arvor, Daher, Corpetti, Laslier, and Dubreuil (2016) and Arvor, Daugeard, et al. (2016) identified 571 artificial water bodies covering a total of 20.8 km² based on visual inspection on Google Earth (Fig. 3). Whereas the impact of the construction of numerous water dams on Amazonian rivers is being actively considered (Fearnside, 2016), the potential negative effects of the multiplication of such ponds on hydrology, biodiversity and global warming on the long term and on large scales are still understudied.

Finally, the adoption of intensive practices was proven to be related to environmental (e.g. slope, elevation, temperature, precipitation) and socio-economic (e.g. soy logistics costs) variables (Spera et al., 2014; VanWey, Spera, de Sa, Mahr, & Mustard, 2013). Arvor, Dubreuil, Ronchail, Simões, and Funatsu (2014) also evidenced that regular and abundant rainfall was a key factor that enabled the adoption of double cropping practices in Mato Grosso. However, the overall Amazon basin ecosystem is now considered “in transition to a disturbance-dominated regime”, involving

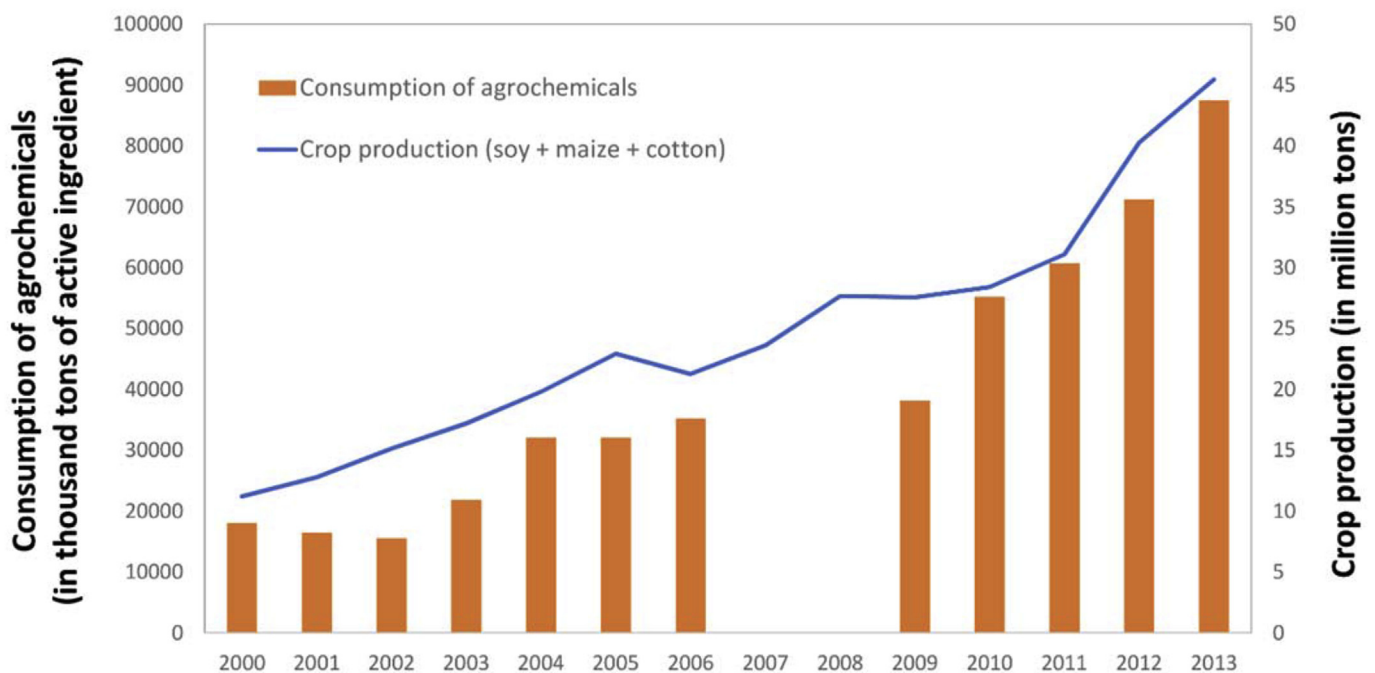


Fig. 2. Comparative evolution of crop production (soy + maize + cotton) and the consumption of agrochemicals in Mato Grosso from 2000 to 2013 (no data available for 2007 and 2008).

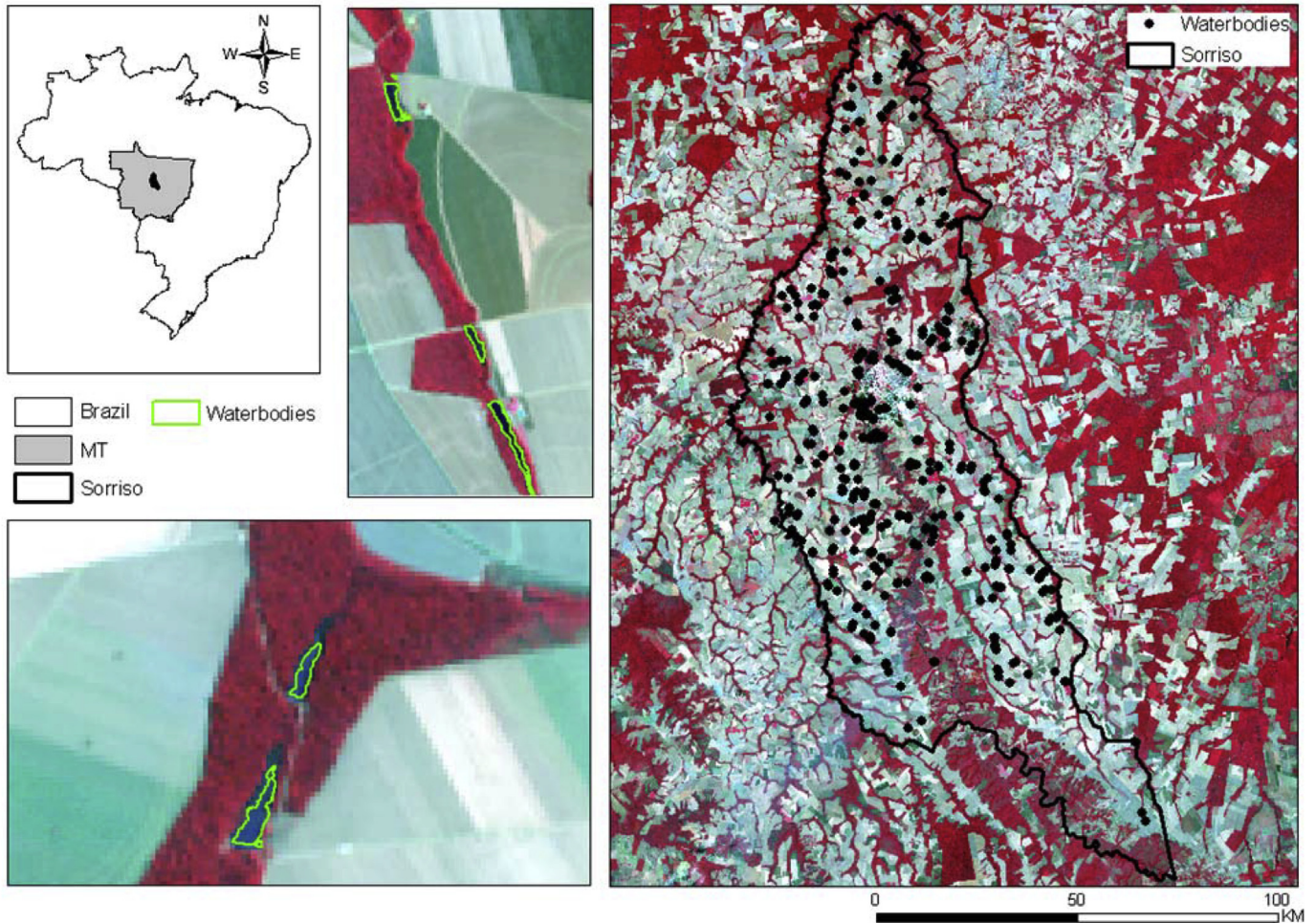


Fig. 3. Location of artificial ponds (N = 146) in the municipality of Sorriso (Mato Grosso) observed on Landsat 8 images in 2014.

important changes in water cycles (Davidson et al., 2012). Many studies have predicted that the high deforestation rates observed during the past decades could induce a shorter rainy season due to a delayed onset in the southern Amazon (Butt, de Oliveira, & Costa, 2011; Debortoli et al., 2015; Dubreuil, Debortoli, Funatsu, Nédélec, & Durieux, 2011; Fu & Li, 2004; Fu et al., 2013). Consequently, beyond the fact that any change in rainfall regimes might lead to substantial losses in productivity (Lapola et al., 2011; Oliveira, Costa, Soares-Filho, & Coe, 2013), it could also revert the tendency towards the adoption of double-cropping intensive practices in the long term (Arvor et al., 2014; Cohn, VanWey, Spera, & Mustard, 2016), calling into question the sustainability of the current intensification process.

Assessing how farmers will adapt to climate change thus represents a huge challenge to be addressed in order to ensure land use sustainability of the Amazon agricultural sector. Local Environmental Knowledge (LEK) has been proven to be of major importance to ensure adaptation to ever-changing environmental conditions (Fernández-Llamazares et al., 2015). However, in a context of a young agricultural frontier, still inhabited by the first generation of settlers who are often themselves the worthy heirs of pioneer families used to migrate towards better life conditions, one might question the ability of farmers to define new strategies based on their LEK and thus question their resilience in the face of global environmental change.

2.3. Underlying reasons for adopting new agricultural practices

The recent efforts to promote the transition towards enhanced conservation agriculture in the soybean frontier bears witness to the will to adopt a win-win agricultural model, i.e. increased economic development and enhanced environmental considerations. However, ensuring such a transition represents a huge challenge for pioneer farmers used to consider the Brazilian Cerrados as “a wasteland, neither productive nor pristine, which through hard work can be made productive” (Ofstehage, 2016). We argue that the future success (or failure) on the long-term of this transition towards land use sustainability depends on the capacity of farmers to change their perception about the environment.

The traditional expansionist model was initially mainly driven by exogenous forces (Lambin & Meyfroidt, 2010). Settlers, capital and technical options that supported agricultural expansion and consequent deforestation were mainly issued from Southern states of Brazil. Nowadays, exogenous reasons still prevail to explain the recent land use changes, which mainly result from initiatives to adapt the model to new policies and remain competitive on national and international markets. Indeed, reasons for change are directly related to economic logics since few producers consider environmental benefits as an incentive to adopt new practices (see Gil et al. (2015) on the adoption of integrated systems and Knowler and Bradshaw (2007) on the net positive financial impact of

conservation tillage adoption at farm level). In this regard, [Nepstad et al. \(2014\)](#) lament that the policies that were proven to be efficient to contain deforestation were based on punitive measures and propose to complement them with positive measures to encourage farmers to adopt sustainable agricultural practices. Definitely, it is still questionable whether the recent progress towards the adoption of new environmental-friendly practices is the result of enhanced environmental considerations or just a consequence of temporary governance and economic conditions. Addressing such a question requires a better understanding on the long term of the socio-economic factors, e.g. age, education, land tenure, off-farm activities as proposed by [Gil et al. \(2015\)](#) and [VanWey et al. \(2013\)](#), influencing the adoption of agriculture conservation practices in the South-Eastern Amazon.

3. Agricultural development in the Amazon: opportunities and threats for society

Land use sustainability in the Amazon is often approached from an environmental perspective ([Galford et al., 2013](#)), yet other dimensions of sustainability deserve to be better considered. On the one hand, we discuss how the rapid development of the agricultural sector in the Amazon frontier has brought major social advances, although it remains dominated by high social inequality, especially with regards to land tenure ([Lapola et al., 2013](#)). On the other hand, we argue that the recent trend towards agricultural intensification could lead to major health concerns which are still too rarely considered.

3.1. Towards a decoupling of soybean production and Human Development Index?

In Mato Grosso, official statistics indicate a significant positive relationship between the Human Development Index (HDI) and soybean production at municipality level. The HDI increased continuously from 1991 to 2010, i.e. during the period of rapid frontier expansion, and remained higher in areas of soybean cultivation ([Fig. 4A](#)). However, the HDI difference between “non-soybean areas” (i.e. municipalities where soybean production is null) and “soybean areas” is being reduced, as is also confirmed by the scatterplots relating HDI and soybean production ([Fig. 4B](#)). Furthermore, a covariance analysis evidences that the linear

models observed for each year (1991, 2000 and 2010) are significantly different, which may be interpreted as a decreasing influence of soybean production on HDI. These results thus indicate that, similarly to [Macedo et al. \(2012\)](#) who evidenced a recent decoupling between soy production and deforestation in Mato Grosso, HDI is also being decoupled from soy production, which could be the result of (i) efficient social policies promoted during the 2000s (*Fome zero, Bolsa Familia*, etc.; [Hall, 2006](#)) and (ii) the diversification of economic and agricultural activities which reduces dependency on a single commodity such as soybean. In this regard, this trend should be considered as a progress towards land use sustainability related to the consolidation of the Southern Amazon agricultural frontier. However, these results need to be validated in the long term. At the scale of the Brazilian Amazon, [Rodrigues et al. \(2009\)](#) evidenced a boom-and-bust development pattern on the frontier: “relative standards of living, literacy, and life expectancy increase as deforestation begins but then decline as the frontier evolves, so that pre- and post-frontier levels of human development are similarly low”. Indeed, development projects in the Amazon region traditionally have little scope for long-lasting development, despite being attractive to an extremely mobile and vulnerable population ([Barcellos, Feitosa, Damacena, & Andreatzi, 2010](#)). Yet, the boom-and-bust hypothesis in the Amazon has recently been contradicted ([Caviglia-Harris et al., 2016](#); [Tritsch & Arvor, 2016](#); [Weinhold, Reis, & Vale, 2015](#)). Commodity-based agricultural activities on the South-Eastern Amazon agricultural frontier may actually reverse the trend towards a bust pattern, through the accumulation of wealth, the establishment of intensive commercial activities and the reinforcement of local institutions that may warrant long term economic and social development. Nonetheless, the last (2005–2006) fall in commodity prices that caused a two year decrease (2006–2007) in soybean cultivated areas in Mato Grosso emphasized the latent weaknesses of the current agricultural model, especially with regards to the indebtedness of farmers ([Arvor, 2009](#)).

3.2. Agricultural intensification: a threat to human health

The recent land use changes also raise major health concerns. Actually, a new epidemiological profile emerged during the last decades ([Fig. 5](#)). While the first stages of deforestation promoted epidemics of vector-borne diseases, such as leishmaniosis and

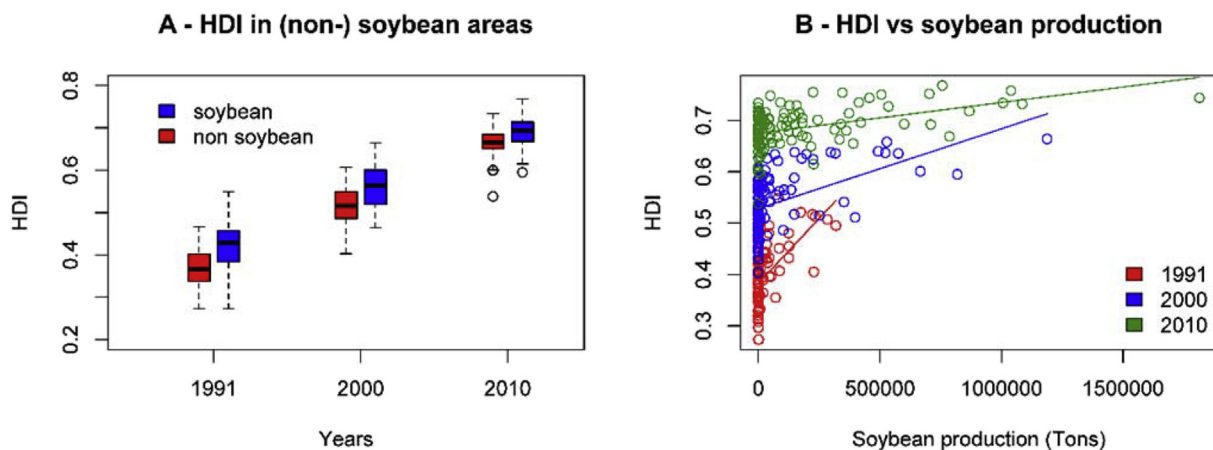


Fig. 4. Evolution of the Human Development Index (HDI) at municipality level in Mato Grosso. (A) Comparative evolution of the HDI in soybean and non-soybean municipalities in 1991, 2000 and 2010. (B) Scatterplots relating HDI to soybean production at the three same dates. The pairwise nested model comparison F-tests all led to p-values $< 4.10^{-4}$. (source: soybean production; Human Development Index; [IDHM, 2013](#)).

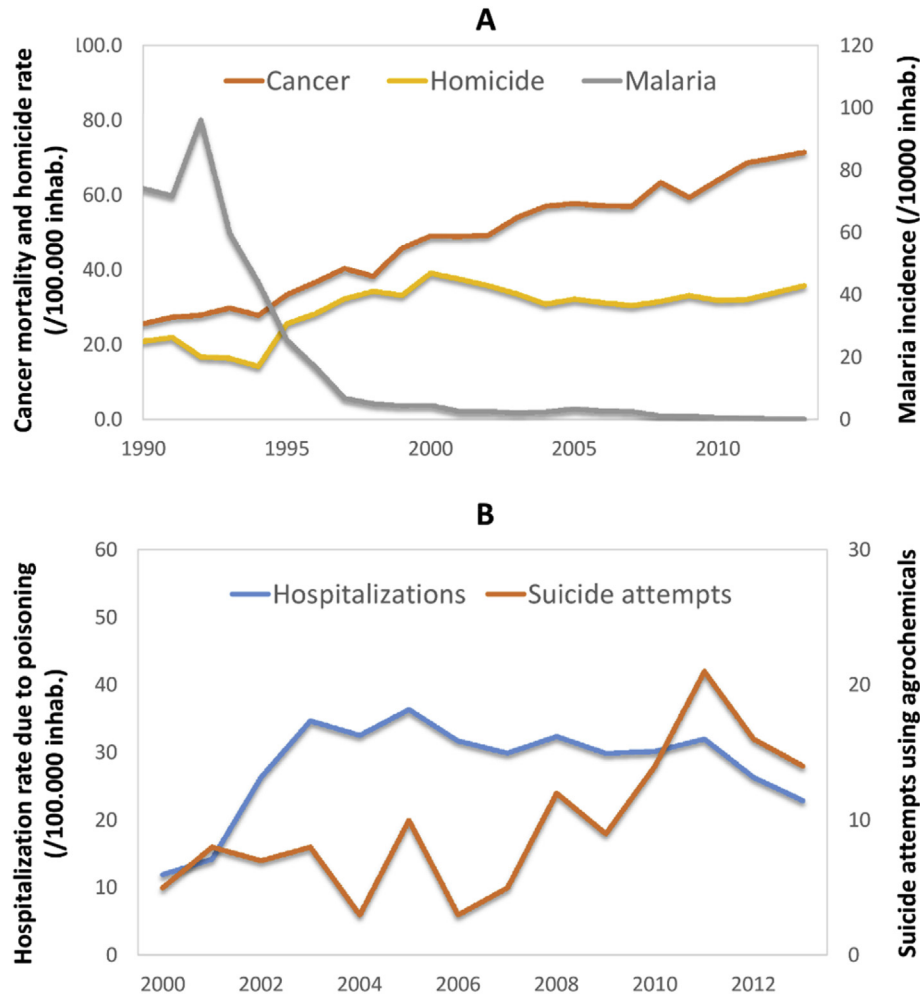


Fig. 5. (A) Malaria incidence in Mato Grosso, according to the Annual Parasite Index (API-SIVEP), calculated as the number of positive blood slides per 1000 inhabitants, and cancer mortality and homicide rates, expressed by the number of deaths per 100,000 inhabitants (SIM), and (B) Hospitalization rates in Mato Grosso, calculated by the number of hospital discharges due to poisoning events per 100,000 inhabitants (SIH), and suicide attempts using agrochemicals as registered by the health notification system (SINAN).

malaria, due to the contact with vector's ecological niches (Stefani et al., 2013), the subsequent conversion of wildlands to large single-crop areas reduced the incidence of such diseases, especially in Northern Mato Grosso where new cases of malaria decreased drastically (Atanaka-Santos, Souza-Santos, & Czeresnia, 2007; Hahn et al., 2014). On the contrary, violence, which is partially expressed by homicide rates, arose quickly in the end of 1990's. The expansion of the frontier was accompanied by illegal appropriation of land parcels, conflicts with indigenous and other traditional population groups, and rapid urbanization promoted by the expulsion of rural population to city peripheries (Souza, Xavier, Rican, de Matos, & Barcellos, 2015). After a rapid increase during the 1990's decade, homicide rates have stabilized at high levels. Moreover, cancer mortality rate rose steadily in Mato Grosso state since 1995, due to genetic, demographic and nutritional conditions but also potentially because of high level of exposure to agrochemicals as it has already been evidenced in other areas of intensive agriculture (INSERM, 2013).

As mentioned previously, the use of agrochemicals increased rapidly in the last decades to support the agricultural intensification process and the diversification to maize and overall cotton crops in Mato Grosso (Fig. 2). Considering that (i) Brazilian farmers are still allowed to use large amounts of agrochemicals banned in other countries, mainly in Europe and the United States,

and (ii) applications are often carried out by plane, it raises important health issues such as acute poisoning and other diseases caused by chronic exposure to agrochemicals for populations working and living in intensive agricultural areas (Recena, Pires, & Caldas, 2006). First studies led in the neighboring state of Mato Grosso do Sul evidenced a close relationship between crop production and health exposure issues (Recena et al., 2006). The role of insecticides such as organophosphates and carbamates as a main cause of human intoxication occurring in crop fields has been pointed out (Belo, Pignati, Dores, Moreira, & Peres, 2012). Such studies should now be applied to other states such as Mato Grosso where the situation is quite worrying and needs to be better considered to take into account the social dimension of land use sustainability. Poisoning became a threatening health problem in Mato Grosso, as revealed by the occurrence of hospitalizations due to poisoning, which increased sharply in the early 2000s (Fig. 5B). The occurrence of an annual mean of 100 notifications of poisoning due to the exposure to agrochemicals (SINAN, 2015), and 860 hospitalizations due to poisoning in the recent years (2010–2013) (SIH, 2015) are worth of concern. This data is certainly underestimated as, according to the Health Ministry, for each recorded case of poisoning notification, other fifty were not registered (Pires et al., 2005). Water and soil contamination, air pollution due to biomass burning

(forest and plantation) and temporary crop production were associated with the large use of agrochemicals in the *cerrado* biome (Soares & Porto, 2007). Similarly, while some studies have evidenced the depressive effects of agrochemical exposure that can lead to suicide (Freire & Koifman, 2013; Pires et al., 2005), it has been observed an increase in the number of suicide attempts using agrochemicals, varying from five cases per year in 2000 to over fifteen in the 2010s.

4. Agricultural development and environmental degradation: a spatial scale issue

For Lambin and Meyfroidt (2010), "reduced land degradation in one place is also to some extent the result of a displacement of food production and wood extraction to other places through trade". Consequently, agriculture in the Southern Amazon might thus still be related to deforestation but through indirect land use changes (Graesser, Aide, Grau, & Ramankutty, 2015; Richards, Walker, & Arima, 2014). Land use sustainability is thus closely related to the spatial scale of analysis. In this regard, it is essential to better consider the indirect land use changes (ILUC) related to the agricultural sector in the Amazon. ILUC refers to land use changes that arise from displacement effects when one land use (e.g. soybeans) encroaches on another land use (e.g. pasture), causing the impacted land use to encroach on wildlands (Walker, 2014). While most studies on the topic have focused on the impacts of ILUC on the Amazon forest (Arima, Richards, Walker, & Caldas, 2011; Lapola et al., 2010; Richards et al., 2014; Walker, 2012; Andrade de S, á, Palmer, & di Falco, 2013), we discuss the fact it is now necessary to better analyze how the recent dynamics observed in the Amazon might affect land use changes in other biomes and even other countries (Fig. 6).

4.1. The slowdown of deforestation in the Amazon and its consequences for the Brazilian Cerrados

Recent studies have analyzed the complex processes of indirect land use changes in the Brazilian Amazon. Richards et al. (2014) explained how land use changes in the Amazon were the result of complex interactions occurring in other regions. They criticized the hypothesis that deforestation in the Amazon would be decoupled from agricultural expansion since they estimated that 32% of deforestation observed in the Amazon biome since 2002 was indirectly attributable to the expansion and promotion of the agricultural sector in Brazil's other southern states. Similarly, Lapola et al. (2010) and Andrade de S et al. (2013) focused on the impact of biofuel plantations on deforestation in the Amazon and Arima et al. (2011) evidenced that crop expansion on pastures in Mato Grosso indirectly encouraged deforestation in the state of Para. Walker (2012) also suggested that deforestation in the Amazon could be related with the forest transition observed in the Brazilian Atlantic Forest.

In contrast, few studies have analyzed how the slowing down of deforestation in the Amazon affects land use changes in other biomes. The case of the Brazilian Cerrado biome, a savanna vegetation known as a biodiversity hotspot (Myers, Mittermeier, Mittermeier, da Fonseca, & Kent, 2000) is especially interesting because it experienced the greatest increase in new cropland in Latin America during the last decade (i.e. a 9.96 Mha increase between 2001 and 2013; Graesser et al., 2015). Although Macedo et al. (2012) did not find any leakage between the slowing down of deforestation and the soy expansion into the Cerrados of Mato Grosso, the Brazilian agricultural statistics collected by IBGE clearly indicate that the new hotspots for soy expansion are located in the Cerrados. Whereas first waves of soy expansion in Brazil started in the Southern states of Rio Grande do Sul and

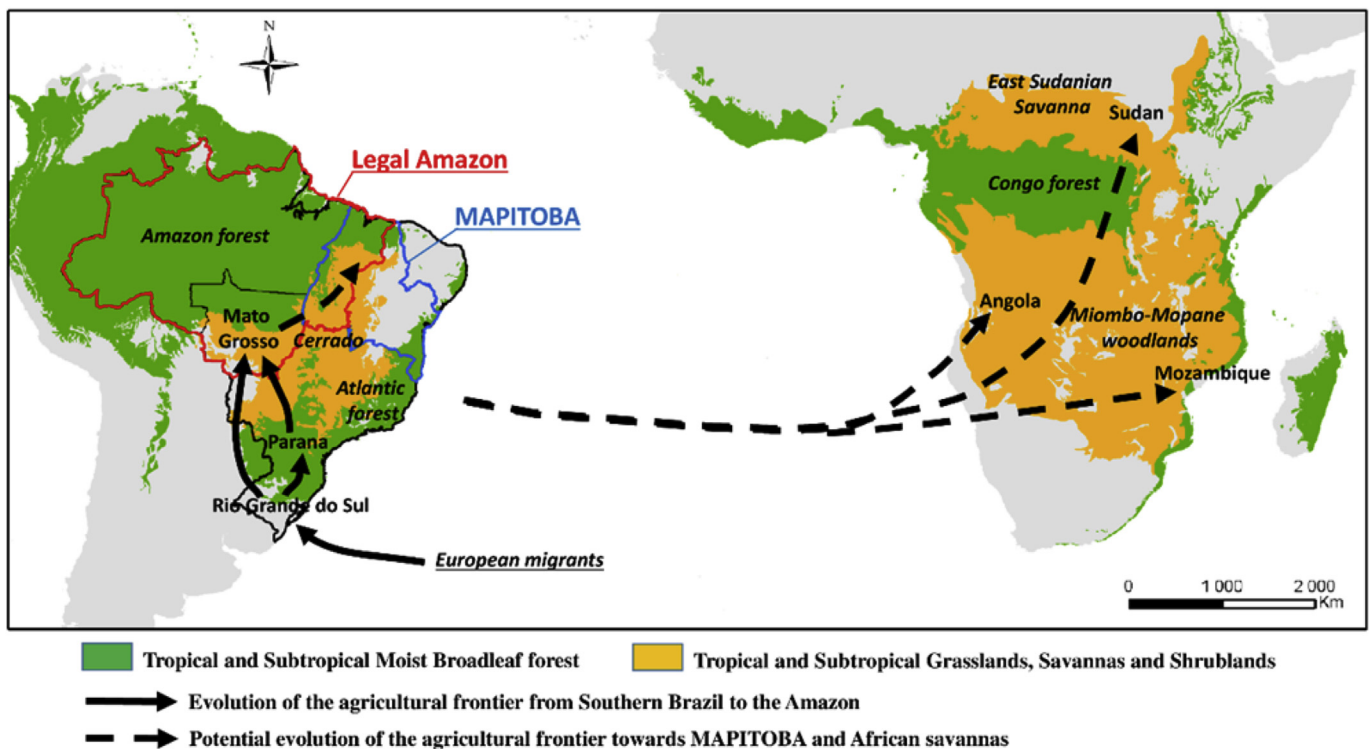


Fig. 6. Evolution of the agricultural frontier from Southern Brazil to the Amazon (Mato Grosso state) and then potentially to MAPITOBA Cerrado areas and African savannas (source for biome extension: TNC. http://maps.tnc.org/gis_data.html).

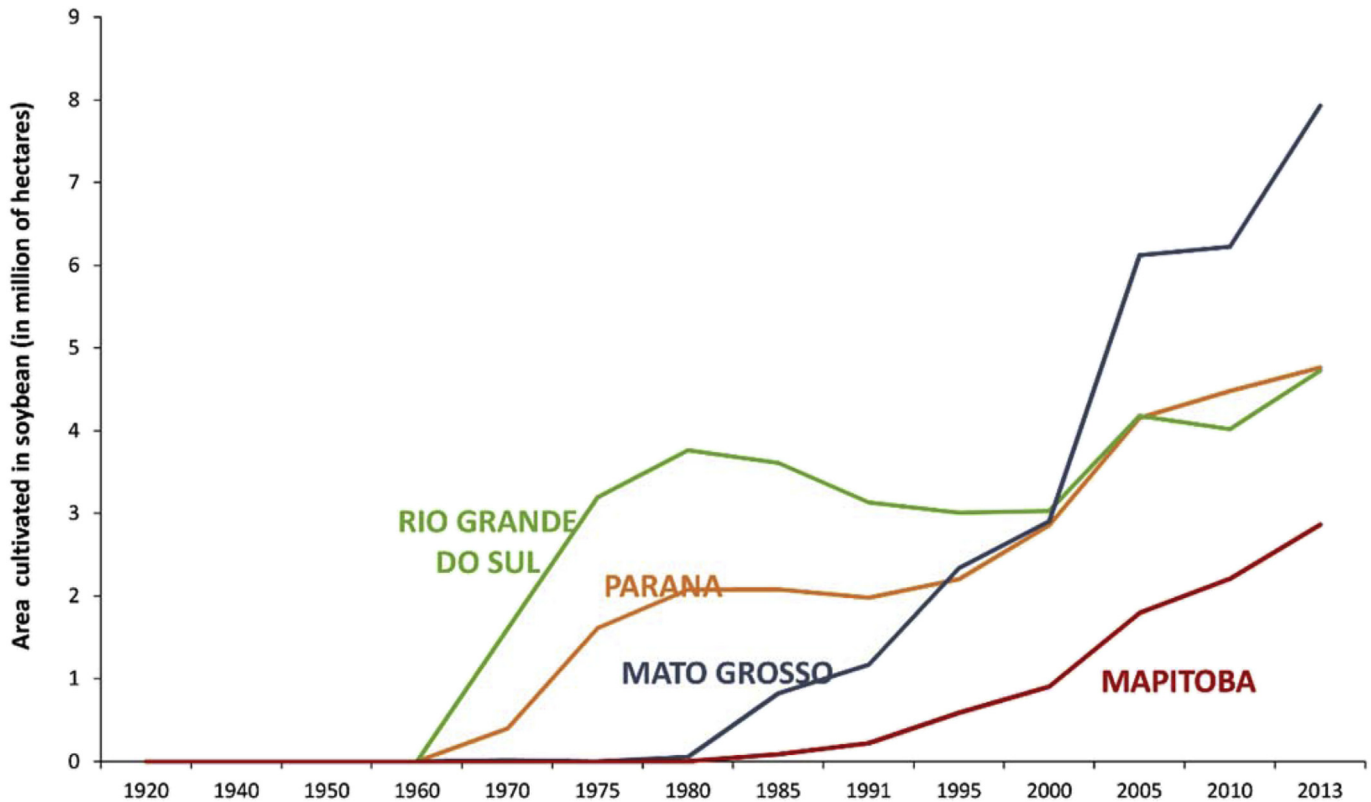


Fig. 7. Long-term historic evolution of the area cultivated with soybean in the Rio Grande do Sul, Parana, Mato Grosso and MAPITOBA regions. The successive waves of soy expansion reached Rio Grande do Sul, Parana, Mato Grosso and finally MAPITOBA in the 1960s, 1970s, 1990s and 2000s respectively.

Parana in the 1960s and 1970s before reaching Mato Grosso in the 1980s (Fig. 6), it currently appears that the last wave of soy expansion (started in the 2000s) is especially located in the states of Maranhão, Piauí, Tocantins and Bahia, also known as Mapitoba (Graesser et al., 2015) (Figs. 6 and 7). Gibbs et al. (2015) suggested that such expansion, of which nearly 40% occurred at the expense of native Cerrado vegetation between 2007 and 2013, might be related to the success of the Soy Moratorium in Mato Grosso and the fact that it does not apply in Cerrado areas.

Thus, additional studies are required to better analyze this leakage processes. Especially, it seems important to evaluate how the recent changes in the Forest Code, which reduce the requirements for protecting natural vegetation on private farmlands and give farmers the possibility of compensating for their lack of preserved areas by protecting natural vegetation outside their farm (Sparovek, Berndes, Barretto, de, & Klug, 2012), impact land use in the Cerrado biome. Moreover the Soybean Moratorium is temporary and regularly renewed, what questions its long-term efficiency to contain new potential agricultural expansion into Amazon or Cerrado areas. In this regard, Gibbs et al. (2015) already argued to expand the Soy Moratorium to a longer time period and to the Cerrado biome.

4.2. Exporting the Amazon agricultural frontier to Africa?

Beyond the land use interactions that can be observed at regional and national scales, one should keep in mind that the Amazon agricultural frontier is the result of globalized dynamics. Crop expansion (and consequent deforestation) in the Amazon has already been proven to be related to global drivers such as the R\$\$ - US\$\$ exchange rates (Richards, Myers, Swinton, & Walker, 2012), the US policy on corn-based biofuels (Laurance, 2007), increasing

world consumption of beef (McAlpine, Etter, Fearnside, Seabrook, & Laurance, 2009) and the European policy for Bovine Spongiform Encephalopathy (BSE) prevention (Elferink, Nonhebel, & Schoot Uiterkamp, 2007). More recently (Ofstehage, 2016), related the agricultural expansion in the Mapitoba area to the general farm crisis in the United States.

In this context, in addition to considering how international drivers affect land use changes in Brazil, it becomes necessary to assess how recent Brazilian policies may affect land use changes in other countries. This is especially relevant at a time where the development of the soybean agroindustrial complex stands as a pillar of Brazil's insertion into a new multi-polar world order (Oliveirade 2015).

While the expansion of the agricultural frontier to neighboring countries in Latin America has been well documented (Graesser et al., 2015; Hecht, 2012; Mackey, 2011), recent studies now address the question of the emergence of a soybean frontier in Africa related to the South American agricultural sector (Gasparri, Kuemmerle, Meyfroidt, le Polain de Waroux, & Kreft, 2015) (Fig. 6). Although soybean expansion to date remains low (750,000 ha in 2013 across Southern Africa as compared to the 620,000 ha of soybean cultivated in the municipality of Sorriso, Mato Grosso), these authors consider that there are around 247 Mha of unprotected areas (croplands, forests and shrubs) which are highly suitable for soybean cultivation (Gasparri et al., 2015).

A few private Brazilian agribusiness actors, among others, have already invested in Africa to benefit from low production costs (almost half the price of that in Brazil; The Crop Site, 2010), the proximity to international export markets such as China and access to new local markets. The Grupo Pinesso, which mainly cultivates commodities in the states of Mato Grosso do Sul, Mato Grosso and

Piauí, benefits from Sudanese government incentives to cultivate 30,000 ha of soybean, cotton, corn, sorghum and beans in 2013 (AMAMBAL, 2015; ANBA, 2013). The SLC Agrícola (SLC Agrícola, 2015), which is also already established in various Brazilian states such as Mato Grosso and the Mapitoba area, is now prospecting for lands to cultivate in Angola, Ethiopia, Tanzania, Mozambique and Ghana (Farmlandgrab, 2014).

However, beyond the investments of private companies in Africa, the interest of the Brazilian agricultural sector for Africa is mainly the result of geopolitical concerns. It represents a way for Brazil to secure raw materials and develop export markets to ensure its own economic growth (Seibert, 2011). In this respect, the agricultural expansion in Africa is mainly supported by knowledge transfer and cooperation under the frame of South-South tele-couplings (Gasparri et al., 2015). A major symbol of such strategy is the Program for the Development of Agriculture in the Tropical Savannas (ProSavana) in Mozambique launched by Brazil, Mozambique and Japan in 2009. This program can be considered as a sister program to the PRODECER (Program for the Development of Cerrados, already supported by Japan) that encouraged agricultural expansion in the Brazilian Cerrados in the late 1980s (Clements & Fernandes, 2013; Oliveirade 2015). ProSavana, spearheaded by the Brazilian Company for Agricultural Research (EMBRAPA) whose research enabled the cultivation of soybean in tropical Cerrados, serves as a framework to support investments by large Brazilian agro-industrial companies with the short-term objective of cultivating 700,000 ha in the Nacala Corridor in Mozambique (Clements & Fernandes, 2013), although the area potentially suitable for intensive agriculture is estimated to 2.8 million ha (Aguiar & Pacheco, 2016).

These increasing investments to develop the African agricultural sector also raise important environmental questions. Oliveirade (2015) considers the expansion of the Brazilian agribusiness to Africa as a way to externalize the negative ecological (and social) costs generated by the agricultural development in Brazil. Indeed, beyond the high yields achieved in the Cerrados and Amazonian forests, the Brazil agricultural boom of the 1990s–2000s is primarily the result of the clearance of large areas of tropical wildlands in an unprecedentedly short time period: 40% and 12.5% of Cerrados and Amazon biomes respectively (MMA, 2015). If similar results were to be achieved in African wildlands, it could actually represent the most important feedback to be ascribed to the new "sustainable" Brazilian agricultural model. The environmental issues are high, especially considering that the Miombo-Mopane woodlands and savannas of Southern Africa are among the last wilderness areas remaining in the world, along with the Congo forest, the New Guinea forest and the Amazon forest (Mittermeier, 2003).

5. Conclusion

In the last decades, Brazil has experienced an important economic surge partly thanks to a dynamic agricultural sector, accounting for 25% of the country's gross domestic product (GDP) (Lapola et al., 2013). Brazil has become an international power, which, in turn, has also increased its environmental responsibility, reaffirmed at the Rio+20 Conference (2012). In this regard, efficient initiatives to control and curb Amazon deforestation were established so that Brazil is poised to become one of the few countries to achieve the transition to a major economic power without destroying most of its forests (Davidson et al., 2012). However, the consolidation of the South-Eastern Amazon agricultural frontier gives rise to new issues with regards to land use sustainability. Taking up these challenges will require the scientific community to develop new indicators, different from the traditional rates of deforestation, crop expansion or agricultural intensification, to

monitor the evolution of these still dynamic territories. Earth Observation data should continue to play a major role in future research on land use change but an increased importance should be given to the monitoring of agricultural practices and landscape ecology at different spatial scales while integration with social sciences should be encouraged. In this regard, studies relating agricultural intensification or deforestation patterns with socio-economic development, using synthetic indicators such as HDI (Caviglia-Harris et al., 2016; Rodrigues et al., 2009; Tritsch & Arvor, 2016; Weinhold et al., 2015) and social indicators (health, poverty, equity, gender and access to education and culture for example; VanWey et al., 2013; Gil et al., 2015; Almeida et al., 2016) are fundamental to understand the underlying motivations of people to adopt new practices and go ahead with sustainability. These social indicators can thus help address the complexity of land use sustainability and understand the vulnerability, resilience and adaptation capacity of these agro-socio-systems (Le Tourneau et al., 2013).

Finally, we emphasize the importance of multi-scale analysis since globalization has created new connections between distant actors and land uses (Lambin et al., 2014). On the one hand, at regional scale, it is necessary to assess if the compensation system implied by the new Forest Code effectively leads to the protection of native vegetation by farmers in distant areas. On the other hand, at global scale, as we emphasized potential relationships between crop production and health hazards for Amazonian inhabitants in intensive agricultural areas, one should also consider that commodities are consumed worldwide, thus potentially diffusing the health concerns outside the sole production areas. Overall, if the opening of a soybean agricultural frontier in the African savannas and its relationship with South America is confirmed, the recent decrease in deforestation observed in the Amazon would appear at global scale as an "illusion of preservation" (Berlik, Kittredge, & Foster, 2002). As a consequence, while Brazil is expected to become a model in terms of agricultural development and environmental governance for other tropical nations in Latin America, Asia and Africa (Ferreira et al., 2014; Martinelli et al., 2010), it would challenge the effectiveness of rather schizophrenic Brazilian domestic policies, e.g. combatting deforestation in the Amazon while building new dams and roads, supporting agricultural expansion in the Cerrados and establishing a new Forest Code which grants amnesty for illegal deforestation in 90% of Brazilian rural properties (Soares-Filho et al., 2014), to mediate present and future conflicts caused by the traditional expansionist agricultural model. While international cooperation is being reinforced to support agricultural development in Africa, environmental policies should also be set at international level to confirm the progress of the Brazilian agricultural sector towards land use sustainability.

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