Tradeoffs between forests and farming in the Legal Amazon Region of Brazil

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ABSTRACT

Deforestation has been a topic of debate in climate change discussions due to its effect on CO_2 emissions. The Amazon Forest, the biggest tropical forest in the world, is located along the north of Brazil. There, expansion of soy and corn production has pushed the production of livestock and other crops toward the Amazon forest, which involves a tradeoff between the area in forests versus these activities. We estimated the tradeoff between agriculture and forest for the 771 municipalities of the Amazon region by finding the *production possibility frontier*, using *Data Envelopment Analysis*. This tradeoff was estimated based on directional output distance functions. We found that, on average, 58% of observable total revenue from livestock, grains and timber production would be foregone to decrease deforestation in 2006 by 93%. We also estimated determinants of efficiency differences across states, which suggested that environmental efficiency was enhanced in municipalities with higher development indexes.

Key words: Amazon Forest, Agriculture, Deforestation, Trade-off.

JEL: Q51, Q54, C61.

1. Introduction

Deforestation has been receiving attention due to effects on the CO_2 cycle – emission and sequestration – and on worldwide biodiversity. Brazil has the biggest tropical forest in the world and has been considerate as good site to apply conservation of forest policies by the *United Nations* (UN), which sponsors the *Reducing Emission from Deforestation and Forest Degradation (*REDD+), since it faces a reducing rate of it in the last years.

Brazilian Amazon forest is distributed along the northern states of the country, which have been affected by agriculture expansion started in the 1990s. The main drivers of deforestation cited in the literature are grains and livestock production (Cattaneo (2001), Morton et al. (2006), Rivero et al. (2009), Richards et. al. (2012), Hargrave and Kis-Kato (2013), Richards et al. (2014), and Araujo et al. (2014)). The Brazilian part of Amazon has been named as Legal

Amazon[1] by the government and it corresponds to the states of Acre, Amazônia, Roraima, Rondônia, Amapá, Para, Mato Grosso, Tocantins and Maranhão in the north of Brazil. This terminology, Legal Amazon, was created by the government in the 1950's with the goal of realizing policies related to socio-economic development of the population that lives there.

The literature has been focusing in analyze the opportunity cost of policy implementation (i.e. Nepstad et al. (2007)) and the impact of farmer behavior on the forest (Vera Diaz and Schwartzman (2005)). The farmer is presumed to estimate the opportunity cost of not producing agricultural commodities such as livestock and grains at the forest land when making the decision about whether to deforest. From the farmer point of view, overall, the opportunity cost of keeping the forest has not been high enough to prevent deforestation.

This paper aims to estimate the trade-off between forest and the main agricultural drivers cited in the literature – grains, livestock and timber production – for the Legal Amazon region. We apply Data Envelopment Analysis (DEA) to a set 771 municipalities stretched in the nine northern states using the Agricultural Census data of 2006. We also calculate directional efficiency measures considering an undesirable output, deforestation, based on Färe et al. (2007). We are not aware of any study that investigates Amazon deforestation using this methodology.

This paper is divided into five sections. Section 2 presents a brief description of the Amazon Forest region and the literature that has discussed it. Section 3 illustrates the theoretical framework adopted and data description. Section 5 discusses the results followed conclusion.

2. Amazon Forest region

In 2006, the Legal Amazon had 40% of its area covered by trees, 48% designated to cattle, and 11% destined to crop production (Brazilian Institute of Geography and Statistics – IBGE, 2014). Among the states, Para has the highest accumulated area of deforestation and highest rate of deforestation, followed by Mato Grosso and Maranhão (National Institute for Space Research – INPE 2014). These states and Tocantins and Rondônia constitute the agricultural frontier in the region, which is known as "arc of deforestation".

[1] In Portuguese Amazonia Legal. According to PNUD (2014), four of those states are between the ten worse states in the Human Development Index per Municipalities and none of them is between the 10 best of it, indicating a bad social-economic development of this area and room for income enhance policy application.

Several studies have been investigating the Amazon Forest region and the deforestation path over the last two decades (Cattaneo (2002), Morton et al. (2006), Rivero et al. (2009), Richards et. al. (2012), Hargrave and Kis-Kato (2013), Richards et al. (2014), and Araujo et al. (2014)). Overall, these studies suggest that agriculture has been driving deforestation and other harmful effects on the forest region such as water contamination. A few studies have evaluated the role of Brazil's participation in REDD+ such as Nepstad et al. (2007), Boner et al. (201), May et al. (2011), and Heres et al. (2013).

Few studies analyzed Amazon deforestation under a different perspective. They focused on the direct consequence of deforestation - CO_2 emission. Nepstad et al. (2007) and Boner et al. (2010) found similar results – an estimated a cost of US$5.5 per ton carbon if the forest were conserved over 30 years. According to them, a compensation to producers would be feasible given the low return per hectare of converted land in the Amazon forest region. At the 2006 deforestation rate, only 60% of the Brazilian Amazon forest would remain by 2050 (Soares-Filho et al. (2006)).

Governmental and international policies toward reducing deforestation have been achieving some results in preserving the Brazilian Amazon Forest, mainly after 2005/06. These institutional policies and its outcomes have been evaluated by a few studies such as Nepstad et al. (2014), Soares-Filho et al. (2014), Nepstad et al. (2013), Stickler et al. (2013), Garret et al. (2013) and Gibbs et al. (2015). Oliveira (2008), Araujo et al. (2009) and Araujo et al. (2010) investigate the strength and characteristics of property rights and found a positive impact of weak property rights on deforestation.

Overall, Nepstad et al (2007) suggested that Brazil is a good candidate for REDD policies due to its ability to reduce and monitor deforestation in Amazon region. They argue that Brazil has been creating several mechanisms to preserve the forest but it is also important to notice that part of the Amazon forest belongs to private owners, farmers, which might be an obstacle to forest preservation. Additionally, they highlighted the positive spillover of such policies on socio-economic enhancement in this region.

Another important issue for deforestation is fire activity, which is present in this region. Quintanilha and Lee Ho (2005) applied DEA to analyze the fire risk monitoring activity in the Amazon forest region. Overall, these studies highlight the negative effect of agriculture on forest and the importance of institutional policies on preserving it.

3. The Model

There are several methodologies to approach the issue of opportunities foregone when preserving forests. Färe et al. (1989) modeled a similar issue using hyperbolic distance measures, but more recently using directional distance functions (Färe et al. 2005; Färe et al. 2006; Färe et al., 2007). We are proposing to use a directional distance function as in Färe et al. (2007) to evaluate the trade-off between forest preservation and agricultural production. We will estimate three different directional distance functions.

The output vector will be contain two sub-vectors (***y***, ***b***) with $\boldsymbol{y} \in R_{+}^{m}$ and $\boldsymbol{b} \in R_{\geq 0}^{j}$ where *y* denotes the desirable output and b undesirable output; and x will be the input vector, $\boldsymbol{x} \in R_{+}^{n}$. Undesirable output consists of deforestation in the Amazon forest driven by agricultural production represented by livestock, grains and timber production. The output correspondence represents the production technology as

$$P(x) = \{(y, b): x \; can \; produce \; (y, b)\}, x \in \Re_{+}^{N}, \boldsymbol{y} \in R_{+}^{m} \; and \; \boldsymbol{b} \in R_{\geq 0}^{j} \qquad (1)$$

which means the input vector *x* can produce jointly the desirable (*y*) and undesirable (*b*) outputs, in the output set, $P(x)$. As in Färe et al. (2007), the output set is compact, desirable outputs are strongly disposable, and undesirable outputs are weakly disposable. This output set is represented in Figure 1 under two different set of characteristics – 0ABCDE and 0BCDE. The latter represents the output set defined by Färe et al. (2007), where null-jointness is assumed while the former does not assume it. The 0BCDE output set assumes that undesirable output is at byproduct in the production of desirable output (if $b = 0$, then $y = 0$). The output set 0ABCDE allows a range 0A of desirable output to be produced ($y > 0$) while the undesirable output is not ($b = 0$). The straight line DE illustrates the strong disposability of desirable outputs while both ABC and 0BC segments represent weak disposability of undesirable output.

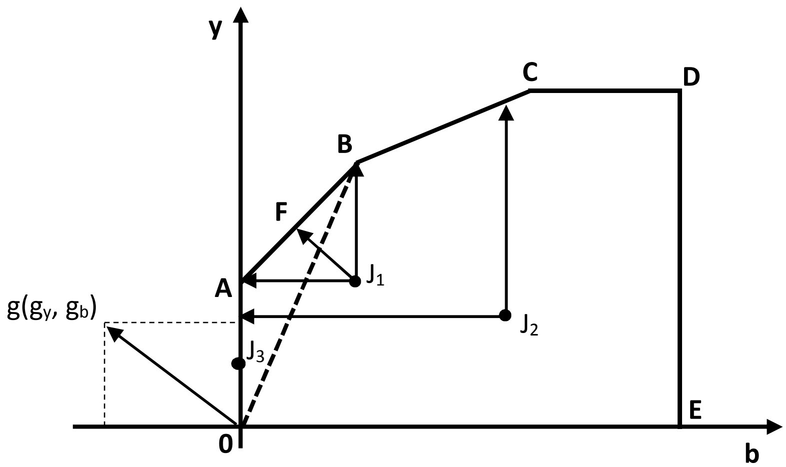

Figure 1: Output Set - *P(x)*, and directional output distance function
Source: Own elaboration.

We identify the output set using three different directional distance functions, where it is possible to model expansion of desirable outputs jointly with reduction of undesirable outputs, or separately. The general form can be represented by

$$\vec{D}_o\left(x, y, b; g_y, -g_b\right) = max\left\{\beta\colon \left(y + \beta g_y, b - \beta g_b\right) \epsilon\, P(x)\right\} \tag{2}$$

where the directional vector is pre-determined and it is defined as $g(g_y, g_b)$. A directional vector of $g\left(g_y, g_b\right) = (1, -1)$ is illustrated in Figure 1. The three models described hereafter have different directional vectors, $D_i\left(y^k, b^k, x^k; g_y, g_b\right)$]. The distance measured for firm k will be zero when the observation k is on the boundary of the feasible technology, identified by linear combinations of the input-output combinations observed in the data.

Three models are fit. First, a directional output distance function is used to model the situation where only the desirable output is allowed to expand – undesirable output does not contract. It can be interpreted as the traditional model of maximizing behavior where only desirables are considered or a situation where decision makers do not do not face environmental regulations. It is represented in Figure 1 by a movement of units J_1 and J_2 up (northern region of the output set). This output set is modeled by assuming a directional vector of $g\left(g_y, 0\right) = (1,0)$. Technical inefficiency is represented by the distance of each observation k to the frontier – i.e. B – J_1 in

Figure 1. The objective function seeks to increase desirable output production of state k while keeping the same level for the undesirable output

$$D_y\left(y^k, b^k, x^k; g_y, 0\right) = \max\{\beta^{k`}: \left(y^k + \beta^{k`} g_y, b^k, x^k\right) \epsilon\ P(x^k)\} = \max \beta^{k*} \quad (3)$$

$$\begin{aligned} \text{Subject to} \quad & \textstyle\sum_{k=1}^{K} z^k y_m^k \geq y_m^k + \beta^{k`} g_y, && m = 1, \dots, M \\ & \textstyle\sum_{k=1}^{K} z^k b_j^k = b_j^k, && j = 1, \dots, J \\ & x_n^k \geq \textstyle\sum_{k=1}^{K} z^k x_n^k, && n = 1, \dots, N \\ & z^k \geq 0, && k = 1, \dots, K \end{aligned}$$

where $\beta^{k^*} = D_y\left(y^k, b^k, x^k; g_y, 0\right)$, weak disposability of undesirable outputs is assumed ($\sum_{k=1}^{K} z_k b_{kj} = b_{kj}$) to model the output set as in Figure 1, and z^k are the intensity variables, where constant return to scale is assumed.

Second, a directional output distance function is used to model an inverse case, where only the undesirable outputs contract while projecting the unit toward to the frontier. This case can be interpreted as an extreme version of an environmental regulation that effectively eliminates all deforestation. This output set is modeled by assuming a directional vector of $g(0, g_b) = (0,1)$. Technical inefficiency is represented by the distance between the observation and the frontier – i.e. A – J_1 in Figure 1. The objective function seeks to decrease undesirable output production of state k without increasing desirable outputs

$$D_b(y^k, b^k, x^k; 0, g_b) = \max\{\beta^{k`}: \left(y^k, b^k - \beta^{k`} g_b, x^k\right) \epsilon\ P(x^k)\} = \max \beta^{k*`} \quad (4)$$

$$\begin{aligned} \text{Subject to} \quad & \textstyle\sum_{k=1}^{K} z^k y_m^k \geq y_m^k, && m = 1, \dots, M \\ & \textstyle\sum_{k=1}^{K} z^k b_j^k = b_j^k - \beta^{k`} g_b, && j = 1, \dots, J \\ & x_n^k \geq \textstyle\sum_{k=1}^{K} z^k x_n^k, && n = 1, \dots, N \\ & z^k \geq 0, && k = 1, \dots, K \end{aligned}$$

where $\beta^{k^*} = D_b(y^k, b^k, x^k; 0, g_b)$, weak disposability of undesirable outputs is also assumed, and z^k are the intensity variables, where constant return to scale are assumed.

Third, a directional output distance function is used to model a simultaneous expansion of desirable outputs and contraction of undesirable outputs. It can be interpreted as a situation where an environmental regulation takes place but allows desirable output expansion. This output set is modeled by assuming a directional vector of $g(g_y, g_b) = (1, -1)$. It has been using in different paper to model a joint production of desirable and undesirable output. Technical inefficiency is represented by the distance between the observation and the frontier – i.e. F – J_1 in Figure 1. The objective function seeks to increase desirable outputs and decrease undesirable output production simultaneously

$$D_{y,b}(y^k, b^k, x^k; g_y, g_b) = \max\{\beta^{k`}: (y^k + \beta^{k`} g_y, b^k - \beta^{k`} g_b, x^k) \epsilon P(x^k)\} = \max \beta^{k*} \quad (5)$$

$$\begin{aligned} \text{Subject to} \quad & \textstyle\sum_{k=1}^{K} z^k y_m^k \geq y_m^k + \beta^{k`} g_y, && m = 1, \dots, M \\ & \textstyle\sum_{k=1}^{K} z^k b_j^k = b_j^k - \beta^{k`} g_b, && j = 1, \dots, J \\ & x_n^k \geq \textstyle\sum_{k=1}^{K} z{z^k}_k x_n^k, && n = 1, \dots, N \\ & z^k \geq 0, && k = 1, \dots, K \end{aligned}$$

where $\beta^{k^*} = D_{y,b}(y^k, b^k, x^k; g_y, g_b)$, weak disposability of undesirable outputs is also assumed, and z^k are the intensity variables, where constant return to scale are assumed.

In our computations all variables are normalized by the mean, so $y_{km} = y^*_{km}/\bar{y}$ where y* represents the actual observation and $\bar{y}$ represents the overall mean, as in Färe et al. (2005). Different normalizing factor have been used in the literature, such as using the maximum of each variable as the normalizing factor (Macpherson et al., 2010). In our case, the maximum desirable output achieved by state *k* under zero inefficiency is found as $y_m^k + \beta^{k`} * \bar{y}$ for the models where $g_y \neq 0$.

The objective of this paper is to estimate the trade-off between agricultural commodities and forest, which can be represented by the slope of the frontier boundary. Färe et al. (1989) and Färe et al. (2007) performed similar procedure using a different method. They compare the output sets under weak and strong disposability for the specifically undesirable commodity. We used the three different orientation directional output distance functions to calculate the quantities of desirable and undesirable outputs on different points of the frontier (i.e. points B, F and A in the Figure 1).

We propose a trade-off measure based on the different quantities achieved by projecting the observed state *k* to the frontier two different directions, designated here as *i* and *j*:

$$Tradeoff_y = \sum_{m=1}^{M} p_{km} * [y_{D_i}^{km} - y_{D_h}^{km}], \quad for\ i \neq h\ and$$
$$Tradeoff_b = b_{D_i}^{kj} - b_{D_h}^{kj}, \quad for\ i \neq h\ and\ where$$
$$y_{D_i}^{km} = y_m^k + \bar{y} * D_i(y^k, b^k, x^k; g_y, g_b) * g_y, \quad i = h = y; b; and\ y, b$$
$$b_{D_i}^{kj} = b_j^k + \bar{b} * D_i(y^k, b^k, x^k; g_y, g_b) * g_b, \quad i = h = y; b; and\ y, b \tag{6i}$$

where $y_{D_i}^{km}$ represents the potential desirable output, on the frontier, considering different directional output distances (D_i can be D_y, D_b, and $D_{y,b}$). The measured tradeoff is the revenue forgone to achieve a reduction in the environmentally bad output (extreme or not, depending of the directional vector assumed). For example, $p_{km} * [y_{km}^{D_y} - y_{km}^{D_b}]$ represents the revenue of desirable output that could be reached while eliminating undesirable output (insofar as possible) while holding current revenue constant (an extreme environmental regulation). This measure will be calculated for each observation and aggregated across states and regions. We will present the tradeoffs in terms of the observable total revenue obtained with desirable outputs and deforestation (rather than as fractions of the mean values):

$$Change\ due\ inefficiency\ for\ y\ (\%) = \left(\frac{Tradeoff_y}{\sum_{m=1}^{M} p_{km} * y_{km}}\right) * 100,$$
$$Change\ due\ inefficiency\ for\ b\ (\%) = \left(\frac{Tradeoff_b}{b_{km}}\right) * 100, \tag{6ii}$$

where the $Tradeoff_i$ for $i = y$ and b were estimated based on equation (6i). The ratio of the two equations in (6ii) reveals relative tradeoff in terms of how much of desirable output must be foregone per unit of undesirable output reduced:

$$Relatve\ tradeoff\ y/b = \left(\frac{Tradeoff_y}{Tradeoff_b}\right), \quad in\ US\$/hectare \tag{6iii}$$

which will be estimated in terms of deforestation area (hectares) and Carbon Dioxide (CO_2) using of MMA/DPCD (2011) conversion argument between one hectare of forest and its content of Carbon. The tradeoffs among the set of equations [(6i)-(6iii)] will be estimated and displayed in the results section. The linear programming described in Equations (3)-(5) were estimated using GAMS.[2]

4. The Application

4.1. Dataset

The Legal Amazon consists of 771 municipalities stretched in nine states (Amapá – AP, Acre – AC, Amazonas – AM, Mato Grosso – MT, Maranhão – MA, Tocantins – TO, Para – PA, Rondônia - RO and Roraima – RR). The dataset consists of 771 municipalities in 2006 obtained in Agricultural Census of 2006 online at *Intistuto Brasileiro de Geografia e Estatistica* (IBGE). Figure 2 illustrates these states and the absolute area deforested in 2006.

We solved the linear programming problems described in Equations (3)-(5) using GAMS. Three agricultural commodities are considered as desirable outputs – livestock, grains and timber production. Deforestation in 2006 is considered as undesirable output, and as inputs we used labor, capital, area, and expenses with fuel, agricultural and cattle inputs. Descriptive statistics are in Table 1 and 2.

[2] We would like to Carl A. Pasurka Jr. for his help sending us the codes for his paper (Färe et al., 2007).

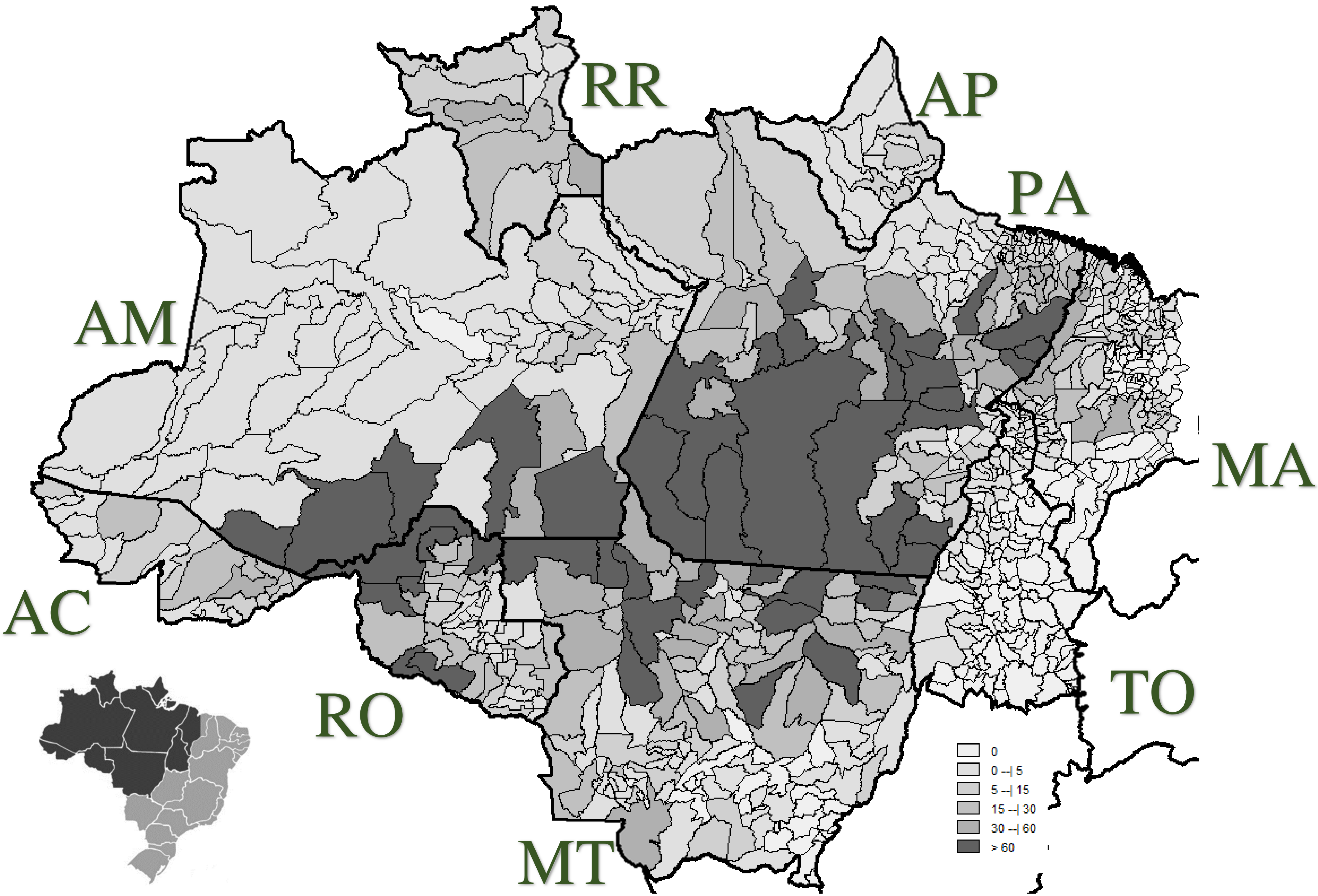

Figure 2: Map of deforestation (hectares) at Legal Amazon (per municipalities) at 2005/06.

Source: Dataset used comes from PRODES (2014)

Deforestation is measured in hectares, obtained from the PRODES/National Institute for Space Research (INPE, 2014) website. The states of Roraima (RO), Mato Grosso (MT), Pará (PA) and Maranhão (MA) have higher absolute and per area deforestation. The variable representing timber production was based on Merry et al. (2009). They used m^3 of wood (in logs) available from IBGE (Table 289) increased by 50% to account for illegal logging not in IBGE. Table 1 shows that the states of PA by RO and AC are the main timber producers. It is worth mentioning that PA is one of the biggest states in area and in value of agricultural production in the Legal Amazon. Deforestation in 2006 as percentage of municipal area is illustrated in Figure 3 in Appendix A.

Livestock was measured as number of cattle slaughtered and sold, given the importance of livestock in the region. Grains are the sum of soybean and corn production (in tons). The output price for grains used is a weighted average of the prices of both crops where the weights are the relative importance of that crop in value of production of the municipality. MT is the main producer of grains in this region.

In the input side, we used six inputs displayed in Table 2. Labor is the number of employees over 14 years old. Some states are labor intensive due to the type of agriculture mainly devoted to subsistence crops. Capital is obtained by summing the number of equipment and machinery in the municipality following Bragagnolo et al. (2010). MT specialized in production for export, and thus it is capital intensive relative to the others. Area consists of total area of the municipalities in hectares.

Table 1: Desirable and undesirable outputs – agricultural GDP, livestock, grains and timber production, and deforestation for Legal Amazon region in 2006, sum across municipalities.

State	Number of municipalities		Deforestation (*ha*) 2005/06	GDP (US$1000)	Livestock (units)	Grains (tons)	Timber (m^3)
RO	52	*Mean*	1005	$9,978.90	26659	5402	31600
		Sum	134370	$518,902.77	1386256	280917	1643199
AC	22	*Mean*	456	$7,758.94	12086	3774	27096
		Sum	23850	$170,696.64	265887	83036	596121
AM	62	*Mean*	298	$6,135.48	2811	333	22403
		Sum	72750	$380,399.52	174291	20658	1388960
RR	15	*Mean*	206	$3,991.37	2929	1659	12800
		Sum	21510	$59,870.58	43933	24884	192000
PA	143	*Mean*	645	$5,918.06	16972	2453	99720
		Sum	511540	$846,282.39	2426957	350725	14259903
AP	16	*Mean*	57	$2,665.43	427	50	14056
		Sum	4840	$42,646.92	6839	806	224895
TO	139	*Mean*	370	$2,670.27	7969	4330	840
		Sum	3330	$371,167.25	1107698	601809	116753
MA	181	*Mean*	321	$4,763.38	4904	7237	1609
		Sum	59230	$862,171.34	887619	1309964	291269
MT	141	*Mean*	2362	$12,820.03	29404	110962	22444
		Sum	259180	$1,807,624.47	4145957	15645607	3164610
LEGAL AMAZON	**771**	***Mean***	1415	$6,562.60	13548	23759	28376
		Sum	**1090600**	**$424,908.38**	**10445437**	**18318406**	**21877709**

Source: Data obtained at IBGE (2014)

Table 2: Sum of inputs (labor, capital, area, fuel, agricultural inputs, and livestock inputs) per state for Legal Amazon region in 2006

State		Labor (employees)	Capital (unit)	Area (hectare)	Fuel (US$ 1000)	Agricultural Inputs (US$ 1000)	Livestock Inputs (US$ 1000)
RO	*Mean*	5341	2646	162190	943	620	2627
	Sum	277757	137582	8433870	49021	32216	136612
AC	*Mean*	4526	1960	160388	456	80	1010
	Sum	99579	43113	3528543	10026	1756	22209
AM	*Mean*	4301	1142	59174	298	80	344
	Sum	266667	70804	3668758	18479	4982	21358
RR	*Mean*	1967	773	114502	206	399	544
	Sum	29509	11595	1717531	3084	5985	8162
PA	*Mean*	5540	1835	160317	645	367	1491
	Sum	792211	262418	22925326	92223	52465	213272
AP	*Mean*	818	252	54612	57	118	97
	Sum	13095	4025	873789	905	1889	1556
TO	*Mean*	1272	692	103510	370	1454	875
	Sum	176831	96146	14387950	51461	202107	121635
MA	*Mean*	4218	1416	63185	321	731	571
	Sum	763473	256303	11436428	58048	132282	103416
MT	*Mean*	2541	1989	345310	2362	18200	5853
	Sum	358336	280452	48688715	333045	2566135	825274
LEGAL AMAZON	***Mean***	**3602**	**1508**	**150014**	**2054**	**9999**	**4845**
	Sum	**2777458**	**1162438**	**115660910**	**616293**	**2999819**	**1453493**

Source: Data obtained at IBGE (2014)
Note: Capital is the sum of machinery; Fuel is the sum of expenses with electricity and fuel; Agricultural inputs is the sum of expenses with seed, pesticides and fertilizer; and Livestock inputs is the sum of expenses with feed, medication and animals.

Expenses on fuel and energy (electricity) were aggregated into one variable. Expenses[3] on seed, pesticides and fertilizers were also aggregated into a single variable to represent other agricultural inputs. Finally, expenses on animal medication, animal purchase and feed were aggregated into one variable to take into account inputs related to cattle. Mato Grosso has higher expenses in these three inputs, which highlights its importance on agricultural production in this region. Overall, states on the agricultural frontier or the "arc of deforestation" (MT, RO, TO, MA, PA) show higher quantity of and expenses on inputs as well as higher level of production, as illustrated on Table 1. It is also important to notice that these states represent the majority (85%) of municipalities in the region. In the application all the variables were divided by their means.

4.2. Empirical Specification

The linear programming problems described in Equations (3)-(5) were estimated using GAMS. We obtain inefficiency indices for each municipality and then calculate the trade-offs between desirables and undesirables. Given the heterogeneity across municipalities we thought it interesting to find factors that might be associated with the difference performance across the municipalities.

We do so by regressing the inefficiency indexes on a number of socio-economic variables (descriptive statistics in Table 3). In addition to state (fixed) effects, we consider a measure of socio-economic development from the United Nations Development Programme (UNDP), the Human Development Index (Indice de Desenvolvimento Humano – IDHM) split in three categories: lifetime expectancy index, education index and Gross National Income (GNI) index. These measures take into account the following dimensions: life and healthy life, knowledge and a decent standard of living (UNDP[4], 2015). These variables correspond to a 2010 index and were obtained at the UNDP website. These indexes range from zero to 1, where values closer to 1 suggest higher development[5]. MT has the highest indexes while AM has the lowest.

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[3] Expenses were obtained from Table 820 on IBGE (SIDRA) website.
[4] This can be found at the website http://hdr.undp.org/en/content/human-development-index-hdi.
[5] UNDP indicates that an IDHM lower than 0.499 is considered very low, between 0.5 and 0.59 is low, between 0.6 and 0.69 is medium, between 0.7 to 0.79 is high, and higher than 0.8 is considered very high.

In the Legal Amazon region, on average, 33% of the area used on agricultural production is based on family farms (agricultura familiar in Portuguese). They use predominantly family labor and have farm revenue as the main source of income. Given the importance of the family farms in this region, we also used the share of family farms in each municipality. This dataset is available online at IBGE website.

We also include the share of the area in farms belonging to any type of association, and the farms' credit access (Programa Nacional de Fortalecimento da Agricultura Familiar – PRONAF). On average, 30% of agricultural area had access to credit (PRONAF) while 29% belongs to an association. As expected, given its technologic level of production, MT has the lowest share of family farms and use of credit in the region. To control for distribution of population between rural and urban we also consider rural population as one of the determinants of inefficiency.

The inefficiencies obtained in Equations (3)-(5) are non-negative values, and include zero for the most efficient farms. We used a Tobit model to estimate the relationship between the inefficiency indexes and the various variables mentioned.

$$f(D_i|x) = \{1 - \Phi(\frac{x\beta}{\sigma})\}^{(D_i=0)}[(2\pi)^{-\frac{1}{2}}\exp\{-(D_i - x\beta)^2/2\sigma^2\}]^{(D_i>0)} \quad (7)$$

where D_i represent the three inefficiencies obtained from Equations (3)-(5); x represents the inputs described in Table 3; Φ is the standard normal cumulative distribution function; β represents the estimated parameters; and σ the standard deviation. Equation (7) was estimated using Stata 14.

Table 3 – Average of the variables used on estimation of inefficiency determinants per state.

State	IDHM	IDHM-L	IDHM-E	IDHM-I	Family Farm	PRONAF	Association	Rural Population
RO	0.64	0.79	0.51	0.65	0.42	0.41	0.42	7946.7
AC	0.59	0.77	0.45	0.59	0.52	0.49	0.41	9149.09
AM	0.57	0.76	0.44	0.54	0.52	0.45	0.18	11.749.92
RR	0.61	0.80	0.50	0.58	0.39	0.39	0.15	7041.33
PA	0.58	0.77	0.45	0.57	0.37	0.34	0.32	16709.73
AP	0.64	0.78	0.54	0.62	0.33	0.28	0.32	4280.62
TO	0.64	0.79	0.54	0.61	0.26	0.24	0.20	2110.35
MA	0.58	0.74	0.49	0.54	0.40	0.37	0.33	10862.39
MT	0.68	0.81	0.57	0.68	0.13	0.12	0.30	3917.17
Legal Amazon	**0.62**	**0.78**	**0.51**	**0.59**	**0.33**	**0.30**	**0.29**	**8711.03**

Source: Own elaboration

5. Empirical results

In this section we present results for the model described in Equations (3)-(5) which consider three livestock, grains and timber production as desirable output, deforestation as undesirable output and six inputs. The average distance (inefficiency) per state obtained are displayed in Table 4.

A higher number of efficient municipalities was found for Equation (4) and (5), where the directional vector related to deforestation is not zero ($g_b \neq 0$). For D_b, 257 municipalities were efficient ($D_b = 0$), which was probably due to the number of municipalities that had zero deforestation in 2006 (212), represented in Figure 1 by the observation J_3. We found that 355 municipalities that deforested in 2006 ($b > 0$) were projected to the zero-bad output axis, such as observation J_2 in Figure 1.

Only 12% of the municipalities were efficient considering the output set modeled by D_y. This result suggests that overall municipalities are inefficient. On average, an output increase equal to 52% of the mean could have been achieved by correcting inefficiency (i.e. for livestock 0.52x10445437 = 5431627). As expected, this result is higher than when considering an output set that takes in account a reduction of undesirable output – deforestation - $D_{y,b}$. For this case, on average, a simultaneous expansion of desirable outputs (livestock, grains and timber production) and contraction of deforestation by 29% of mean values could occur when inefficiency is corrected. This represents a decrease of 410 ha on average, for each municipality (i.e. 0.29*1415 = 410). An interesting result was obtained by the output set modeled by $D_{y,b}$. On this case, zero deforestation was obtained in 146 (19%) municipalities after projecting to the frontier.

Table 4 – Summary of distances measured for the model with livestock, grains and timber production as desirable output and deforestation in 2006 as undesirable output

	$D_y(y^k, b^k, x^k; 1,0)$		$D_b(y^k, b^k, x^k; 0,1)$		$D_{y,b}(y^k, b^k, x^k; 1,1)$	
State	**Average**	**Max**	**Average**	**Max**	**Average**	**Max**
RO	0.88	2.73	1.82	25.59	0.56	2.82
AC	0.47	2.41	0.71	2.37	0.38	1.95
AM	0.30	1.92	0.81	16.66	0.16	1.45
RR	0.48	1.36	0.98	2.57	0.37	0.89
PA	0.62	4.11	2.28	53.69	0.49	3.52
AP	0.14	0.67	0.20	0.60	0.10	0.38
TO	0.18	1.27	0.02	0.24	0.01	0.24
MA	0.25	2.82	0.22	3.39	0.12	2.08
MT	1.10	5.22	1.26	15.31	0.56	4.17
Legal Amazon	0.52	5.22	0.94	53.69	0.29	4.17

Source: Own elaboration

By examining the output set modeled by $D_b$in Table 4, we see that states in the agricultural frontier (MT, RO and PA) could decrease deforestation more (in terms of its average) than other states, without decreasing output. Figure 4 shows the histogram of the inefficiency measures obtained from Equation (3), where the objective function seeks to maximize expansion of desirable outputs keeping constant deforestation. Around 70% of observations were smaller than 0.6, which suggests that these municipalities could have achieved output increases of 60% of their averages[6], without additional deforestation.

[6] We also estimated this inefficiencies considering outliers. When we take out observations that had inefficiency higher than 3 (only 14 observations) an average of 0.45 is found for the region and of 0.82 for MT, instead of 0.52 and 1.1, respectively.

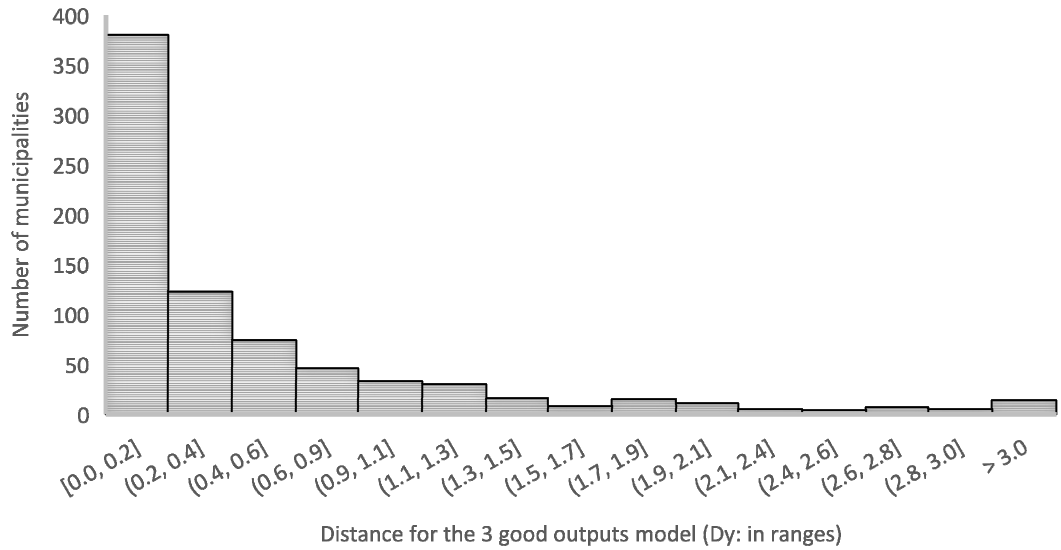

Figure 4 – Histogram of the inefficiency (distance - D_y) obtained from the three desirable outputs model
Source: Own elaboration.

The geographic distribution of these measures (D_y and D_b) is displayed in Figure 5. Darker municipalities indicate higher inefficiency. Higher inefficiencies are clustered in the agricultural frontier states (MT, PA, MA, RO, TO). Interestingly, it shows a link between these two measures, except for state of Tocantins (TO). TO has shown high level of inefficiency considering D_y but has not shown for D_b due to very low rates of deforestation in 2006 compare to other states (see Table 1).

The main objective of this paper is to evaluate the tradeoff between agricultural commodities and forest. These tradeoff measures are described in the set of Equations (6). First, we compare the quantities obtained by projecting to the frontier with the directional vector $(g_y, g_b) = (1,0)$, with the quantities obtained by projecting along the vector $(g_y, g_b) = (0,1)$. The difference between these two quantities gives an idea of how much desirable output the municipality has to forego to achieve the largest reduction in undesirable outputs possible without decreasing desirable outputs from their 2006 level.

Table 5 reports the average and the sum of these reductions in output and deforestation for municipios within each state. The fourth column shows the size of these differences in terms of observable total revenue, while columns 7 shows the average minimum fraction of 2006 deforestation achievable without reducing desirable outputs (column 8, shows the fraction of deforestation reduced). Overall, an average of 58% of total revenue from livestock, grains and timber production would have to be foregone to decrease deforestation in 93% of 2006 level.

A deforestation contraction would be more noticed in states at the agricultural frontier such as MT, MA, PA and RO. These states would not observe a smaller total revenue decrease compared with other states, given its already efficient level of production.

Figure 5 – Map of inefficiencies – D_y(left) and D_b(right) – for the Legal Amazon municipalities
Source: Own elaboration

Table 5: Trade-off between Agricultural commodities (livestock, grains and timber production) and Forest for Legal Amazon in 2006

Difference A = $y + \bar{y} * D_y(y^k, b^k, x^k; 1,0) - D_b(y^k, b^k, x^k; 0,1) = (y + \bar{y} * \widehat{D_y}) - y$							
	Total Revenue (US$ 1000)			**Deforestation (ha)**			
State	**Average**	**Sum**	**% wrt observable GDP**	**Average**	**Sum**	**% Deforested**	**% Saved**
RO	$5,439.39	$282,848.04	82.87	2579.36	134126.54	0.18	99.82
AC	$3,113.69	$68,501.18	111.39	999.70	21993.34	7.78	92.22
AM	$2,587.94	$160,452.32	319.80	1144.84	70980.38	2.43	97.57
RR	$4,639.12	$69,586.80	237.02	1392.65	20889.73	2.88	97.12
PA	$5,077.76	$726,119.70	66.12	3226.81	461434.42	9.80	90.20
AP	$1,160.65	$18,570.33	394.87	289.26	4628.19	4.38	95.62
TO	$1,227.33	$170,598.73	56.02	22.10	3071.22	7.77	92.23
MA	$1,626.19	$294,339.91	84.18	304.87	55181.25	6.84	93.16
MT	$6,875.00	$969,374.44	39.15	1788.96	252242.91	2.68	97.32
Legal Amazon	**$3,580.27**	**$2,760,391.45**	**58.54**	**1328.86**	**1024547.97**	**6.06**	**93.94**

Source: Own elaboration

Note: For deforestation the difference is: $b - [b - \bar{b} * D_b(y^k, b^k, x^k; 0,1)] = b - (b + \bar{b} * \widehat{D_b})$. "wrt" means with respect to

This tradeoff was also evaluated with projection along the $g(g_y, g_b)=(1,-1)$ vector illustrated in Figure 1. Results are quite similar with respect to change in the total revenue from desirable outputs but they differ with respect to area deforested. Table 6 shows that on average 57% of observable total revenue for this region would have to be forgone, while around 30% of what was deforested in 2006 would be saved.

Although only half of the deforested area could be saved by these efficiency gains in MT, it corresponds to 10% of total deforested in the region. On the other hand, PA could save 80% of its deforested area, which also corresponds to around 10% of total deforestation in 2006. With respect to the total revenue, although MT would forego only 38% its observable total revenue by minimizing deforestation rather than maximizing desirable outputs, this amount corresponds to around 35% of total revenue that would be foregone.

Next step was to estimate how much of total revenue would have to be foregone for each hectare less of deforestation. We did this calculation for each state and the region using the sum of total revenue foregone (column 3 in Table 5 and 6) and the sum of deforestation foregone or saved forest (column 6 in Table 5 and 6). Table 7 presents the results for each of the differences calculated and considering a measure of a ton of Carbon Oxide (CO_2). MMA/DPCD (2011) establishes that one hectare of forest has 100 tons of carbon (tC) and one tC is equivalent to 3.67 tCO_2. Thus, once the price of one hectare of deforestation in terms of foregone total revenue with desirable outputs is estimated is possible to calculated similar measure for tCO_2.

Table 6: Trade-off between agricultural commodities and Forest considering a distance measure that moves the units to the frontier expanding agricultural commodities and contracting deforestation for Legal Amazon in 2006

	Difference B = $[y + \bar{y} * D_y(y^k, b^k, x^k; 1,0)] - [y + \bar{y} * D_{y,b}(y^k, b^k, x^k; 0,1)] = (y + \bar{y} * \widehat{D_y}) - (y + \bar{y} * \widehat{D_{y,b}})$						
	Total Revenue (US$ 1000)			**Deforestation (ha)**			
State	**Average**	**Sum**	**% wrt true GDP**	**Average**	**Sum**	**% Deforested**	**% Saved**
RO	$5,229.17	$271,916.77	79.67	794.90	41335.01	69.24	30.76
AC	$3,094.56	$68,080.29	110.70	536.94	11812.57	50.47	49.53
AM	$2,585.70	$160,313.23	319.52	228.96	14195.76	80.49	19.51
RR	$4,628.03	$69,420.39	236.46	525.59	7883.86	63.35	36.65
PA	$5,015.12	$717,161.53	65.30	692.03	98959.71	80.65	19.35
AP	$1,160.27	$18,564.39	394.74	141.04	2256.59	53.38	46.62
TO	$1,226.89	$170,537.26	56.00	20.56	2857.91	14.18	85.82
MA	$1,621.25	$293,445.67	83.92	168.26	30454.62	48.58	51.42
MT	$6,742.52	$950,695.48	38.40	790.01	111391.71	57.02	42.98
Amazon Legal	**$3,528.06**	**$2,720,135.01**	**57.69**	**416.53**	**321147.75**	**70.55**	**29.45**

Source: Own elaboration

Note: For deforestation the difference is: $b - [b - \bar{b} * D_{y,b}(y^k, b^k, x^k; 0,1)] = b - (b + \bar{b} * \widehat{D_{y,b}})$

Tocantins is clearly an outlier in these results. When not considering it, the average price of tCO2 decreases to US$ 6.90, which shows the robustness of the results since when taking its observation out the price does not change much. Forest and tCO_2 price increases considerably between difference A and difference B. This occurs because larger amounts of CO2 (deforestation) are reduced in difference B.

Table 7: Ratio of foregone agricultural commodities and foregone deforestation (saved forest)

State	Total Revenue (US$) / Def (ha)		In terms of tCO2	
	Difference A	**Difference B**	**Difference A**	**Difference B**
RO	$2,108.81	$6,578.36	$5.75	$17.92
AC	$3,114.63	$5,763.38	$8.49	$15.70
AM	$2,260.52	$11,293.03	$6.16	$30.77
RR	$3,331.15	$8,805.38	$9.08	$23.99
PA	$1,573.61	$7,247.00	$4.29	$19.75
AP	$4,012.44	$8,226.73	$10.93	$22.42
TO	$55,547.54	$59,672.03	$151.36	$162.59
MA	$5,334.06	$9,635.51	$14.53	$26.25
MT	$3,843.02	$8,534.71	$10.47	$23.26
Legal Amazon	**$2,694.25**	**$8,470.04**	**$7.34**	**$23.08**

Source: Own elaboration

Table 7 shows the average opportunity cost for a one hectare reduction in deforestation is US$ 2,694.25 for the whole region. Overall, states in the agricultural frontier have shown higher loss of agricultural production per forest saved than states out of it, except for PA. Similar results were found when analyzing the results for the price of a tCO_2. We found an average price of US$ 7.34 tCO_2 per year, or about US$ 61 when the perpetuity is discounted at a 12% rate). These opportunity costs are higher than what has been found in the literature for this region. Nepstad et al. (2007), for example, found a present value average of US$ 5.5 for tCO_2 over 30 years.

5.1. Efficiency determinants

In this section we evaluate the impact of socio-economic factors on the inefficiency estimated by Equations (3)-(5). We estimated equation (7), with fixed state effects using MT as the reference. For D_y we found statistically significant negative differences between other states and MT showing that these states have lower level of inefficiency due to non-observable effects (as you can see in Table 4). A different result was obtained for $D_{y,b}$ and D_b, where only TO and MA had shown a statistical lower level of inefficiency due to non-observable fixed effects.

Table 8: Tobit estimation of efficiency determinants, Equation 7

	$D_y(y^k, b^k, x^k; 1, 0)$	$D_{y,b}(y^k, b^k, x^k; 1, 1)$	$D_b(y^k, b^k, x^k; 0, 1)$
Family Farm	-1.5159**	-1.2091**	-9.3327***
	(0.5901)	(0.5416)	(3.0634)
Credit – PRONAF	1.532**	1.3322**	9.0485***
	(0.6175)	(0.5667)	(3.2054)
Associated	0.1442	0.1266	-0.3002
	(0.1565)	(0.1489)	(0.8432)
IDHM-Education	-0.6236	-1.1631**	-10.1383***
	(0.4845)	(0.4622)	(2.6113)
IDHM- lifetime	0.0645	-1.1294	-18.2805***
	(1.1725)	(1.1385)	(6.4261)
IDHM-Income	3.0589***	2.4001***	18.6657***
	(0.7453)	(0.7116)	(4.0259)
Rural Population	2.4e-05***	2.1e-05***	0.0001***
	(3.01e-06)	(2.75e-06)	(1.5e-0.5)
Constant	-0.8261	0.3023	8.4257
	(0.8678)	(0.8472)	(4.7807)
State fixed effects	*Yes*	*Yes*	*Yes*
Sigma			
Constant	0.7038***	0.6311***	3.5489***
	(0.0195	(0.0204)	(0.112)

Source: Own elaboration

The fraction of family farms is negatively (significantly) related to efficiency measured by all three methods, while the fraction using PRONAF has the opposite result – it has a significant positive relationship to efficiency by all three measures. The IDHM income measure of development is also positively and significantly related to efficiency across the three measures. Rural population has a significantly positive effect on efficiency, of similar size across the three measures.

Overall, results shown a sharp decrease on deforestation given inefficiency correction, when considering directional output distance that takes in account contraction of deforestation. The tradeoff results have shown a higher tCO_2 price than what was found in the literature (i.e. Nepstad et al. (2007)), and even higher considering states at the agricultural frontier. We also found that socio-economic development would lead to smaller inefficiencies and consequently to lower level of deforestation. Thus, the implementation of policies that take in account socio-economic development in this region would indirectly decrease deforestation.

6. CONCLUSIONS

This paper evaluates the tradeoff between the forest and agricultural commodities in the Brazilian Amazon Forest for 2006 using measurement by three different directional output distance functions. The main objective is to find the total revenue that has to be foregone to decrease deforestation.

We found that 58% of average total revenue from livestock, grains and timber production would have to be foregone to decrease deforestation by 93% of the 2006 level. Potential deforestation contraction is greater in states at the agricultural frontier such as MT, MA, PA and RO. An average price for reducing deforestation by one hectare, in terms of foregone agricultural revenues, was estimated at US$ 2,694.25. The states in the agricultural frontier have shown higher tradeoff between agricultural production and forest, except for PA. We estimated an average price of US$ 7.34 per ton of CO_2 emissions averted each year, which is higher than what has been found in the literature for this region.

Overall, we found that by decreasing inefficiency, deforestation could decrease substantially, and therefore that policy toward improvement of efficiency factors in this region could play an important role in decreasing deforestation by improving efficiency.

Several other limitations arise from the dataset used in this paper, such as a high level of aggregation (municipal level instead of farm level data) and the availability of data for only one year, which precludes a temporal analysis of deforestation.

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APPENDIX A

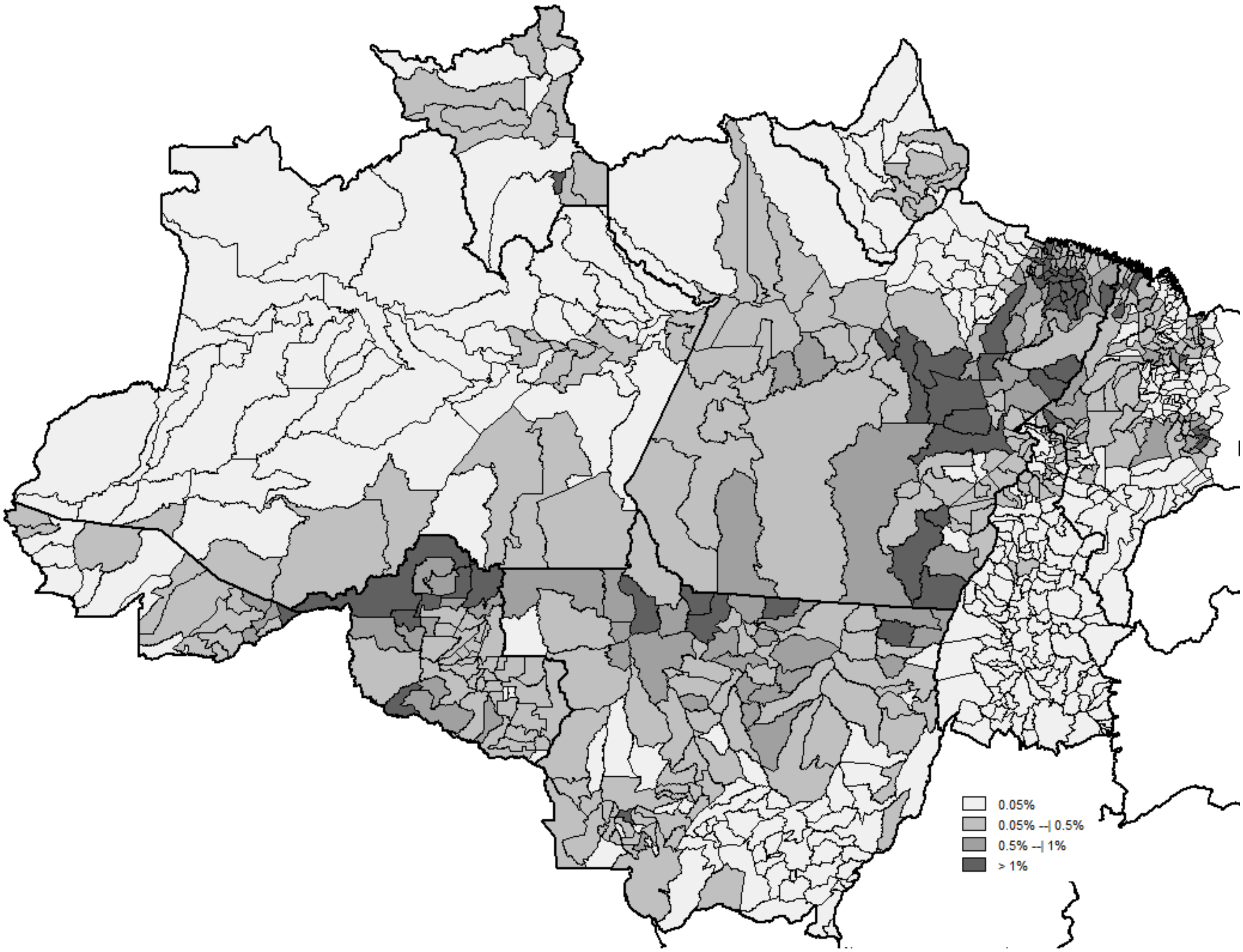

Figure 3: Deforestation area as a percentage of municipal area at Legal Amazon in 2006.
Source: PRODES (2014)