IT IS NOT ENOUGH TO BE 'TECH': TRANSGENIC SOYBEAN YIELD SHOCK EFFECT ON DEFORESTATION AND LAND USE IN BRAZIL

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Keywords: Deforestation. Soybean yield shock. Agribusiness intensification.

Theme: (iii) sustainable land use and deforestation.

ABSTRACT

Based on the introduction of transgenic soybean seed in Brazil, this paper estimates the potential effects of this agricultural yield shock on the land use of the three main Brazilian biomes. Using an empirical model of differences-in-differences at 9 km × 9 km pixel level and detailed MapBiomas, the study calculated whether the potential increase in soybean productivity following transgenic seed introduction influenced the expansion or decrease in the main natural and agribusiness land use, considering possible heterogeneities between the Amazon, Cerrado and Mata Atlântica biomes. Results suggest that, in the Amazon, effects of this shock behave similarly to a Jevons paradox—in which the increase in productivity of the land production factor would have further encouraged its use or occupation. In biomes with more consolidated land use, such as the Mata Atlântica and Cerrado, this yield shock was unable to sustain a Forest Transition trajectory based on land sparing. For both biomes, the main perceived transitions resulted in less productive and profitable agribusiness uses for soybeans; whereas in the Amazon it was possible to observe a decrease in native vegetation for not only soybean occupation, but also for less profitable agribusiness uses, such as pastures. As the intensification of agribusiness production and productivity gains are desired and strategic for national development, this article contributes to further understand that these strategies do not automatically lead to a path of environmental conservation. Public policies responsible for supervising and monitoring illegal activities must be able to prevent deforestation expansion and go hand in hand with the sustainable development of the agribusiness sectors, avoiding the social costs of potential negative externalities, so this development is synergistic with combating climate change.

INTRODUCTION

In 2020, the agribusiness sector accounted for about 72.9% of greenhouse gas (GHG) emissions in Brazil. Of the total GHG emissions, 46.2% resulted from changes in land use, namely the occupation of primary forest by agribusiness. Direct emissions from the agribusiness sector, in turn, accounted for 26.7% of Brazil's total GHG emissions—more than the 18.2% of the energy sector's GHG emissions.[1] Besides this contribution of the Brazilian agribusiness sector to GHG emissions and, consequently, to the problems associated with climate change, forest loss by deforestation lead to several other issues such as impaired ecological balance, deterioration of water regulation, air quality and other ecosystem services, in addition to the loss of biodiversity and potential derived income.

Deforestation of tropical forests worldwide and particularly in Brazil is often associated with several factors ranging from market mechanisms (ASSUNÇÃO; GANDOUR; ROCHA, 2015), land speculation, regulatory frameworks and public policies (ASSUNÇÃO *et al.*, 2020; BURGESS; COSTA; OLKEN, 2018; GANDOUR, 2018; HARGRAVE; KIS-KATOS, 2013; SANT'ANNA; COSTA, 2021), to lack of supervision and governance (CORREIA-SILVA; RODRIGUES, 2019; REYDON; FERNANDES; TELLES, 2020). Although many studies contribute to measure and explain the impact of these factors, the dynamics of land occupation and transition remains generally unknown.

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[1] Data collected from the Greenhouse Gas Emissions and Removals Estimating System (SEEG). Available at: https://plataforma.seeg.eco.br/total_emission. Access in: Oct. 31, 2022.

In particular, an important component for understanding the transition patterns of land use and deforestation that is largely ignored by the literature is the importance of intensification and productivity gains in agricultural production. If, on the one hand, some plausible mechanisms can explain the negative impact of agribusiness productivity gains on deforestation, on the other, this effect may be ambiguous depending on the context—such as in the Jevons paradox, in which technological progress increases the efficiency of input use but fails to reduce its consumption. In Brazil, some preliminary evidence indicates that agricultural yield shocks promoted by access to electricity (ASSUNÇÃO *et al.*, 2017; SZERMAN *et al.*, 2022) and the 1970s soybean revolution in the Cerrado (ASSUNÇÃO; BRAGANÇA, 2015) would have been able to spare land and stop deforestation. But despite the technological advances in agribusiness in the late 20th century and in the 21st century, the expansion of agricultural uses, such as soybean and sugarcane production, and pasture over native vegetation remained.

Thus, this article seeks to address the following question: what are the potential direct effects of a yield shock on land use in Brazil? More specifically, our main contribution is to estimate by means of a non-binary difference-in-difference model how the transgenic soybean yield shock generated in the late 1990s may have heterogeneously impacted land occupation among Brazilian biomes. To do so, we start from the methodological contribution of Bustos, Caprettini, and Ponticelli (2016), who studied the effects of transgenic soybean on the industry and the labor market, and the detailed historical series of land use by MapBiomas 6 (2021).[2]

This work seeks to contribute to the literature by estimating the effects on land use of a major relevant yield shock for Brazilian agriculture—as was the case with the introduction of transgenic soybean seed—based on an identification strategy consolidated by Bustos, Caprettini, and Ponticelli (2016). Further, it estimates these effects from a highly detailed basis, both in the time dimension, with annual data between 1993 and 2012, and in the spatial dimension, with a 9 × 9 km pixel level. Moreover, estimates were made separately for the three main Brazilian biomes, allowing to consider potential heterogeneities.

Results indicate that in the Amazon biome, the transgenic soybean yield shock had significant effects on forest decrease and increased uses, such as pasture and soybean, suggesting a Jevons paradox for land use in this biome, so that yield shocks cannot act alone as an alternative to conservation policies. In the Mata Atlântica and Cerrado biomes, where land use is more consolidated, the effects on native vegetation are not significant, but the yield shock replaced less profitable uses, such as pasture and other temporary crops, with soybeans. In these cases, the transgenic soybean yield shock would not have been able to automatically lead to a forest transition trajectory.

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[2] MapBiomas consists of an Annual Mapping Project of Land Use and Coverage whose purpose is to understand the dynamics of land use in Brazil and make available annual georeferenced data on the use of Brazilian land.

Including this introduction, this paper is divided into eight sections. The second one presents a literature review on the relationship between yield shock and deforestation and land use, and on land occupation and forest transition. The third section outlines the main variables of this study and their constructions. The fourth section presents some descriptive statistics and land use transition matrices, which assist in interpreting the main results. The fifth section presents the empirical strategy and the model used for identifying the effect of transgenic soybean yield shock on land use. The sixth section discusses the main results of the empirical model and the event-studies. Finally, a brief section of concluding remarks closes this article.

LITERATURE REVIEW

In Brazil, some preliminary evidence on causality between yield shocks and deforestation is noteworthy. Assunção and Bragança (2015) found, in the context of the soybean revolution between 1960 and 1985, that regions which became more prone to soybean and intensification did not increase their deforestation relatively, rather pasture was replaced by agriculture and forest areas even increased in these regions. Using a different empirical strategy, Assunção and others (2017) and Szerman and others (2022) show that agricultural productivity gains from the electrification of several regions reduced deforestation in these municipalities. In the theoretical field, these arguments are supported by similar models, where a maximizing individual with considerable credit constraint has to allocate his capital to a unit of land with either cattle or agriculture—the former being less capital-intensive than the latter. After an agriculture yield shock (or more capital-intensive generic land use), the capital allocation moves further towards agriculture, making global production less extensive, while increasing the area of agriculture and secondary forest resulting from pasture abandonment. In the absence of capital constraint, the effect of this yield shock for the individual maximizer would be to expand the lands of more capital-intensive production without replacing or abandoning less capital-intensive production.

With the insufficiency of appropriate public policies to curb deforestation, productivity gains and intensification should be able to partially fulfill this function through some mechanisms, as argued by Szerman and others (2022). One such example is the replacement of less productive crops for others with higher yield potential as an alternative to increased production by extensive margin. Technological advances enable new investments and better infrastructure, also reducing the need to occupy more land for increased production, and may be correlated at the same time with increased production intensity and better enforcement conditions of law and property rights.

Such mechanisms and some others are recognized by international literature and follow some of the initial propositions of forest transition theory established by Mather (1992) in the 1990s and later developed. Simply put, forest transition theory consists of a logical chain in which, first, agricultural areas are expanded and forests decrease in response to the accelerated growth in demand for agricultural products, due to population growth; in later periods, with the decrease in population growth and the agricultural revolutions that introduce considerable productivity gains, the deforestation rate drops to a point where there is more agricultural area than necessary to meet current demand. Thus, productivity gains are understood as essential to "save" land and allow forest transitions to be established, in line with the theoretical models proposed by Assunção and Bragança (2015) and Szerman and others (2022) for Brazil.

But if yield gain is a necessary condition to reduce deforestation or even lead to forest transition, it should not be understood as a sufficient condition. Mather (1992) already emphasized that the relation between demand growth and yield growth should not deterministically induce forest transition movements because "complicating factors" such as urbanization, land use policy and trade patterns can divert their trajectory. Thus, the necessary condition of increased yield to meet population demand with a smaller agricultural area should be associated with the actions and perceptions of communities and governments that forests and their ecosystem services are beneficial and necessary.

Some contributions in the forest transition literature seek to systematize the paths by which different forest transition trajectories can occur and what are their respective necessary conditions (LAMBIN; MEYFROIDT, 2010; MEYFROIDT; LAMBIN, 2011; RUDEL, 2009; RUDEL *et al.*, 2005). Among these contributions is the theoretical framework developed by Lambin and Meyfroidt (2010). According to these authors, a forest transition trajectory sustained through yield shocks and agricultural intensification would only be possible if this intensification occurred by either forest scarcity, or empowering of small rural producers. Otherwise, the result on the forest transition trajectory is uncertain and may vary according to a number of other conditions (labor market, immigration, production for local or global supply, profitability, conservation policies).

Interpreting the models of Assunção and Bragança (2015) and Szerman and others (2022) from this theoretical framework, it is unlikely that the productivity gains observed in Brazil are an alternative to forest conservation policies or automatically lead to a forest transition path. Since intensification in Brazil does not occur due to land scarcity—on the contrary, in practice there is land availability in a country with an almost open border—, or even through the intensification of small rural producers, since rural concentration in Brazil is not a resolved issue (SANT'ANNA, 2017), the effects of these yield shocks depend on several other conditions.

Outside the forest transition literature, many studies highlight potential mechanisms that may impede or hinder a sustained conservation trajectory. It is essential to consider, for example, the type of technological progress, the agricultural products that benefit most and the price-demand elasticities, the effect on the production cost and profitability, the impact on the price of land, the quality of governance, and the definition of property rights (BYERLEE; STEVENSON; VILLORIA, 2014; CEDDIA *et al.*, 2014; EWERS *et al.*, 2009; GARRETT *et al.* 2018; GIL *et al.*, 2018; HORNBECK, 2010; KUBITZA *et al.*, 2018; PHELPS *et al.*, 2013). Another relevant point raised by Szerman and others (2022) is the effect of increased production on the extensive margin if the yield shock increases the farmer's profit more than the 'outside option,' that is, more than the opportunity cost of offering the workforce outside of agribusiness.

Other authors highlight the importance of the phenomenon known as Indirect Land Use Change (ILUC), where agricultural intensification in a given location can stimulate deforestation in other areas, especially at the deforestation frontier (ARIMA *et al.*, 2011; RICHARDS; WALKER; ARIMA, 2014). Finally, we must highlight the importance of technological innovations that generate increased demand for agricultural products, such as biofuels in Brazil, which have ambiguous results in terms of GHG emissions by indirectly stimulating forest occupation (FERREIRA FILHO; HORRIDGE, 2014; LAPOLA *et al.*, 2010; SÁ; PALMER; DI FALCO, 2013; SEARCHINGER *et al.*, 2008). Thus, despite the tempting idea that incentives for the market to become more efficient can also promote forest conservation, appropriate public policies should consider possible trade-offs and minimize potential negative externalities.

In Brazil, where land ownership rights are ill-defined and the deforestation frontier is, in practice, almost open, it is especially interesting that a realistic theoretical model incorporates in the function of expected land returns a component of speculative capital gain with the consolidation of 'new land' property rights. Young (1997) proposes a portfolio model where the individual seeks to maximize their expected return with the assets they have at their disposal. Overall, there are two main components of assets: a current component, related to the returns on production of the asset in the present, and a capital component, which aims to capture the potential depreciation or appreciation of the asset—simply, the difference between the purchase value and the sale value of the asset. In the case of an asset such as an agricultural land on the deforestation frontier, occupation and initial production can make the capital component positive and high from the producer's perspective, since it can consolidate his right of ownership over that land and value it in this commodification process.[3] Once this ownership right is consolidated and can be transferred to third parties, the expected return of the land can be much greater than just the current production component.

Considering what is tacitly known about the Brazilian context in recent decades, very significant productivity gains have been observed in capital-intensive crops, such as soybeans, parallel to the expansion of the deforestation frontier with the occupation of forest by pastures. Thus, in the Brazilian macro context, the theoretical framework proposed by Assunção and Bragança (2015) and Szerman and others (2022) do not seem to have operated as a predominant force, in the sense that significant gains in yield added to the capital restriction should replace an extensive trend with more intensive agribusiness. Particularly, the expansion of soybean in recent decades, driven by the innovative introduction of its transgenic seed, occurred both in areas partially occupied by soybeans and other crops, as well as in primary forest areas—as can be seen in the descriptive statistics of MapBiomas 6, in the fourth section. In this context, it is expensive to add new evidence to this literature, considering an important yield shock of the most relevant agricultural crop for the country, and potential heterogeneities between biomes at different stages of land occupation.

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[3] Importantly, here we do not consider potential depreciation effects on the value intrinsic to the conserved forest.

CONSTRUCTION OF VARIABLES AND DATABASES

This section details how the interest, dependent, and control variables were calculated to build the database that supports the empirical results of this work. First, the database is a year-by-grid panel covering a twenty-year period (1993-2012). The 9 km × 9 km grid chosen as the unit of analysis is the smallest possible aggregation that allows to estimate the transgenic soybean yield shock (variable of interest), following data provided by the Global Agro-Ecological Zones (GAEZ, 2012).[4] The chosen period includes twenty years, with six years of pre-treatment observations and fourteen years of post-treatment observations. We opted for the interval between 1993 and 2012 because it is a considerably long period, either in the pre-treatment, with six years of observations, and even more in the post-treatment, with fourteen years. An even longer period was chosen for post-treatment so that potential effect delays could be captured. More years could be added to the sample, but this would hinder data processing and add little to treatment timing, bringing other episodes that could eventually dirty the results.

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[4] Available at: https://www.gaez.iiasa.ac.at. Access in: Oct. 27, 2022.

Variable of interest: cross-section and time dimension

To identify the effects of the transgenic soybean introduction on land use in Brazil, we first had to construct a variable of exogenous interest capable of representing this impact in each region. For this, we followed an identification strategy similar to that of Bustos, Caprettini, and Ponticelli (2016), where the variable of yield shock identification was constructed by combining two variables of different dimensions: a cross-section variable of the additional production potential with the introduction of transgenic soybean, and a time dimension variable, considering the year in which the transgenic soybean seed becomes a potential factor for agricultural production.

Following entirely the proposition of Bustos, Caprettini and Ponticelli (2016), the cross-section variable used *the Global Agro-Ecological Zones* (GAEZ/FAO v3.0) base, which provides the yield potential per hectare from different input levels. Data were estimated and georeferenced in zones consisting of 9 km x 9 km grids, using several primary data from 1960 to 1990. For each grid/pixel, the georeferenced base informs the soybean yield potential in tons per hectare by using low-level inputs (traditional crops)[5]

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[5] "Under the low input, traditional management assumption, the farming system is largely subsistence based and not necessarily market oriented. Production is based on the use of traditional cultivars (if improved cultivars are used, they are treated in the same way as local cultivars), labor intensive techniques, and no application of nutrients, no use of chemicals for pest and disease control and minimum conservation measures" (BUSTOS; CAPRETTINI; PONTICELLI, 2016, p. 20).

and high-level inputs (advanced management).[6] Thus, from the difference in yield potential between low-level inputs and high-level inputs, one can obtain a proxy of the potential yield shock generated with the introduction of a new technology, such as transgenic soybean seeds.

Given the cross-section variation of the different productivity gains following the introduction of a new technology, we must define a time cut-off for establishing the pre-treatment and post-treatment period, that is, the year in which the yield shock actually starts. In the case of transgenic soybeans, this cut-off is not trivial. Only in 2003, with the Provisional Measure issued by then president Luís Inácio Lula da Silva, was there legal authorization for commercializing transgenic soybeans—and only in 2005 was a new legislation implemented that allowed to commercialize transgenic soybeans without the need for EIA/RIMA reports. Under the legal framework of the 2003 provisional measure, Bustos, Caprettini, and Ponticelli (2016) define this year to mark the time cut-off. As the authors' empirical strategy uses the frequency of the censuses (agribusiness and demographic), for practical purposes, we established 1996 and 2000 as pre-treatment years and 2007 and 2010 as post-treatment years.

However, the history of transgenic soybean planting in Brazil dates back to before 2003, with records of the first transgenic soybean seeds being introduced in the national territory in 1997,

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coming from Argentina (CASTRO, 2006). The first yields of transgenic soybean harvested in Brazil were recorded in 1998, with the CTNbio (National Technical Commission for Biosafety) giving the first favorable opinion authorizing planting with Monsanto’s RR[7] transgenic seeds without the need for an EIA/RIMA. Still in 1998, an injunction preventing this authorization was granted, and the planting was not allowed commercially. Nonetheless, some estimates indicate that in 1998 about 6.2% of the soybean planted area in Brazil—mainly in the South—was of transgenic seeds (CIB, 2018), so most of this production was illegal and its derivatives were not discriminated on the label. Judicial disputes continued in the following years; however, in the field, transgenic soybeans were never used: in 2002, it is estimated that about 20% of the area harvested from soybeans was from transgenic seeds—in some states, such as Rio Grande do Sul, this number may have reached 50% in 2003.[8] Thus, although the main legal frameworks on transgenic soybeans date from 2003 and 2005, 1998 was considered the year that transgenic soybeans were introduced in the country (CÉLERES, 2018; CIB, 2018), including several reports celebrating its twentieth anniversary in 2018 (20 ANOS..., 2018).[9]

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[7] The transgenic seed RR (Roundup Ready) made the plant more resistant to herbicides such as glyphosate.

[8] See Castro (2006) for the context of transgenic soybeans in the period prior to the 2003 approval.

[9] Available at: https://exame.com/brasil/20-anos-depois-da-aprovacao-transgenico-se-torna-regra-no-campo/. Access in: Oct. 27, 2022.

To construct the yield shock variable, we applied the difference between the high-level input and the low-level input for the observations after 1998, as in equation (1) below:

$$CP_{it} = \begin{cases} 0 \; se \; t < 1999 \\ high\ input_i - low\ input_i \; se \; t \geq 1999 \end{cases} \tag{1}$$

Where, for each grid *i* in each year *t*, the soybean yield shock variable (*CPit*) assumes the value 0 if the observation is prior to 1999 and assumes the value equivalent to the difference between $high\ input_i$ and $low\ input_i$ if the observation is from 1999.

Control variables must also be added to the base to capture potential biases in the desired inference. However, as the study is based on a considerably disaggregated and unconventional unit of analysis (GAEZ/FAO v3.0 *grids*) and on observations that span twenty years, to add controls these variables must be georeferenced and have an extensive historical series of said georeferencing. Thus, only two groups of variables could be added. First, from the estimates of Matsuura and Willmott (2018) and the application of this base conducted by Costa, Sant'Anna, and Young (2021), we extrapolated[10] the averages and deviations regarding the historical temperature and precipitation averages for each grid from the closest meteorological observations. Finally, given the importance of protected areas in conserving forests and restricting types of land use (GANDOUR, 2018; NOLTE *et al.*, 2013), from the shapefile provided by the

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[10] From the closest neighbors between the grids and the points of Matsuura and Willmott's estimates (2018).

Ministry of the Environment,[11] it was also possible to create a historical series of the area (in hectares) in each grid of Sustainable Use and Integral Protection Conservation Units. Ideally, it would be beneficial to add the areas protected by Indigenous Lands to the database, given their importance in stopping deforestation; however, their available shapefiles do not inform the year of creation of such areas, making it difficult to build a historical series.

Dependent variables

To estimate the effects of the transgenic soybean yield on land use, we must calculate the areas of each land use of interest for the study. Use of the Annual Mapping Project of Land Use and Coverage in Brazil (MapBiomas) represents a disruptive innovation in this sense, since it allows to follow the evolution of more than twenty categories of land use from 1985 to the present day, at a considerably high resolution (30 × 30 m pixel).[12] For the present study, the twenty-four categories were grouped into nine categories of interest (Chart 1).

These nine categories largely follow the aggregations at different levels of MapBiomas, where categories 3, 4, 5 and 49 are natural forest formations (*Forests*); categories 11, 12, 32, 29 and 13 are Non-Forest Natural Formations (*FNNF*); categories 23, 24, 30, 25 are Non-Vegetated Areas (ANV); and categories 33 and 31 are Water Bodies (*Water*). Exceptions are the aggregation of Perennial Crops

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[11] Available at: http://mapas.mma.gov.br/i3geo/datadownload.htm. Access in: Oct. 27, 2022.

[12] The georeferenced rasters from the Brazilian soil use of MapBiomas Collection 6 can be downloaded at: https://mapbiomas.org/colecoes-mapbiomas-1?cama_set_language=en. Access in: Oct. 27, 2022.

(coffee and citrus) with Planted Forest (*FP + AgPerene*); the aggregation done, in some cases, of Pasture and Agribusiness Mosaic (*Pasture*); and the breakdown of Temporary Crops into *Soybean*, *Sugarcane* and other temporary crops (*AgTemp*).

Chart 1. Aggregate land use categories from MapBiomas 6

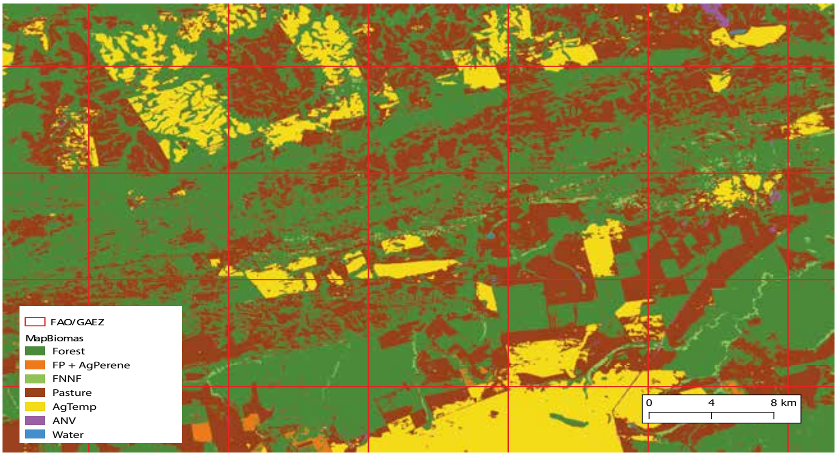
Aggregate land use	MapBiomas Category 6
Forest	Forest Formation (3); Savanna Formation (4); Mangrove (5); Wooded Restinga (49)
FP + AgPerene	Planted Forest (9); Coffee (46); Citrus (47)
FNNF	Flooded Field and Swamp Area (11); Campestrian Formation (12); Apicum (32); Rocky Outcrop (29); Other FNNF (13)
Pasture (+ Mosaic)	Pasture (15); Mosaic of Agriculture and Pasture (21)
Soybean	Soybean (39)
Sugarcane	Sugarcane (20)
AgTemp	Rice (40); Other Temporary Crops (41)
ANV	Beach and Dune (23); Urban Infrastructure (24); Mining (30); Other ANV (25)
Water	Aquaculture (31); River, Lake and Ocean (33)

Source: Own preparation from MapBiomas (2021).

Finally, for compatibility between MapBiomas data and the GAEZ/FAO v3.0 database grids, it was necessary to perform a statistics per zone for each aggregate use of MapBiomas from an identification mask in which each GAEZ/FAO base grid corresponds to a unit of analysis. That is, for each 9 km × 9 km GAEZ/FAO pixel, we added the areas of each coverage for each year—and likewise for the Conservation

Units areas.[13] Figure 1 provides a visual example, where the red grids correspond to each unit of analysis (or each GAEZ/FAO base grid) that had the area of each coverage inside summed.

Figure 1. Example of the overlap between the GAEZ/FAO base mask and MapBiomas



Source: Own preparation based on MapBiomas (2021) and GAEZ (2012).

DESCRIPTIVE STATISTICS AND TRANSITION MATRIX

Now that the main variables used in this study have been presented, this section will focus on some descriptive statistics. Table 1 presents three tables containing the statistics for the three biomes of interest, as well as the pre- and post-treatment statistics.

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[13] Geoprocessing of these data was performed using the *Dinamica* EGO *software* and its raster calculators and the statistical functors by zone.

Table 1. Descriptive statistics of the main variables used

	Pre-treatment				Post-treatment			
	Average	Max.	Min.	Deviation	Average	Max.	Min.	Deviation
				Mata Atlântica				
Forest	2457.56	8636.82	0	2054.89	2455.68	8638.98	0	2014.04
FNNF	280.15	8364.98	0	914.17	270.53	8369.38	0	860.38
Soybean	237.45	6752.52	0	809.29	521.12	7647.16	0	1306.61
Sugarcane	106.23	7223.3	0	552.08	202.45	7316.88	0	749.68
Pasture	3095.19	8583.43	0	2472.95	2831.89	8519.33	0	2379.96
Mosaic	1255.17	6542.43	0	866.18	1369.02	6505.04	0	885.14
AgTemp	685.97	6902.91	0	1148.59	377.24	6647.88	0	686.07
Rice (AgTemp)	6.82	4974.65	0	108.93	13.17	5817.51	0	168.56
Coffee (AgPer)	12.6	2901.48	0	71.36	20.97	2673.14	0	104.39
Citrus (AgPer)	0.56	1209.19	0	13.23	1.36	2222.94	0	25.9
FP	114.96	7186.09	0	463.44	165.83	6880.17	0	532.03
UC (PI)	117.36	8623.61	0	787.37	164.21	8623.61	0	905.96
UC (US)	318.48	8665.85	0	1399.25	489.26	8665.85	0	1707.61
Precipit	1465.9	3209.5	167	482.98	1458.91	3578	263.1	389.98
Temp	20.78	27.6	11	3.02	20.97	27.8	10.6	2.89
CP_soy	0	0	0	0	1.85	3.94	0	0.97
CP_corn	0	0	0	0	1.06	8.72	-0.12	1.81
CP_cotton	0	0	0	0	0.17	1.05	-0.07	0.2
	Pre-treatment				**Post-treatment**			
	Average	**Max.**	**Min.**	**Deviation**	**Average**	**Max.**	**Min.**	**Deviation**
				Cerrado				
Forest	4378.41	8638.98	0	2537.64	4046.68	8638.98	0	2480.33
FNNF	904.78	8611.11	0	1619.86	858.18	8611.11	0	1570.85
Soybean	143.41	8329.83	0	629.58	378.99	8564.19	0	1116.59
Sugarcane	63.23	7796.03	0	508.17	103.14	7846.19	0	623.72
Pasture	2206.82	8227.8	0	2208.38	2324.59	8361.92	0	2220.33
Mosaic	540.54	6655.7	0	674.3	528.26	6645.36	0	677.82
AgTemp	188.44	8528.86	0	599.43	156.82	8107.43	0	472.72
Rice (AgTemp)	0.54	3702.18	0	27.72	1.05	5160.91	0	41.74
Coffee (AgPer)	4.15	1595.38	0	29.8	7.77	3062.03	0	62.99

(continues)

(continuation)

	Pre-treatment				Post-treatment			
	Average	Max.	Min.	Deviation	Average	Max.	Min.	Deviation
				Cerrado				
Citrus (AgPer)	1.69	2906.51	0	43.14	3.77	4340.8	0	70.23
FP	49.5	6876.22	0	324.64	63.16	6894.55	0	372.53
UC (PI)	87.09	8647.83	0	765.28	204.06	8647.83	0	1169.15
UC (US)	166.2	8665.85	0	1096.28	378.22	8665.85	0	1623.68
Precipit	1362.43	2565.7	272.8	325.37	1444.47	2645.3	317.1	323.44
Temp	23.99	29.2	16.2	1.91	24.17	29.2	15.9	1.93
CP_soy	0	0	0	0	2.04	3.65	-0.54	0.72
CP_corn	0	0	0	0	1.08	8.3	-1.88	1.72
CP_cotton	0	0	0	0	0.19	1.11	-0.19	0.22

	Pre-treatment				Post-treatment			
	Average	Max.	Min.	Deviation	Average	Max.	Min.	Deviation
				Amazônia				
Forest		8638.98	0	2057.25	6975.19	8638.98	0	2362
FNNF		8620.73	0	1125.07	325.54	8608.42	0	1138.62
Soybean		7164.42	0	63.54	23.32	8397.7	0	263.65
Sugarcane		2237.86	0	11.4	1.01	4364.8	0	42.46
Pasture		8514.39	0	1472.15	981.98	8578.75	0	1912.48
Mosaic		1803.94	0	31.2	1.04	2286.32	0	18.75
AgTemp		5268.88	0	65.14	11.04	3701.1	0	92.73
Rice (AgTemp)		0	0	0	0	0	0	0
Coffee (AgPer)		0	0	0	0	0	0	0
Citrus (AgPer)		0	0	0	0	0	0	0
FP		6982.92	0	81.93	4.77	7103.29	0	110.25
UC (PI)		8647.83	0	1592.02	616.68	8647.83	0	2111.5
UC (US)		8665.85	0	1685.52	1082.92	8665.85	0	2693.01
Precipit		5293.6	421.7	511.43	2285.61	4702.4	625.9	520.39
Temp		29.5	16.3	1.23	26.27	30.8	16.4	1.19
CP_soy		0	0	0	1.56	3.1	0	0.52
CP_corn		0	0	0	0.74	6.62	0	1.11
CP_cotton	0	0	0	0	0.04	0.79	-0.06	0.09

Source: Own preparation based on MapBiomas (2021), GAEZ (2012), Ministério do Meio Ambiente (BRASIL, [2007]), Matsuura and Willmott (2018).

The descriptive statistics of the grids for the three main Brazilian biomes were separated for the six years pre-treatment (1993 to 1998) and for the fourteen years post-treatment (1999 to 2012). The first group of variables (in hectares) corresponds to the main aggregate land uses (ranging from *Forests* to *FP*);[14] the second group consists of the Conservation Units, divided into Integral Protection and Sustainable Use (also measured in hectares); the third group corresponds to the two meteorological variables, with annual rainfall averages (mm/year) and monthly temperature averages (ºC); finally, the last group consists of the Potential yield shock variables (ton/year), where the variable *CP_Soy* is our variable of interest, whereas *CP_Corn* and *CP_Cotton* are controls created following the same methodology as *CP_Soy*—from the difference between low-level input and high-level input of the respective crops.

A brief analysis of these descriptive statistics allows two types of comparison: between the biomes and between the pre- and post-treatment periods. Among the biomes, we observe how the Amazon preserves, on average of its grid areas, a much larger area of natural vegetation (*Forests* + *FNNF*) than the Cerrado, which, in turn, also preserves considerably more than the Mata Atlântica. Conversely, an average grid of the Mata Atlântica concentrates mostly *Pasture* (and *Agribusiness Mosaic*) and, to a lesser extent, temporary crops, followed by the Cerrado and, lastly, the Amazon. Regarding evolution, note that areas of natural vegetation decrease considerably post-treatment in

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[14] The descriptive statistics of the land use variables are in hectare to facilitate interpreting the values; however, to estimate the coefficients from the regressions proposed in the following section, we used the natural logarithm of these variables, adding in a unit of their values to avoid error in the observations that were equal to zero.

the Amazon and the Cerrado but hardly change in the Mata Atlântica, since natural uses are much more saturated in this biome (CALABONI *et al.*, 2018; WALKER, 2012). As for anthropogenic uses, *Pasture* expands considerably in the Amazon, more timidly in the Cerrado, and shrinks in the Mata Atlântica, phenomenon that is probably related to the expansion of Soybean, Sugarcane and other agriculture crops—uses that, in general, are more profitable and that have also expanded in the Cerrado and the Amazon. Finally, considering the potential soybean yield shock—which intuitively is zero before treatment in all observations—, on average, it seems to have been more intense in the Cerrado, followed by the Mata Atlântica and the Amazon.

Transition matrix

These descriptive statistics of the land uses help to understand the order of magnitude of such uses in each biome and give an initial notion of which uses expanded and shrunk in the proposed period. But land use transitions can be dynamic, that is, a forest converted to pasture can give way, years later, to other temporary crops, such as soybeans, instead of the forest being directly converted to soybeans. Thus, the transgenic soybean yield shock may have positive effects not only in soybean areas, but also in the area of land uses that can serve as intermediate uses for soybeans—especially in deforestation frontiers, where pasture occupation often serves as a means of consolidating deforestation (ALVARENGA JUNIOR, 2014). The objective of this subsection is therefore to identify whether there are intermediate uses for soybeans, that is, anthropogenic uses that precede soybeans, and what would be the magnitude of these intermediate uses in each biome.

Algebraically, we start from the MapBiomas database (2021)[15] for constructing a direct transition matrix between *t0* and *t2* called,MTD_{t0}^{t2} a square matrix of dimension *n* (equivalent to the number of land uses), where the rows represent the source uses (at *t0*) and the columns represent the target uses (at *t2*). Importantly, elements on the main diagonal of this grid represent the area in which uses have not changed; the sum of its lines is equivalent to the area of that use at t0, as the sum of a given column represents the area of that use at t2; the sum of all elements of this matrix is equivalent to the total area of the region. To obtain a net direct transition matrix MTD_{t0}^{t2}, where the elements represent the balance of the transitions between *t0* and *t2*, one can subtract MTD_{t0}^{t2} from its transpose ($MTDL_{t0}^{t2} = MTD_{t0}^{t2} - MTD_{t2}^{t0}$). This new matrix $MTDL_{t0}^{t2}$ has the elements of its main diagonal always equal to zero; whereas the opposite elements (e.g., element *i*=1 and *j*=3 versus element *i*=3 and *j*=1) always have the same value with opposite signs; the sum of all elements of this matrix equals zero. From the matrix $MTDL_{t0}^{t2}$ it is possible to estimate if the uses have a positive or negative balance with the others.

However, it is not yet possible from this matrix to calculate whether a transition that occurred between *t0* and *t2* took place by an intermediate land use at *t1*. To do so, we can construct a matrix of

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[15] Available at: https://mapbiomas-br-site.s3.amazonaws.com/Estat%C3%ADsticas/Cole%C3%A7%C3%A3o%20 6/1-ESTATISTICAS_MapBiomas_COL6.0_UF-BIOMAS_v12_SITE.xlsx. Access in: Oct. 27, 2022.

net intermediate transitions by summing intermediate matrices and subtracting their transpositions, according to equation (2):

$$MTTL_{t0}^{t2} = [(MTD_{t0}^{t1} + MTD_{t1}^{t2}) - (MTD_{t1}^{t0} + MTD_{t2}^{t1})], \text{ where } MTIL_{t0}^{t2} = MTTL_{t0}^{t2} - MTDL_{t0}^{t2} \quad (2)$$

In this case, $MTTL_{t0}^{t2}$ is the net total transitions matrix, which sums all direct and intermediate transitions that occur in the two time windows (from *t0* to *t1* and from *t1* to *t2*). In this operation, the direct transition areas are still added (for example, if a given area maintained its use of *t0* for *t1* and only transitioned from *t1* to *t2*, then the element of this transition is still considered). Thus, for this calculation we subtracted from $MTIL_{t0}^{t2}$ the direct net transition matrix B_{t0}^{t2}. The matrix elements $MTIL_{t0}^{t2}$ therefore only consider the transitions that actually occurred intermediately between *t0* and *t2*. In the case of two time windows considering the net transitions from *t1* to *t2* would be enough, but in longer periods, with more windows for intermediate transitions, this operation is more efficient.

Following this methodology to identify possible intermediate uses for soybeans, the next subsections will briefly present the net total and intermediate transition matrix for the three biomes of interest. Tables 2, 3 and 4 summarize the matrix elements $MTTL_{t0}^{t2}$ (numeric values in black), and the values corresponding to the matrix $MTIL_{t0}^{t2}$ values below the values in black, blue for positive balances and red for negative balances). For this exercise, we considered the period from 1990 to 2020, since the transitions per biome were already available at MapBiomas and are processed more easily, and the window established for intermediate transitions was every five years. To facilitate matrix presentation, columns (target categories of transitions) outside our interest have been hidden. All the elements of the matrices are measured in hectare.

Mata Atlântica: transitions in a consolidated region

The Mata Atlântica biome, covering most of the Brazilian coast and home to the largest population concentrations in the country, shows consolidation of primary forests by anthropized areas since the occupation by European colonizers. As shown in the descriptive statistics (table 1), therefore, of the three largest biomes, the Mata Atlântica has the lowest rate of *Forests*, but the highest concentration of anthropogenic uses *Soybean*, *Sugarcane*, *AgTemp*, *Pasture* and *Mosaic*. Thus, analysis of the *MTTL* and *MTIL* grids of this biome for agribusiness uses is expected to reflect such advanced stage of occupation.

As an example, considering the *AgTemp* > *Soybean* transition in table 2, considering the five-year window between 1990 and 2020, we observe a balance of net total transitions of 3.99 million hectares, of which 633 thousand hectares were net intermediate transitions (that is, they were not *AgTemp* in 1990, but became *AgTemp* between 1995 and 2015, before the *Soybean* observed in 2020). Thus, important characteristics of other land uses with *Soybean* are identified. Of the uses with most significant transitions, *Soybean* seems to be a net recipient of all, especially *AgTemp*, *Pasture*, and *Mosaic*. However, only *AgTemp* and *Mosaic* seem to derive their positive balances from intermediate donors to *Soybean*. Thus, in the Mata Atlântica, despite *Pasture* having ceded a large area to *Soybean* in the period, *MTIL* suggests that these *Pasture* areas in 1990, which became *Soybean* in 2020, had some intermediate use.

Analyzing the *Pasture* use line, we observe that this use is a liquid intermediate donor only for *Mosaic*, while *Mosaic* itself appears to be a liquid intermediate donor for *AgTemp*.

Table 2. MTTL and MTIL of agribusiness uses in the Mata Atlântica, 1990-2020.

	Net transition of the intermediate matrix every 5 years				
	AgTemp	**Sugarcane**	**Mosaic**	**Pasture**	**Soybean**
AgTemp	0	414,114	74,443	154,007	3,996,671
	0	-47,541	-864,766	372,360	633,080
Water	-16,926	-1,424	58,973	-85,089	-974
	-3,146	-442	19,505	-2,166	-449
ANV	-75,881	-24,222	-317,887	-249,597	-16,129
	-5,331	4,204	-69,376	38,452	-3,697
Sugarcane	-414,114	0	-1,804,187	-1,784,774	-1,913
	47,541	0	-1,030,220	957,884	-17,227
Forest	-85,004	15,113	-1,003,796	-375,071	69,201
	-482	-33,695	-353,908	455,342	-303,061
FNNF	29,884	-491	138,153	-10,073	74,145
	16,723	-799	76,393	11,576	-108,885
FP+AgPer	-160,736	-8,234	-736,047	-881,472	-18,652
	85,367	-11,295	-206,144	459,431	-64,106
Mosaic	74,443	1,804,187	0	-7,920,443	1,351,337
	864,766	1,030,220	0	-2,974,882	546,358
Pasture	-154,007	1,784,774	7,920,443	0	1,280,302
	-372,360	-957,884	2,974,882	0	-682,016
Soybean	-3,996,671	1,913	-1,351,337	-1,280,302	0
	-633,080	17,227	-546,358	682,016	0

Source: Own preparation from MapBiomas (2021).

For the Mata Atlântica, therefore, some transition land use trajectories deserve to be highlighted: *AgTemp* > *Soybean*; *Mosaic* > *Soybean*;

Mosaic > *AgTemp* > *Soybean*; *Pasture* > *Mosaic* > *Soybean*. Importantly, the net conversion of *Forest* and *FNNF* to *Soybean* exists, albeit not as significant or direct—in the case of *Forest*, the main intermediate for *Soybean* would be *Pasture*, whereas for *FNNF* the main intermediate for *Soybean* seems to be *Mosaic*. Finally, considering that *Sugarcane* is also an important crop in the region, and given its considerable expansion in this period, its trajectories seem relevant to highlight: *Mosaic* > *Sugarcane*; *AgTemp* > *Mosaic* > *Sugarcane*; *Pasture* > *Mosaic* > *Sugarcane*. Thus, in the case of *Sugarcane*, the only intermediate use that seems to be relevant is *Mosaic*.

Cerrado: history of a heterogeneous occupation

The Cerrado biome presents a heterogenous regionalization: while it covers occupied and consolidated territories for many decades, as in the states of São Paulo and Minas Gerais, it also makes up the Legal Amazon and the section known as 'Arc of Deforestation'—a region in the Legal Amazon that concentrates municipalities with accelerated deforestation rates in recent decades. Thus, land use transitions in this regional area are expected to reflect an intermediate context, while presenting some characteristics similar to the Mata Atlântica and others closer to that will be described for the Amazon.

In analyzing the transitions presented in table 3, we observe that *Soybean* showed a positive balance in the total transitions with all uses in the period (except for *Sugarcane*, which had a negative balance, albeit to a lesser extent). Similar to the Mata Atlântica, *Soybean* in the Cerrado received a significant amount of *AgTemp*, *Pasture* and

Mosaic areas, where *AgTemp* and *Mosaic* would have been the main intermediate uses. But in this case, *Soybean* also occupied significant *Forest* and *FNNF* areas, although these transitions had intermediate uses considering the intermediate transition balances of *Forest* and *FNNF*, these intermediate uses can be *AgTemp*, *Mosaic* and *Pasture*.

Table 3. MTTL and MTIL of agribusiness uses in the Cerrado, 1990-2020

Net transition of the intermediate matrices every 5 years					
	AgTemp	**Sugarcane**	**Mosaic**	**Pasture**	**Soybean**
AgTemp	0	492,120	-1,185,334	52,339	4,331,553
	0	9,469	-1,227,608	253,064	2,058,341
Water	-1,478	-52	-15,104	-62,661	-1,503
	-1,046	-56	-6,917	-12,244	-1,446
ANV	63,270	-1,968	-7,280	-44,718	194,646
	78,376	-2,949	33,308	72,657	124,043
Sugarcane	-492,120	0	-1,073,086	-906,970	-208,639
	-9,469	0	-631,776	638,611	-141,574
Forest	1,231,351	72,447	2,945,936	12,010,831	2,235,581
	550,954	-122,590	926,439	917,945	-2,630,251
FNNF	792,223	10,397	499,852	866,988	1,233,421
	493,057	-13,127	233,438	20,482	-484,365
FP+AgPer	-69,054	-2,447	-573,437	-985,793	-28,561
	-27,923	-6,530	-308,387	227,768	-60,640
Mosaic	1,185,334	1,073,086	0	-3,518,524	2,893,045
	1,227,608	631,776	0	-2,188,456	1,206,952
Pasture	-52,339	906,970	3,518,524	0	4,567,823
	-253,064	-638,611	2,188,456	0	-71,125
Soybean	-4,331,553	208,639	-2,893,045	-4,567,823	0
		141,574	-1,206,952	71,125	0

Source: Own preparation from MapBiomas (2021).

Thus, considering the trajectories of potential importance for *Soybean* in the Cerrado between 1990 and 2020, the following should be highlighted: *AgTemp* > *Soybean; Mosaic* > *Soybean; Pasture* > *Mosaic* > *Soybean; Pasture* > *Mosaic* > *AgTemp* > *Soybean; Forest (FNNF)* > *AgTemp* > *Soybean; Forest (FNNF)* > *Mosaic* > *Soybean; Forest (FNNF)* > *Pasture* > *Mosaic* > *Soybean*. Other transition characteristics in the Cerrado are important to note: loss of natural vegetation in this biome is quite significant, occurring mainly for *Pasture* among the agribusiness uses mentioned; the use of *Sugarcane* expanded considerably in the period, but mainly in the areas already consolidated by 1990, where its main intermediate use would be *Mosaic*.

Amazon: expansion of the border and a repeated history

Finally, the Amazon biome is a region of dense tropical forest, with important carbon storage capacity, biodiversity protection, and of paramount importance for water regulation. Of difficult access due to its vegetation and enshrined location, with low population concentration, the consolidated areas in anthropogenic uses are proportionally smaller. In recent decades, however, deforestation in the Amazon has been accelerated, pushing the deforestation frontier in. In this case, anthropogenic occupation is expected to congregate on the border, as much of the agribusiness expansion occurs in areas not previously consolidated.

Table 4, which presents the MTTL and MTIL between 1990 and 2020 for the Amazon, shows a significant expansion of *Soybean*, especially considering that this land use was practically non-existent in the early 1990s (table 1). This expansion occurs mainly in areas of *Pasture*, Forest and *AgTemp*. As for the uses, *Soybean* has a positive intermediate balance only for *Pasture* and *AgTemp*. Conversely, *AgTemp* was a minor use in 1990 and yet it appears to be an important intermediate use for *Soybean* (almost the entire *AgTemp > Soybean* transition occurs intermediately), whereas the *Forest > Soybean* transition, although very expressive, practically only occurs by intermediate uses—in this case, the important intermediate use being *Pasture*.

Table 4. MTTL and MTIL of agribusiness uses in the Amazon, 1990-2020

	Net transition of the intermediate matrices every 5 years				
	AgTemp	**Sugarcane**	**Mosaic**	**Pasture**	**Soybean**
AgTemp	0	17,465	0	-1,036,511	1,268,370
	0	17,304	0	-858,702	1,187,618
Water	651	5	0	-23,791	-163
	-2,322	5	0	-35,417	-269
ANV	-1,330	0	0	-108,289	-485
	-1,113	0	0	-29,490	-469
Sugarcane	-17,465	0	0	-52,936	8,439
	-17,304	0	0	6,526	8,513
Forest	793,412	3,051	0	38,079,692	532,310
	332,524	-6,213	0	2,934,578	-3,145,031
FNNF	78,076	15,650	0	714,830	126,029
	18,699	3,958	0	35,569	-21,771
FP+AgPer	-1,602	-15	0	-164,336	-615
	-1.568	-15	0	-81,103	-616
Pasture	1,036,511	52,936	0	0	3,242,403
	858,702	-6,526	0	0	1,972,023

(continues)

(continuation)

Net transition of the intermediate matrices every 5 years					
	AgTemp	**Sugarcane**	**Mosaic**	**Pasture**	**Soybean**
Soybean	-1,268,370	-8,439	0	-3,242,403	0
	-1,187,618	-8,513	0	-1,972.023	0

Source: Own preparation from MapBiomas (2021).

Potentially relevant trajectories for *Soybean* transition in the Amazon are *Pasture* > *Soybean; AgTemp* > *Soybean; Pasture* > *AgTemp* > *Soybean; Forest* > *AgTemp* > *Soybean; Forest* > *Pasture* > *Soybean*. Besides *Soybean*, we note the large expansion of *Pasture* in areas previously occupied by *Forest*; the expansion of *AgTemp*, which was barely significant in 1990, into *Pasture* and *Forest* areas besides having ceded areas it occupied between 1990 and 2020 to *Soybean*; and, finally, the timid expansion of *Sugarcane*, which continues to be a not very relevant crop in the biome.

EMPIRICAL STRATEGY

In this second section, based on the literature review, the importance of productivity gains and the intensification of agribusiness for the so-called *land sparing* was highlighted. On the other hand, other studies argue that this mechanism involves a set of requirements and is not necessarily an automatic path. In the fourth section, we identified how the transitions to soybean land use seem to occur in each Brazilian biome and how they show no consistent trajectory towards a forest transition. Narratives based on theory or descriptive statistics are relevant to support interpretations of the recent Brazilian scenario, but do not allow attributing causality on whether yield shocks were or are capable of reducing agribusiness occupation. In fact, yield (and demand) shocks for soybeans and sugarcane, along expansion of their cultivated areas, have occurred in the last thirty years. However, to evaluate in practice whether productivity gains were able to “spare land” we must build a counterfactual, seeking to observe whether the existence of a certain yield shock would be able to avoid an even more serious scenario in terms of land occupation.

Thus, our main objective is, starting from the methodological contribution of Bustos, Caprettini, and Ponticelli (2016), to identify how the soybean yield shock, linked to the innovation of transgenic seed, affected the different land uses in three different Brazilian biomes. Unlike the present study, Bustos, Caprettini, and Ponticelli (2016) delve into potential structural transformations in the industry derived from the heterogeneous effects of introducing transgenic soybean in different municipalities.[16] Based on the methodological contribution of how to exogenously estimate the yield shock generated by transgenic soybean, this article seeks to extrapolate the contributions of Bustos, Caprettini, and Ponticelli (2016) to identify changes in different land uses generated by transgenic soybean introduction.

For this purpose, the empirical strategy adopted consists of a difference-in-difference model with annual observations and a fixed effect in both dimensions. The unit of analysis *i* is the GAEZ/FAO

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[16] We can highlight the study by Dias, Rocha, and Soares (2019), which uses similar empirical strategies to identify the effects of glyphosate in health outcomes.

grid, in which the high-level input and low-level input variables are made available. Regarding the application of Bustos, Caprettini, and Ponticelli (2016) and other works that seek to identify the effects of yield shock in deforestation, the present study starts from greatly detailing the database by using the smallest possible unit of analysis (grid instead of municipalities) and annual observations (instead of decennial observations, retrieved from the agribusiness and demographic censuses). Such advance was only possible due to the georeferenced and annual database provided by MapBiomas and the processing of these annual data, aggregating them in a small unit of analysis such as the 9 km by 9 km grids. The generic empirical model used can be seen in equation (3):

$$Coverage_{it} = \alpha + \beta * (high_i - low_i) * post1998_t + \sum_{n=1}[\rho_n * X_{itn}] + \lambda_t + \mu_i + \varepsilon \quad (3)$$

Where *i* is the 9 km by 9 km grid and *t* is the year. Generic dependent variable Coverage$_{it}$ can take the area[17] of any land use in each grid *i* and year *t*. In turn, the coefficient of interest β measures the yield potential generated by the transgenic soybean shock in different soil uses. As seen in the third section, this independent variable consists of the difference interaction between the high-level input and low-level input of soybean yield (in tons per hectare) with a dummy for the years after 1998. Coefficient ρ_n captures the effects of the *n* controls, which consist of the meteorological variables—annual precipitation and temperature by grid—in the areas of Conservation Units (broken down by sustainable use and full protection) in each grid *i* and year *t*. Subsequently, variables that seek to capture specific UF trends and additional controls that

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[17] The results presented use the natural logarithm of the area plus one (to avoid zero logarithm).

represent potential yield shocks of transgenic corn and cotton seeds were also included, calculated similarly to the transgenic soybean yield shock—except for timing, since corn was introduced in 2006 and cotton in 2008 (CÉLERES, 2018; CIB, 2018).

This generic model was replicated separately for the three main Brazilian biomes—Amazon, Cerrado and Mata Atlântica in terms of area.

This is because, as seen in fourth section, the stage of land use occupation and consolidation in these biomes differ greatly, so we must highlight potential heterogeneities on the effect of transgenic soybean.[18] To correct correlations in the standard errors of the estimated coefficients, we added a correction of standard errors from a two-way cluster to the unit of analysis *i* and the UF-year level[19]—a correction that seeks to be more restrictive than a cluster only in *i*.

The empirical strategy adopted to infer the effects of the transgenic soybean yield shock on the different land uses assumes, as hypothesis, that the effect caused by this shock is only perceived—that is, is statistically different from zero—after the year in which treatment begins. A pre-treatment effect of the variable measuring soybean yield shock means that the result found post-treatment reflects a previously existing trend. Thus, in an empirical strategy where the timing of the variable of interest is fundamental, performing robustness tests to assess the existence of a pre-treatment trend is key. To do so,

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[18] Initially, the model was reproduced for Brazil as a whole but interpreting results of regions with such distinct characteristics is not so clear, so we decided to present them by biomes.

[19] A cluster for each grid that is in the same UF and in the same year.

event-studies will also be presented to verify the existence or not of pre-treatment trend, following the specification in equation (4):

$$C_{it} = \alpha + \sum_{t=1993}^{1997}[\beta_t * (high_i - low_i)] + \sum_{t=1999}^{2012}[\beta_t * (high_i - low_i)] + \rho * X_{it} + \lambda_t + \mu_i + \varepsilon \quad (4)$$

Where a β coefficient is calculated for each year t except for 1998, the last year before treatment, which we omitted for a better understanding of the graphs. This β coefficient aims to capture whether there is a yield gain effect in pre-treatment (from the coefficients found in the first summation) and in post-treatment (from the coefficients calculated in the second summation). Statistically non-significant pre-treatment coefficients points to no effect of the variable of interest before treatment, which is desirable in a difference-in-difference model. The model also included meteorological controls, PA area, fixed effects and control by UF trend, as well as the two-way cluster by grid and by UF-year to correct standard errors.

On the one hand, greater detailing of the database built contributes by capturing the variance of the variables used and allowing a more accurate coefficient estimation of the yield shock in the area of different land uses. Its size and the spatial and time dimension of the observations hinder including other control variables and empirical strategies (and robustness tests) that require greater computational power — such as spatial models that also seek to identify indirect effects of transgenic soybean on land use. In any case, based on an exogenous and consolidated identification strategy by Bustos, Caprettini, and Ponticelli (2016), with detailed pixel-level observations from FAO/GAEZ data, the inclusion of additional controls and the search to consider potential heterogeneous effects between biomes, the empirical strategy proposed and applied in this article is valid for recovering the proposed effects. Thus, the following results are a relevant contribution for discussing the direct effects of yield shocks on land use, as well as the existence of a forest transition trend in Brazil or the prevalence of a Jevons paradox.

KEY RESULTS

In this section, coefficients of the main results for the Amazon will be presented in table 5, for the Cerrado, in table 6, and for the Mata Atlântica, in table 7. These three tables show three distinct panels containing: (A) the meteorological controls (precipitation and temperature) and PA area; (B) the controls of A and a linear trend variable by UF; (C) the controls of A, UF trend and additional controls for potential yield shock of transgenic cotton and corn. All tests performed also included fixed effects at t and i, as well as the two-way cluster at i and UF-year to correct standard errors.

Table 5 shows the effects of soybean yield shock (in tons per hectare) for the area of each land use (in %) in the Amazon. Following the specification of Panel A, we highlight the following results: column (1) suggests that the increase of one ton per hectare caused by the transgenic soybean shock in grid i generated a 36.4% average increase in the soybean area. A direct effect of the transgenic soybean yield shock on the increase in *Soybean* area was probably the most expected result. Similarly, the shock of one ton per hectare caused by transgenic soybean also seems to have expanded the area of *Pasture* (+ *Mosaic*) and *AgTemp* by 27.6% and 24.5%, respectively. This may seem a less obvious result, at first, but considering the transition matrices discussed in the fourth, the transgenic soybean shock may have encouraged the occupation of areas with greater potential, whether with *Pasture* or other crops, given that consolidation in the Amazon generally occurs through these uses.

Table 5. Differences-in-differences of soybean CP in Amazonian soil uses, 1993-2012

Variables	**(1) Soybean (%)**	**(2) Forest (%)**	**(3) FNNF (%)**	**(4) Pasture (%)**	**(5) AgTemp (%)**	**(6) Sugarcane (%)**	**(7) FP and AgPerene (%)**
Panel A: Meteorological and UC controls and two-way cluster by UF-ANO grid							
Soybean yield shock (t/ha)	0.364***	-0.057***	-0.002	0.277***	0.246***	0.003*	-0.001
	(0.085)	(0.009)	(0.007)	(0.053)	(0.058)	(0.002)	(0.002)
Panel B: Controlling by UF and two-way cluster trend by grid and UF-year							
Soybean yield shock (t/ha)	0.213***	-0.032***	0.007	0.122***	0.132***	-0.003**	0.002
	(0.057)	(0.004)	(0.005)	(0.033)	(0.037)	(0.001)	(0.002)
Panel C: Controlling by UF trend and potential clash with cluster by grid and UF trend							
Soybean yield shock (t/ha)	0.193***	-0.033***	-0.001	0.166***	0.081**	-0.003**	0.000
	(0.059)	(0.005)	(0.005)	(0.033)	(0.039)	(0.001)	(0.002)
Observations	987.640	987.640	987.640	987.640	987.640	987.640	987.640
Fixed Effects and UF trend	S	S	S	S	S	S	S
Cluster	TW	TW	TW	TW	TW	TW	TW
Frequency	Annual	Annual	Annual	Annual	Annual	Annual	Annual

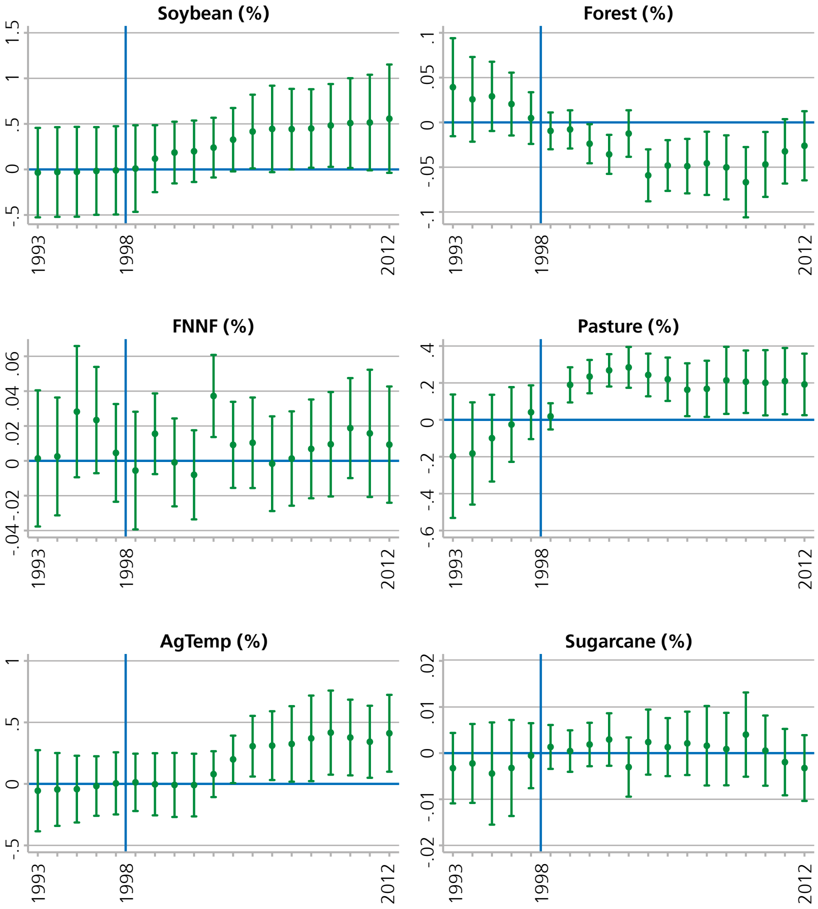
Source: Own preparation.

But if these agribusiness land uses showed significant increases in their areas from the soybean yield shock, the potential increase of one ton per hectare in soybean production generated by the transgenic seed shocked caused, on average, a 5.7% reduction in the *Forest* area. Importantly, the lower coefficient found applies to an average area of *Forest* per grid in the Amazon much larger than the average area of other agribusiness uses (as seen in table 1), in which the expansion of *Pasture* as an effect of the soybean yield shock should also be highlighted, since this use is much more relevant than the others.

Thus, the results found suggest that the transgenic soybean yield shock generated in the Amazon biome replaced areas of *Forest* by *Soybean*, *AgTemp* and, mainly, *Pasture*, contrary to the results found by Assunção and Bragança (2015) and Szerman and others (2022). We found no significant effects for the other uses, which was expected given their lower participation in the total area of the biome. Moreover, the inclusion of additional controls in Panel B and C decreased the magnitude of the estimated soybean yield shock effects, but maintained both the significance and the direction of the coefficients for all land uses except for Sugarcane, where the coefficient gained significance but maintained a small magnitude.

Besides the significance and direction of the coefficients found, for the results of a difference-in-difference model to be valid we must also consider the pre-treatment trends of the variable of interest. As treatment is continuous in our case, we decided to prepare an event-study, as outlined in the fifth section. Figure 2 shows that the pre-treatment trend in the *Soybean*, *Forest*, *Pasture* and *AgTemp* uses are statistically equal to zero, despite a declining and non-significant behavior in the case of *Forest* and ascending and non-significant in the case of *Pasture*. Post-treatment effects are perceived (statistically different from zero), even if with some lag—as is the case mainly for *Soybean* and *AgTemp*, with lags of up to five years. As in table 5, we observed no significant effects for *Sugarcane* and *FNNF* in the Amazon.

Figure 2. Event-study of the effect of soybean CP on the six main land uses for the Amazon biome



Source: Own preparation.

As seen in the fourth section, possible gaps in the effect of a *Soybean* yield shock in the Amazon should be considered, since the transition to uses such as *Soybean* and *AgTemp* are not immediate and may require a longer time to occur. Given the soybean yield shock found, the response seems to be faster in the *Forest* decrease and *Pasture* increase, and slower in the increase of other uses, such as *Soybean* and *AgTemp*. This result is consistent with a border opening that occurs by intermediate transitions, from *Forest* to *Pasture* for, only then, other temporary agriculture (*AgTemp*) and, finally, for *Soybeans*. We also observe an apparent decrease in the effect on *Pasture*, which may be occupied by *Soybeans* after opening part of the border.

Table 6 presents the coefficients calculated for the Cerrado as in table 5. As characterized in the fourth section, this biome covers part of the Legal Amazon, with municipalities that make up the deforestation frontier, and regions consolidated by agribusiness uses for many decades. Thus, the expected results should reflect a mixed scenario between the Amazon and the Mata Atlântica, where *Soybeans* and other agribusiness uses should expand, bolstered by the soybean yield shock, mainly on less productive agribusiness uses, while generating losses in natural vegetation, such as *Forest* and *FNNF*.

Analysing the coefficients in Panel A, we can identify positive effects of the yield shock from one ton/hectare of transgenic soybean in the average area of *Soybean* (38.5%), *Sugarcane* (17.0%) and *FP + AgPerene* (3.6%). If, on the one hand, the effect on the *Soybean* area is relatively direct, the same cannot be said about the positive effects on the *Sugarcane* and *FP + AgPerene* areas. In the latter case, the coefficient presents a smaller magnitude and does not maintain its significance in the most restrictive specifications. In the case of *Sugarcane*, the result suggests a certain complementarity between the expansion of *Soybean* with the use of *Sugarcane*—or that some omitted variable associated with the expansion of this use is also correlated with the soybean yield shock.

Conversely, agribusiness uses considered to be less profitable, such as *Pasture* (+ *Mosaic*) and *AgTemp*, and natural vegetation, such as *Forest* and *FNNF*, seem to be negatively affected by the transgenic soybean yield shock. *Forest* loses, on average, 1.8% of their area per year for each ton per hectare of soybean generated by the yield shock, whereas *FNNF* loses 2.6%. In turn, the results for *Pasture* and *AgTemp* are even more expressive in percentage terms: for each ton per hectare of yield generated by the transgenic soybean shock there is an average loss of 29.0% of *AgTemp* area and 18.3% of *Pasture* (+ *Mosaic*) area per year, considering that an average grid in the Cerrado has 32% of its area occupied by *Pasture*. These results point to the mixed nature of the Cerrado, located between a region on the deforestation border and a region partially occupied, since the uses stimulated by soybean yield shock seem to occupy both *Forest* and *FNNF* (to a lesser extent), as well as *Pasture* (+ *Mosaic*) and other temporary agriculture (*AgTemp*), which tend to have lower profitability per hectare.

Table 6. Differences-in-differences of soybean CP in soil uses in the Cerrado, 1993-2012

Variables	**(1) Soybean (%)**	**(2) Forest (%)**	**(3) FNNF (%)**	**(4) Pasture (%)**	**(5) AgTemp (%)**	**(6) Sugarcane (%)**	**(7) FP and AgPerene (%)**
Panel A: Meteorological and UC controls and two-way cluster by grid and UF-ANO							
Soybean yield shock (t/ha)	0.385***	-0.018***	-0.026***	-0.183***	-0.290***	0.170***	0.036***
	(0.028)	(0.004)	(0.007)	(0.028)	(0.049)	(0.026)	(0.013)
Variables	**(1) Soybean (%)**	**(2) Forest (%)**	**(3) FNNF (%)**	**(4) Pasture (%)**	**(5) AgTemp (%)**	**(6) Sugarcane (%)**	**(7) FP and AgPerene (%)**
Panel B: Controlling by UF and two-way cluster trend by grid and UF-year							
Soybean yield shock (t/ha)	0.414***	-0.007**	-0.029***	-0.108***	-0.089***	0.134***	0.006
	(0.035)	(0.003)	(0.006)	(0.017)	(0.024)	(0.029)	(0.013)
Panel C: Controlling by UF trend and potential clash with cluster by grid and UF trend							
Soybean yield shock (t/ha)	0.455***	-0.008***	-0.022***	-0.105***	-0.043*	0.120***	0.006
	(0.037)	(0.003)	(0.007)	(0.017)	(0.025)	(0.027)	(0.013)
Observations	492,500	492,500	492,500	492,500	492,500	492,500	492,500
Fixed Effects and UF trend	S	S	S	S	S	S	S
Cluster	TW	TW	TW	TW	TW	TW	TW
Frequency	Annual	Annual	Annual	Annual	Annual	Annual	Annual

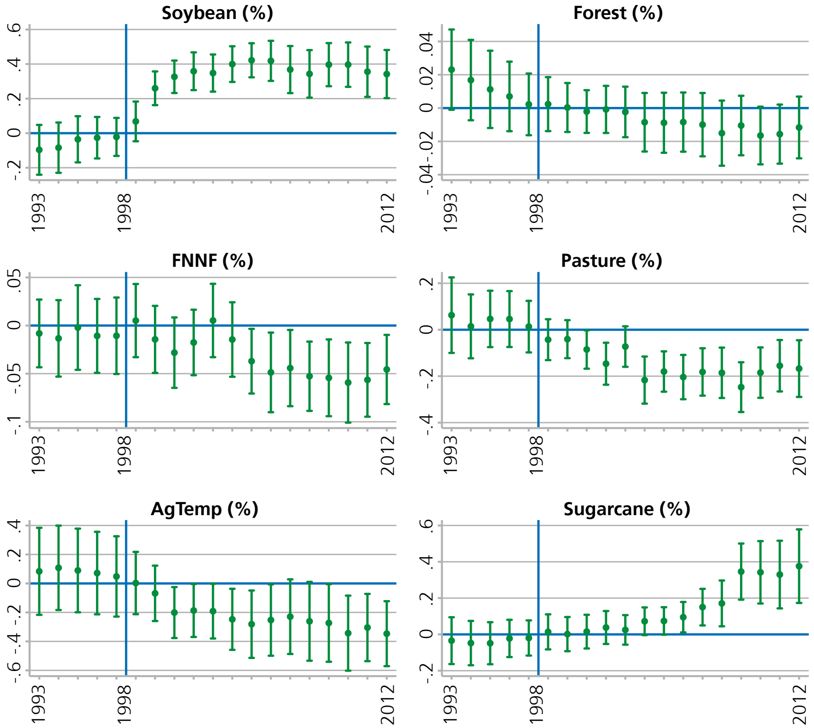
Source: Own preparation.

Coefficients found in panels B and C point to similar results, except for the loss of magnitude of the soybean yield shock in the *AgTemp* area (in the case of Panel A, significance is also lost to 5%). Lower magnitude for *Forest* and a loss of significance for the positive effect in *FP* + *AgPerene* are also observed. Thus, the additional specifications indicate robust results, leaving us with the analysis of the event-study pre-treatment trend illustrated in figure 3.

In analysing the event-studies for the Cerrado, all pre-treatment trends appear to be statistically insignificant, suggesting that the significant results found in table 6 and figure 3 do not result from an omitted pre-treatment variable that would be correlated with the yield shock—although *Forest* use show a statistically non-significant declining pre-treatment trend. Considering the post-treatment trends for *Soybeans*, the estimated effect occurs almost immediately after treatment, indicating that producers respond to the yield shock much faster in this biome than in the Amazon. This can be due both to the greater land occupation of the region, which facilitates transitioning from one agribusiness use to another, and to the greater proximity to Southern Brazil, where the transgenic soybean seed entered illegally at first.

As for the effect on the *Forest*, besides the not-significant declining pre-treatment trend, the post-treatment effects of the soybean yield shock, when compared with the last pre-treatment year (1998), do not seem to maintain significance. Thus, the effect of the soybean yield shock on the decreased *Forest* area in the Cerrado seems not to sustain itself as the others. The safest and most conservative option based on the robustness test is to consider no statistically significant effects of the transgenic soybean yield shock in the *Forest* area.

Figure 3. Event-study of the effect of soybean CP on the six main land uses for the Cerrado biome



Source: Own preparation.

More counterintuitively, the event-study indicates that the effect of soybean yield shock on *Sugarcane* use does not seem to result from a pre-treatment trend, as the pre-treatment coefficients are statistically equal to zero and relatively stable. Moreover, we observe an important gap until the effect on the *Sugarcane* area is perceived. This may point to some omitted variable relevant to the expansion of the *Sugarcane* area after 2002/2003 that is also related to the transgenic soybean yield shock, or to some benefit or complementarity in the use of *Sugarcane* with the expansion of the *Soybean* area induced by the transgenic soybean yield shock. In any case, further tests and studies are needed to verify this result.

Finally, table 7 presents the coefficients of the previous specifications for the Mata Atlântica biome. Panel A shows, in its Columns (1) and (6), that a soybean yield shock of one ton per hectare increases in each grid *i* and year *t* 43.3% of the *Soybean* area and 37.4% of the *Sugarcane* area—results that show similar significance and magnitude as those observed for the Cerrado. Another positive effect of the soybean yield shock was found in the *Forest* area (1.0%), result that possibly corroborates the preliminary contributions of Assunção and Bragança (2015) and Szerman and others (2022), and agrees with the forest transition observed by Calaboni and others (2018) for the Mata Atlântica.

On the other hand, the *FNNF* loses, on average, 1.5% of its area per year per ton per hectare due to the transgenic soybean yield shock in the Mata Atlântica. In percentage terms, this is a more expressive result than *Forest* gains in the biome, but *FNNF* use is much less representative than *Forest* use—even though both are saturated in the biome (table 1). *Pasture* (+ *Mosaic*), *AgTemp* and *FP+ AgPerene* are the mains uses which lose areas to others: these uses lose each a ton per hectare of soybean yield shock (7.9%, 37.6% and 10.7%, respectively), noting that the *Pasture + Mosaic* area represents about half of a generic grid *i* of the Mata Atlântica.

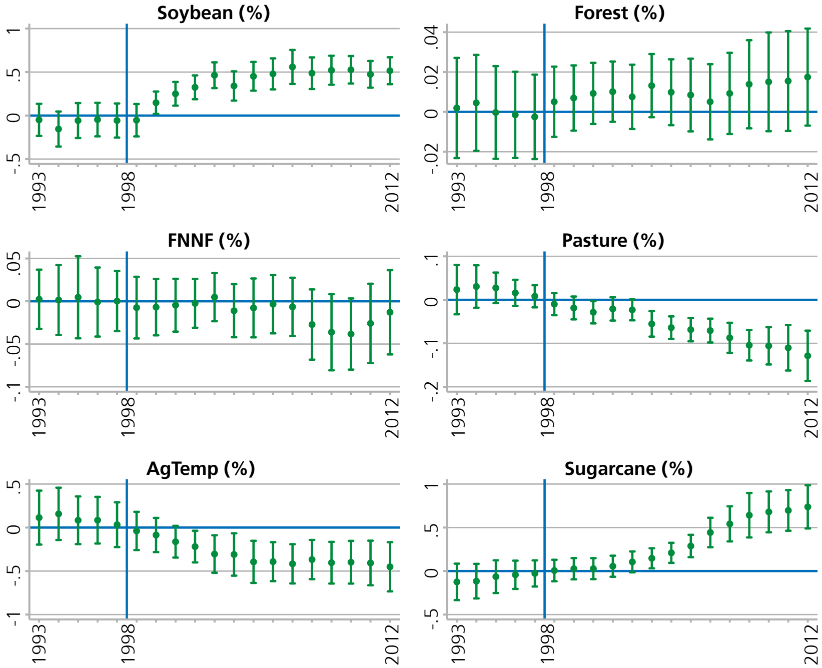
Table 7. Differences-in-differences of soybean CP in soil uses of the Mata Atlântica, 1993-2012

Variables	**(1) Soybean (%)**	**(2) Forest (%)**	**(3) FNNF (%)**	**(4) Pasture (%)**	**(5) AgTemp (%)**	**(6) Sugarcane (%)**	**(7) FP and AgPerene (%)**
Panel A: Meteorological and UC controls and two-way cluster by grid and UF-ANO							
Soybean yield shock (t/ha)	0.433***	0.010**	-0.015**	-0.079***	-0.376***	0.374***	-0.107***
	(0.043)	(0.004)	(0.007)	(0.010)	(0.054)	(0.049)	(0.028)
Variables	**(1) Soybean (%)**	**(2) Forest (%)**	**(3) FNNF (%)**	**(4) Pasture (%)**	**(5) AgTemp (%)**	**(6) Sugarcane (%)**	**(7) FP and AgPerene (%)**
Panel B: Controlling by UF and two-way cluster trend by grid and UF-year							
Soybean yield shock (t/ha)	0.219***	0.020***	-0.019**	-0.037***	-0.224***	0.188***	-0.070***
	(0.027)	(0.003)	(0.009)	(0.008)	(0.042)	(0.038)	(0.025)
Panel C: Controlling by UF trend and potential clash with cluster by grid and UF trend							
Soybean yield shock (t/ha)	0.234***	0.018***	-0.014	-0.035***	-0.174***	0.099***	-0.059**
	(0.030)	(0.003)	(0.009)	(0.008)	(0.038)	(0.029)	(0.024)
Observations	281,900	281,900	281,900	281,900	281,900	281,900	281,900
Fixed Effects and UF trend	S	S	S	S	S	S	S
Cluster	TW	TW	TW	TW	TW	TW	TW
Frequency	Annual	Annual	Annual	Annual	Annual	Annual	Annual

Source: Own preparation.

Analysing the Panels B and C, we observe that all coefficients, except for *Forest* and *FNNF*, present lower magnitude, but the same sign and significance level. Regarding the positive effect on the *Forest* area, the specifications with additional controls have considerably higher coefficients, whereas in the Panel C specifications, the *FNNF* coefficient loses significance. Continuing the robustness tests, figure 4 presents the event-studies for Mata Atlântica. Overall, the conclusions are similar to those observed in the event-studies for the Cerrado, that is, the results for *Soybean*, *Pasture* and *AgTemp* seem robust in the pre-treatment trend test, whereas the same cannot be said for the *Forest* and *FNNF* coefficients—which seem to be non-significant when compared with the year immediately prior to treatment. In the case of the effect on *Sugarcane*, the results point to similar conclusions as those discussed for the Cerrado.

Figure 4. Event-study of the effect of soybean CP on the six main land uses for the Mata Atlântica biome



Source: Own preparation.

FINAL REMARKS

Yield shocks in agribusiness, such as those generated by introducing transgenic soybean seeds, can both induce land sparing and generate other externalities in the price of land, profitability of agribusiness production, and the supply of these products. The forest transition theory, despite considering the intensification of agribusiness production as a key component, also points out how this intensification alone does not lead to a reforestation path, rather introducing a Jevons paradox scenario for land use. Yield shocks in agribusiness should be encouraged, as they are in line with environmental and land use policies that help induce conservation.

Considering the main results described in the last section and the context discussed in the course of this essay, some highlights deserve attention. First, the soybean yield shock has more significant effects in the Cerrado and Mata Atlântica than in the Amazon, taking place mostly in areas already occupied by agribusiness. This may be because it is more economically advantageous to expand soybean use in areas that are already consolidated and closer to economic axes and international markets than on the deforestation frontier. Soybean expansion at the border can be time-consuming if there is a primary need to consolidate this border.

Results for the Amazon are important to describe the border area consolidation process and discuss how yield shocks in near-open border areas can increase deforestation. In this case, introduction of a technology capable of more efficient land use for producing an agricultural commodity ends up expanding land occupation, generating a Jevons paradox for the land production factor. Similarly, yield shocks in regions with saturated natural uses such as the Cerrado and, mainly, the Mata Atlântica, may influence land sparing but do not seem to lead to a consistent forest transition trajectory in this context.

Effects on *Sugarcane* use in the Cerrado and Mata Atlântica are not obvious and can even be considered counterintuitive since a soybean yield shock should stimulate the transition to *Soybean* use and not so much for *Sugarcane*. In this case, as observed in the transition matrices, *Sugarcane* does not act as an intermediate use for *Soybean*. Thus, there must be some kind of spillover of *Soybean* expansion over the *Sugarcane* area; however, for more serious conclusions, further studies should seek to better understand this correlation.

Importantly, the estimated coefficients reflect net effects observed in the regions and in the post-treatment years. For example, while the soybean yield shock may increase the *Pasture* area as an intermediate use for *Soybean*, it also reduces this same *Pasture* area by using it for *Soybean*. Thus, signal and significance of the coefficient found depend on the strength of these two effects in each region. Moreover, these effects may increase or decrease over time, with the yield shock first stimulating the *Pasture* area by expanding the border, but then giving way to *Soybean* or other more profitable uses after a certain period.

Finally, we highlight the importance of discussing these effects considering the heterogeneities between the biomes, especially their stages of occupation. The heterogeneous results found in this study mostly reflect findings expected from certain regional characteristics, so that generalizing the effects of yield shocks and agribusiness intensification can lead to misinterpretations.

These results suggest that, in the context of the transgenic soybean seed and the ensuing potential yield shock, agricultural intensification was not sufficient to generate a land sparing movement towards forest transition. On the contrary, in agricultural frontiers the yield shock further encouraged the conversion of forest areas into pasture, for only then some of these pasture areas to become soybean crops. Thus, our findings are in agreement with several studies and with the forest transition theory, which argues that there is no automatic path from agricultural intensification to forest conservation and revegetation. Environmental policies must aim to prevent that the economic incentives generated by yield shocks be consolidated into perverse incentives from an environmental perspective.

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