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The Cost of Forest Preservation in the Brazilian Amazon: The "Arc of Deforestation"

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We estimate the trade-off between agricultural production and forest preservation for the municipalities in Brazil's agricultural frontier, the so-called "arc of deforestation," using census and deforestation data for 2006. We use a nonparametric directional output distance function that allows us to identify the gradients of the production possibility frontier, which are the trade-offs of interest. We found that, on average, $979 is forgone in annual livestock, timber, and grain revenues to conserve 1 hectare of forest. This translates, *ceteris paribus*, to an average present value of costs to permanently sequester CO_2 of $16.36/t, higher than most previous estimates.

Key words: CO_2 sequestration cost, directional distance function, trade-off

Introduction

Brazil has the largest tropical forest in the world, constituting a significant carbon sink and highly relevant to worldwide biodiversity. More than 10,000,000 hectares (ha) of this area were deforested during 2004–2006, resulting in major increases in atmospheric CO_2. While the world population would benefit from reducing carbon emissions by reducing this rate of deforestation, Brazilians would bear the cost in terms of forgone revenues from timber and agricultural production. In recognition of this situation, Norway and other entities have contributed more than $1,000,000,000 to Brazil through the Amazon Fund to preserve the forest (http://www.fundoamazonia.gov.br/en/home/). The payments are based on an estimate of benefits forgone by Brazilians equivalent to $5/t of CO_2 sequestered in the forest if it is not deforested. The research reported here re-examines the validity of this $5/t estimate, in fact finding that the forgone benefits are about 3 times that amount.

Early studies—such as those by Margulis (2004), Vera-Diaz and Schwartzman (2005), Nepstad et al. (2007) and Börner and Wunder (2008)—estimated returns per hectare that can be achieved on deforested land: from livestock, grain, and timber and other agricultural activities (previous studies are subsequently reviewed in more detail).[1] Most such studies follow one of two approaches: the inductive approach uses micro-level enterprise budget estimates then combines them in some way so as to reflect average income streams from deforested land at the regional level; the deductive approach uses aggregate data (at the regional level) to estimate those average income streams. Our study follows the deductive approach but uses a different method from that of Börner and Wunder, who also used aggregate municipality data as well as results from other studies.

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[1] Cattaneo (2001), Morton et al. (2006), Rivero et al. (2009), Richards et al. (2012), Hargrave and Kis-Katos (2013), and Richards, Walker, and Arima (2014), among others, have also explored the link between agricultural activities and deforestation in the Amazon.

Background

Agricultural expansion in the last 3 decades has driven Amazon deforestation in the northern region of Brazil. The primary agricultural frontier, also known as the "arc of deforestation," comprises municipalities with high levels of deforestation driven by agriculture. The arc of deforestation includes municipalities from the states of Acre, Amazônia, Roraima, Rondônia, Pará, Mato Grosso, and Maranhão. In this paper, we focus on municipalities in this region that deforested more than 10,000 ha during 2004–2006. In 2006, almost 1,000,000 ha (around 10,000 km^2) were deforested in the Brazilian Amazon, 83% in the arc of deforestation. The revenues obtained from livestock, grain, and timber activities as well as deforestation activities are clustered in the outer boundary of the arc of deforestation (see Figure 1).

Livestock, one of the main activities in this region, is considered the main driver of deforestation by, for example, Cardille (2003), Margulis (2004), and Rivero et al. (2009). Cardille and Foley also suggested crop production as a main driver. Nepstad et al. (2007) and Quintanilha and Lee Ho (2006) indicated that timber activity is an important driver of deforestation.

The literature has produced a wide range of shadow price estimates for sequestering a ton of CO_2, from $1.00/t to $50.00/t of CO_2 (Myers Madeira, 2008). Margulis (2004) estimated the shadow price of deforestation, accounting not only for timber logged but also for existence value and ecotourism. He estimates an opportunity cost of $137.99/ha/year that includes forgone revenue from rice, cattle, soy, corn, timber, and nontimber products, but he does not convert this to a cost for CO_2 sequestered if the deforestation were forgone.

Vera-Diaz and Schwartzman (2005) used secondary data from the literature to construct enterprise budgets for estimating the 30-year present value of costs to sequester CO_2 for that period of time.[2] Using a 10% discount rate and an average carbon content of 155t/ha, they estimate the present value of average forgone income at $6.10/t of CO_2 sequestered (though their estimates ranged from $3.90 to $6.10 depending on the assumptions used).

Nepstad et al. (2007) estimated the opportunity cost of forest preservation over 30 years to be $5.65/t of carbon, or $1.54/t of CO_2. Their findings are based on a spatial dynamic modeling system proposed by Soares-Filho et al. (2006) that integrates soy rent, cattle rent, and logging rent from models developed by Vera-Diaz et al. (2008), Merry et al. (2009), and others.

Börner and Wunder (2008) constructed a typical 10-year trajectory of land transition over time involving timber extraction, crop production and cattle ranching, using census data at the municipal level and data from other studies.[3] They used a discount rate of 10%, an average carbon content of 110 t/ha of carbon, and a linear projection of deforestation from 2000–2006 to 2007–2016. They obtained a wide range of opportunity costs across space. They estimated that an opportunity cost of $2.32/t of CO_2 would compensate for forgone income on 40% of the projected deforestation in the state of Mato Grosso and on 93% in the state of Amazonas. To compensate for income forgone from 100% of the projected deforestation, a price of $12.36/t of CO_2 would be necessary. Vera-Diaz and Schwartzman (2005), and Börner et al. (2010) used similar approaches and obtained similar results.

Ickowitz, Sills, and de Sassi (2017) estimated the opportunity cost of preserving 1 hectare of forest by smallholders producing crops and large livestock in Brazil (at study sites in the states of Acre, Amapá, Mato Grosso, and Pará) and five other countries during 2010–2012. Their cost estimates ranged from $142.42/ha to $1,522.00/ha,[4] which they translate to between $2.89/t and $21.02/t of CO_2 using a 30-year present value approach.[5]

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[2] Vera-Diaz and Schwartzman (2005) named it Break Even Carbon Price, "that is, the price of carbon at which conservation of standing forests becomes financially attractive for loggers and ranchers" (p. 94).

[3] Börner et al. (2010) focused on the entire Brazilian Amazon, and Börner, Mendoza, and Vosti (2007) focused on payment for environmental services rather than on identifying the opportunity cost.

[4] They use an exchange rate of R$1.76 = US$1.00 (obtained from http://data.worldbank.org/indicator/PA.NUS.FCRF).

[5] Carbon content also plays an important role in the opportunity cost estimates; we used 145–221 t/ha of carbon for this study's estimates.

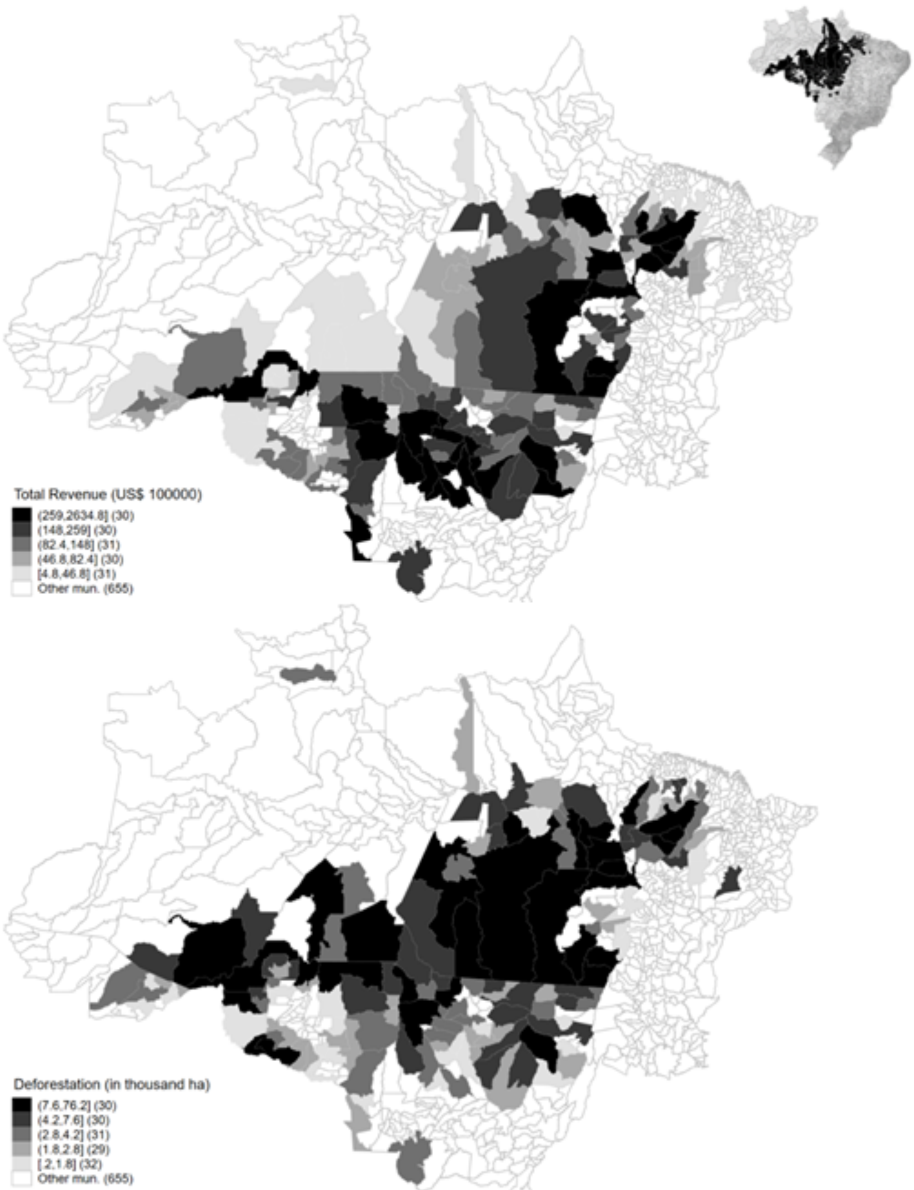

Figure 1. Total Agricultural Revenue and Deforestation in the Arc of Deforestation, Legal Amazon, Brazil, 2006

Notes: "Other mun." in these maps represents municipalities that are not used in the estimation of equation (3).
Source: Data are from the Brazilian Institute of Geography and Statistics (IBGE) (2014) and the National Institute for Space Research (INPE) (2014).

Two assumptions that affect all these estimates are carbon density and discount rate. To standardize comparisons, we have adjusted each of their results to reflect our own assumptions of 132.2 t/ha of carbon and a discount rate of 10%.[6] Margulis's (2004) opportunity cost translates to \$2.84/t of CO_2, Vera-Diaz and Schwartzman's (2005) to at most \$7.59/t, Nepstad et al.'s (2007) to

[6] For these authors, we first performed a reverse NPV analysis to recover estimates of the annuity forgone due to preserving the forest. We calculated the present value of this annuity in perpetuity by dividing by 0.10, then divided this by the amount of CO_2 sequestered using the rate of 132.2 t/ha. We could not adjust for differences in exchange rates because not all articles report the exchange rate used.

\$1.08/t, Börner and Wunder's (2008) to \$3.14/t, and Ickowitz, Sills, and de Sassi's (2017 to a range of \$2.42/t to \$20.68/t at individual sites.[7] Comparable estimates of the opportunity cost of carbon sequestration in forests in Bolivia range from \$2.47/t to \$5.77/t of CO_2 sequestered (Stich, 2009; Malky, Leguía, and Ledezma, 2012; Müller et al., 2013).

Most of these estimates of values forgone by preserving forest are based on inductive approaches:[8] per hectare agricultural costs and returns estimated for a few specific locations are assumed to approximate the average regional-level trade-offs. In our research, we examine aggregated data directly to estimate the relationship between deforestation and increased returns from agricultural and logging activities.

Nepstad et al. (2014), Gibbs et al. (2015), Hargrave and Kis-Katos (2013), and Soares-Filho et al. (2014) suggested that regulation has reduced deforestation to some extent.[9] Soares-Filho et al. provided a critical review of the Forest Code. Although the new Forest Code, approved in 2012, has given amnesty for illegal deforestation, it continues to require conservation of 80% of the property area in the Amazon biome and has created Areas of Permanent Preservation. Soares-Filho et al. argued that the Forest Code has severely restricted deforestation on private property, even though enforcement is difficult.

In this paper, we estimate the trade-off between agricultural income and forest preservation in the arc of deforestation region. Given associated CO_2 emissions, deforestation is explicitly modeled as an undesirable output, while livestock, grain, and timber production are desirable outputs. This approach will allow us to estimate a shadow price for reducing CO_2 in terms of forgone income.

Model

In this paper, we seek to estimate the stream of income given up by forgoing deforestation. Forgone net revenue consists of timber marketed and income from agricultural production. We estimate this trade-off by calculating gradients of the current-year, municipality-level production possibility frontier (PPF) between deforestation and livestock, grain, and timber, conditioned on resources available. We treat deforestation, which is also a proxy for CO_2 emissions, as an undesirable output, one that cannot be costlessly disposed of. The calculated trade-offs and information on prices of desirable outputs (livestock, grain, and timber) allow us to identify a shadow price of deforestation, which is the net revenue sacrificed for each additional hectare of forest that is preserved rather than deforested. Using the average carbon content per hectare from the Brazilian government Amazon Fund contracts, we convert this potential stream of income into the present value of the cost per ton of CO_2 sequestered in the present.

Our study provides an alternative, deductive approach to complement the mostly inductive studies in the literature. We use aggregate municipality-level data to infer how much agricultural production is forgone when less land is deforested. By combining aggregate data from 152 municipalities in 2006, we identify the PPF for desirable agricultural outputs and undesirable deforestation; from this we evaluate the amount of agricultural output forgone for a 1-hectare reduction in deforestation.

There are two advantages to analyzing aggregate data rather than micro data. First, we avoid the sampling errors and estimation errors inherent in the development of micro-level budgets, which are derived from estimates of the benefits and costs of specific enterprises. Sampling errors arise because a single representative budget will not represent the range of circumstances within a region. These errors can be reduced but not eliminated by considering smaller, more homogeneous subregions. Beyond these sampling errors, errors in budgeting costs and benefits of enterprises are common (deriving from errors in estimating yields and prices appropriate even for the "representative"

[7] For this estimate, we also converted to the exchange rate we are using (R\$2.17 = US\$1.00).

[8] Exceptions are Börner and Wunder (2008) and Börner et al. (2010), who also used municipality data.

[9] Soares-Filho et al. (2014) suggested that the Forest Code fails to regulate deforestation in other biomes, such as the Cerrado and Caatinga.

situation) as well as errors in imputing those estimates to represent the regional average. A second advantage of aggregate analysis is that the data are readily available from government reports, without recourse to extensive farm management data.

Disadvantages of the aggregate approach include hidden errors in the aggregated data or discrepancies between the reported aggregate variables and the conceptual variables used to describe the production possibilities set. In our study, for example, deforestation as measured by satellite is not strictly a binary phenomenon, because deforestation often occurs over time and often incompletely, whereas our model assumes that the number of hectares deforested in a given year is unambiguously identifiable. Further, there may be systematic biases in the data when some variables are systematically over- or underreported. Input variables might not be consistently measured across regions because the quality of inputs and resources may differ. We have not made any correction for quality differences in land or cattle, for example. Our input variables from the 2006 Census of Agriculture are gross proxies for actual flows rather than estimates of the flows themselves, in particular for capital.

Another disadvantage of our approach is that we treat a municipality, rather than a firm, as a decision-making unit. The optimization theory we use applies more directly at the firm level. By aggregating, we implicitly assume a constant distribution of firms within each municipality (although this issue is minimized in our calculations because we use data for only 1 year). Also, at high levels of aggregation, there might be insufficient variability within the data to accurately identify the critical trade-off between agricultural output and reduced deforestation, in particular when using parametric specifications of the relationship in an econometric approach. We minimize this issue by using data envelopment analysis (DEA), a nonparametric, nonstochastic programming approach. The advantage of DEA is that no mathematical specification is needed, since the feasible set is identified by convex combinations of observed input and output combinations, whereas an econometric approach requires a specific mathematical form that may not be appropriate. However, with DEA, erroneous outlier data points can substantially misrepresent the true feasible technology, and there is no error structure specified that helps one to evaluate the reliability of the estimates of the boundaries of the feasible technology.

One of the implications of our model is that some municipalities will be located inside the estimated technological frontier established by other municipalities, implying that they are technologically inefficient. This in turn implies that if they simply became efficient, they could costlessly achieve more agricultural output, less deforestation, or both. In our study, we assume that the marginal rate of transformation we estimate is achievable by all municipalities, regardless of our estimate of their efficiency. We do not address the question of why measured inefficiencies occur, nor whether and how technical efficiency might be improved—we simply take it as given as we estimate the marginal rate of transformation between forest preservation and agricultural production.

Given the contribution of deforestation to greenhouse gas emissions in this region and the importance of earnings from deforested land to the livelihood of farmers in the region, our study makes a valuable contribution by providing new estimates of the agricultural income forgone when deforestation is reduced, free from the sampling and estimation errors inherent in micro-budget-based estimates utilized by most previous studies (though subject to other weaknesses, as just described).

We use a directional distance function, as in Färe, Grosskopf, and Pasurka (2007), to model the PPF. The output vector has two subvectors $(\boldsymbol{y},\boldsymbol{b})$, with both desirable outputs $\boldsymbol{y} \in R^m_+$ (livestock, grain, and timber) and undesirable outputs $\boldsymbol{b} \in R^s_{\geq 0}$ (in our case, just one—deforestation). The input vector is $\boldsymbol{x} \in R^n_+$ (labor, capital, land, fuel, cattle inputs, and other agricultural inputs). The output correspondence represents the production technology as

(1) $$P(\boldsymbol{x}) = \{(\boldsymbol{y},\boldsymbol{b}) : x \text{ can produce } (\boldsymbol{y},\boldsymbol{b})\},\ \boldsymbol{x}\ \varepsilon\ \Re^n_+, \boldsymbol{y} \in R^m_+ \text{ and } \boldsymbol{b} \in R^s_{\geq 0},$$

where $P(\boldsymbol{x})$ is the set of desirable ($\boldsymbol{y}$) and undesirable ($\boldsymbol{b}$) outputs that can be produced by inputs $\boldsymbol{x}$. As in Färe, Grosskopf, and Pasurka (2007), the output set is compact, inactivity is possible ($\{0\} \in$

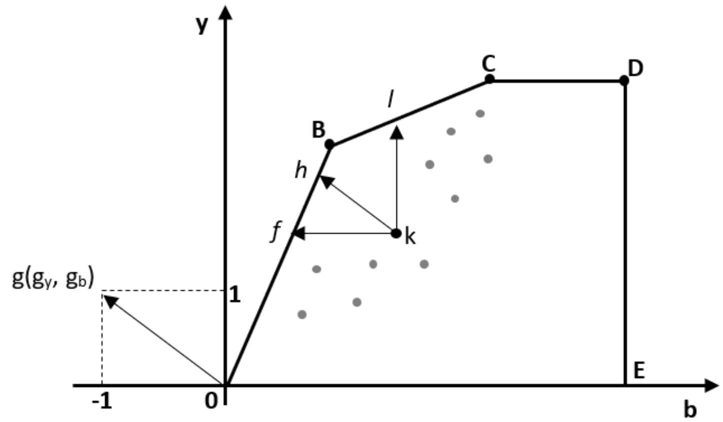

Figure 2. Output Set: $P(x)$**, and Directional Output Distance Measures**

$P(\boldsymbol{x})$, $\forall x$), $\boldsymbol{y}$ are strongly disposable, and $\boldsymbol{b}$ are weakly disposable. This last property means that there are costly disposal fees or restrictions on the production of undesirable outputs.[10] Figure 2 illustrates the output set for the case of a single good output and a single bad output. The segment DE illustrates the strong disposability of the desirable output, while the 0BC segments represent weak or costly disposability of the undesirable output.

The output directional distance function we use to represent the production frontier with one undesirable output is

$$(2) \qquad \vec{D}^{j}\left(\boldsymbol{x}, \boldsymbol{y}, b; \boldsymbol{g}_{y}^{\boldsymbol{j}}, -g_{b}^{j}\right) = \max\left\{\beta : \left(\boldsymbol{y} + \beta \boldsymbol{g}_{y}^{\boldsymbol{j}},\ b - \beta g_{b}^{j}\right)\ \varepsilon\ P(\boldsymbol{x})\right\},$$

where the predetermined directional vector is defined as $\boldsymbol{g^j} = \left(\boldsymbol{g_y^j}, g_b^j\right)$ and subscript j refers to output directional distance functions with different directional vectors. This function describes the technology by projecting all output bundles to the frontier in the direction chosen. On the production frontier, this directional distance function has a value of 0.

The positively sloped boundary 0BC indicates that regulations such as disposal fees or restrictions on undesirable output production impose a trade-off between desirable and undesirable outputs. This structure implies a positive marginal rate of transformation (MRT) between these two types of output, such that deforestation is reduced only by decreasing production of livestock, grain, or timber.

The distance for a municipality (the unit of observation) will be 0 when its output bundle locates it on the boundary of the feasible technology, and the unit is said to be technically efficient. We use DEA,[11] to calculate the output directional distance function and the PPF implied. The linear piecewise technology is identified by solving the following problem for each municipality k using

[10] In addition to Färe, Grosskopf, and Pasurka (2007), who described the approach and properties in detail, Macpherson, Principe, and Smith (2010) discussed them and the suitability of the approach in the context of environmental and economic assessment.

[11] DEA (data envelopment analysis) is a mathematical programming nonparametric, nonstochastic method commonly used to estimate production frontiers for the purpose of efficiency and productivity analysis Färe, Grosskopf, and Lovell (1994) in the presence of multiple outputs and multiple inputs, especially when prices are not available. The method allows easy imposition of regularity conditions of the technology (such as monotonicity and concavity) and is free of specification errors. Given its nonstochastic nature, it is particularly useful for small datasets. Its drawbacks include sensitivity to outliers and lack of probabilistic inference.

Table 1. Models with Alternative Directional Vectors, $\boldsymbol{g} = \left(\boldsymbol{g}_y, g_b\right)$ in Equation (3)

Models	Directional Vectors	Description
A	$\boldsymbol{g^A} = (\mathbf{1}, -1)$	Simultaneous expansion of all desirable outputs and contraction of undesirable output given inputs
Y	$\boldsymbol{g^Y} = (\mathbf{1}, 0)$	Expansion of all desirable outputs, given undesirable output and inputs
E	$\boldsymbol{g^E} = (\mathbf{0}, -1)$	Contraction of undesirable output, given desirable outputs and inputs

the Generalized Algebraic Modeling System (GAMS):[12]

$$\vec{D}^j(\boldsymbol{y}^k, b^k, \boldsymbol{x}^k; \boldsymbol{g}^j, g_b^j) = \max\left\{\beta^k : (\boldsymbol{y}^k + \beta^k \boldsymbol{g}_y^j, b^k - \beta^k g_b^j, \boldsymbol{x}^k) \in P(\boldsymbol{x}^k)\right\} = \beta^{k*},$$

(3)
$$\begin{aligned}
\text{subject to} \sum_{k=1}^{K} z^k y_m^k &\geq y_m^k + \beta^k g_y^j,\ m = 1,\ \ldots,\ M \qquad j = Y, A, E \\
\sum_{k=1}^{K} z^k b^k &= b^k - \beta^k g_b^j, \\
x_n^k &\geq \sum_{k=1}^{K} z^k{}_k x_n^k,\ n = 1, \ldots,\ N \\
z^k &\geq 0,\ k = 1, \ldots, K
\end{aligned}$$

where $\beta^{k^*} = \vec{D}^j\left(\boldsymbol{y}^k, b^k, \boldsymbol{x}^k; \boldsymbol{g_y^j}, g_b^j\right)$ is the distance of municipality k from the frontier (a measure of inefficiency); $m = 1,\ \ldots,\ M$ refers to desirable outputs; $n = 1, \ldots,\ N$ refers to inputs; k identifies values for municipality k; $\boldsymbol{z}^k$ are intensity variables used to identify the feasible production set within the linear combination of observed points for all municipalities, with constant returns to scale imposed by the inequality constraint; and j refers to directional distance functions with alternative directional vectors $\boldsymbol{g^j}$. Weak disposability of undesirable outputs is imposed ($\sum_{k=1}^{K} z^k b^k = b^k$) so as to model the output set as in Figure 2.

To project the observed output bundles to alternative points on the frontier, between which the gradients will be calculated, we use equation (3) with the alternative directional vectors reported in Table 1. Model Y employs the directional vector $\boldsymbol{g^Y} = \left(\boldsymbol{g}_y, g_b\right) = (\mathbf{1}, 0)$, so that the objective function is to maximize production of the three desirable outputs $\boldsymbol{y}$ while keeping the undesirable output at the same level and without increasing inputs. Technical inefficiency of municipality k is represented in Figure 2 by the distance from k to l (here we represent on the vertical axis only one of the three good outputs that are being projected simultaneously). The projection to l represents an output bundle with the largest feasible production of desirable outputs holding constant the levels of deforestation and inputs.

[12] Equation (3) is the DEA implementation of definition (2). This maximization problem identifies the multidimensional production set (in our case, four outputs and six inputs) comprising observations on 152 municipalities in the arc of deforestation and all linear combinations of them. It does so by minimizing the distance to the frontier of each of these 152 observations. The frontier is defined by the convex hull of the efficient observations in this multidimensional space. The directional distance is 0 for these observations and positive for municipalities that are not on the efficient frontier. To identify the feasible technology set, the first constraint ensures that the levels of good outputs are within the levels demonstrated by the observed data. The second constraint does the same for the level of undesirable outputs, and the third ensures that the level of inputs is no greater than levels demonstrated by the observed data. The fourth constraint imposes constant returns to scale by restricting the intensity variables used in constructing the output and input sets to be nonnegative. The set of observations thus constituted identifies a convex production set consistent with an input set. The last row indicates that we run this problem for the three distance directions, shown in Table 1.

Model E (for environmental, contraction of undesirable outputs) employs the directional vector $\boldsymbol{g^E} = (\boldsymbol{g}_y, g_b) = (\mathbf{0}, -1)$, which decreases undesirable outputs while maintaining constant levels of desirable outputs with no increase in inputs. Technical inefficiency using this model is represented in Figure 2 by the distance from k to f. Point f represents the output bundle given the largest possible contraction of deforestation while holding constant desirable outputs with no increase in inputs.

Model A (for a movement of all outputs) employs the directional vector $\boldsymbol{g^A} = (\boldsymbol{g}_y, g_b) = (\mathbf{1}, -1)$, increasing desirable outputs while simultaneously decreasing undesirable output. Technical inefficiency in this direction is represented in Figure 2 by the distance from k to h.

Rather than measuring the trade-off as the MRT at the point on a facet to which each observation is projected, we estimate the aggregate regional trade-off corresponding to point l versus point f in Figure 2. The aggregated vertical distance between l and k from model Y represents the quantities of livestock, grain, or timber that must be given up to decrease deforestation by the amount equal to the horizontal distance between f and k from Model E. To obtain a dollar value of this trade-off, we multiply the change in desirable outputs by their prices. We presume that the forest will be preserved indefinitely, which means that the income from livestock and grains must be given up in perpetuity. Income from timber occurs only in the first year after deforestation, so the present value of income given up to preserve the forest consists of immediate income from all three desirable outputs plus the present value of the future stream of income from livestock and grain.

To be mathematically explicit, then, for a given region, we estimate the opportunity cost of forest preservation, measured in present value of dollars forgone per hectare of forest preserved,[13] as

$$\text{(4)} \qquad \text{Opportunity cost} = \frac{\sum_{k=1}^{K}\left[\sum_{f=1}^{2} p_f^k \Delta y_f^k / d + p_h^k \Delta y_h^k\right]}{\sum_{k=1}^{K} \Delta b^k},$$

where

$$\text{(5)} \qquad \Delta y_m^k = \left[y_{m,\,D_y}^k - y_{m,D_b}^k\right],\ m = 1,\ \ldots,\ M,$$

$$\text{(6)} \qquad \Delta b^k = b_{D_y}^k - b_{D_b}^k,$$

and f indexes the two desirable outputs livestock and grain; p_m is the price of output m obtained from the census; d is the annual discount rate; y_h is the quantity of timber produced; and K is the number of municipalities in the region. This implicitly assumes constant output prices and constant yields in the future, and as such it is a *ceteris paribus* analysis of income forgone rather than a prediction of what will actually happen in the future.[14]

We calculated the opportunity cost measure in equation (4) by first solving models Y and E for each municipality to obtain Δy_f^k and Δy_b^k. Second, we aggregate these quanitites across municipalities. Third, we evaluate equation (4) using these estimates at a discount rate of 0.10. To convert from hectares deforested to CO_2 emitted, we use an estimated density of 485 t/ha of CO_2 (132.2 t C), obtained from the Brazilian Ministry of Environment (MMA) (2011) and the Amazon Fund (2015), yielding our estimate of the regional average opportunity cost of indefinitely sequestering 1 ton of carbon.

Our approach assumes that production technology, land productivity, and output prices do not change over time.[15] We have estimated a single-year production technology using data from a cross

[13] We project the constant income stream (known as an annuity) into perpetuity (making it a perpetuity). At a discount rate of 10% per year, the present value of a \$1/year perpetuity is \$1/0.10 = \$10, as we show in the first term of the numerator of equation (4). The present value of a \$1/year annuity for 30 years is \$9.43, so at this discount rate there is only a 5.7% difference in present value whether we project the constant income stream out for 30 years or in perpetuity.

[14] Other studies converted current values to simulated streams through time as follows: Ickowitz, Sills, and de Sassi (2017) assumed that current streams would persist for 30 years. Both Börner and Wunder (2008) and Börner et al. (2010) used a time horizon of 10 years. These studies also assumed prices and productivity to be constant over time.

[15] An equal increase of 10% in all output prices would lead to a 10% increase in the trade-off. Our approach does not use any input prices, as the production set is constructed for a given set of inputs.

section of municipalities for the year 2006, so our results do not reflect productivity change over time. Future technical change could be biased toward agricultural outputs or toward deforestation, either of which would have implications for our estimates.

A reviewer expressed a legitimate concern about the time path of grain and livestock production in years subsequent to deforestation. Our projection assumes that current agricultural payoff from a deforested tract will persist into the future, but it is possible that land productivity could change over time after deforestation. Ickowitz, Sills, and de Sassi (2017), for example, assert that under slash–burn agriculture, net income from repeated cropping of the same plot could drive returns toward 0 and lead to clearing new land. It seems evident to us that declining yields would indeed characterize slash–burn agriculture, but it also seems likely that for commercial agriculture, yields would increase in the first years after deforestation, as fertilizer and management techniques more than offset tendencies toward diminishing land productivity. In the context of our approach and data, we have no way to measure the path of average productivity after deforestation, so we assume it to be constant. A potential advantage of the inductive approach is that farm management budgets for specific agricultural technologies can be developed to represent yield changes through time after deforestation, as Börner and Wunder (2008) and Börner et al. (2010) have done. These trajectories for different technologies can then be weighted by land use shares to yield estimates of average opportunity cost trajectories through time. We note again, however, that the process of budgeting these individual trajectories and weighting them by assumed technology adoption shares is subject to a considerable amount of error in estimating the average trajectory of agricultural earnings after deforestation. Given these considerations, it is not clear to us whether average trajectories increase or decrease in years after deforestation, so it is unclear whether assuming them to be constant as we have done provides an upper or a lower bound for the true present value of future income streams.

Data

The Legal Amazon consists of more than 700 municipalities in nine Brazilian states (Amapá, Acre, Amazonas, Mato Grosso, Maranhão, Tocantins, Pará, Rondônia, and Roraima). In this paper, the arc of deforestation, a subset of this region, consists of 152 municipalities that deforested more than 10,000 ha[16] over 2004–2006.[17] These municipalities are on the agricultural frontier (Figure 1), considered to be the main area of deforestation. The dataset consists of agricultural outputs and inputs by municipality obtained from the 2006 Agricultural Census from IBGE and deforestation data obtained from from INPE National Institute for Space Research (INPE) (2014). While yearly data on deforestation at the municipality level are available every year since 2000 and yearly output data at the municipality level are available from the Brazilian Institute of Geography and Statistics (Brazilian Institute of Geography and Statistics (IBGE), 2014), input quantities are available only in the Agricultural Census. Input data at the municipality level are necessary to identify the production set in equation (1) and estimate the directional distance function in equation (2), as seen in the third restriction in equation (3). We therefore estimate the trade-off using data for 2006.

Livestock, grain, and timber production are desirable outputs. Inputs are labor, capital, land area, production expenses such as energy and fuel, and cattle inputs. Our measure of the quantity of timber produced (in cubic meters of wood) follows Merry et al. (2009) by increasing the census report of timber production by 50% to account for illegal logging not reported in the census. We assume that what is reported in the census is legal commercialization and that the additional 50% occurs from illegal logging. Livestock output is measured as number of head sold. We measure grain output as

[16] We have examined different thresholds: 15,000 ha; the average deforested land of all municipalities in the Legal Amazon (8,173 ha); and the average of the municipalities that have deforested during the period 2004–2006 (10,022 ha). Opportunity cost estimates were very close and not sensitive to this selection criterion.

[17] Margulis (2004, Chapter 2, Figure 1) presents a geographical distribution of what he names the "arc of deforestation," which is similar to the geographical distribution of our "arc of deforestation."

Table 2. Descriptive Statistics for Outputs and Inputs, 152 Municipalities in the Arc of Deforestation, Legal Amazon, Brazil, 2006

Variables	Mean	Std. Dev.	Min.	Max.
Outputs				
Livestock (head sold)	31,280	29,700	755	167,495
Grain (metric tons)	53,547	201,968	0	2,000,000
Timber (m^3)	98,378	246,159	0	2,100,000
Deforestation in 2006 (ha)	6,121	8,857	230	76,190
Inputs				
Labor (no. of employees)	5,308	4,443	490	37,360
Capital (units)	2,486	1,564	364	11,283
Cleared area (ha)	259,016	170,045	53,560	1,380,170
Fuel (US$1,000)	4,554	12,007	0	141,351
Ag. inputs (US$1,000)	22,571	108,303	0	1,100,000
Cattle inputs (US$1,000))	8,236	7,601	194	37,226

Notes: All variables are for 2006 except Cleared Area, which is for 2005.
Sources: Data are from the Brazilian Institute of Geography and Statistics (IBGE) (2014) and the National Institute for Space Research (INPE) (2014).

total tons of soybean and corn produced. Output prices were calculated by dividing total reported value of production by reported quantity produced.

We measure deforestation as the number of hectares deforested in 2006, [18] as identified by the National Institute of Space Research (National Institute for Space Research (INPE), 2014). Figure 1 illustrates that higher levels of deforestation and of agricultural revenue are clustered in the outer border of the arc of deforestation.

We measure labor as the number of employees over 14 years of age and land as hectares of cleared land in the municipality in 2005 (National Institute for Space Research (INPE), 2014).[19] We measure capital by adding the number of pieces of equipment and number of landowners in the municipality following, Bragagnolo, Spolador, and Barros (2010). Fuel consists of expenditures on fuel and energy, and agricultural inputs are aggregate of expenses from seed, pesticides, and fertilizers. Cattle as an input we approximate as the aggregate of expenses of animal medication, animal purchases, and feed.

To solve the optimization problem in equation (3), we normalize variables by their mean,[20] $y_m^k = y_m^{k*}/\bar{y}_m$, where y_m^{k*} represents the actual observation and $\bar{y}_m$ represents the overall mean of output m. This means, for example, that the maximum desirable output achieved by municipality k under technical efficiency (i.e., when the observation is projected to the boundary) is found as $y_m^k + \beta^k \bar{y}_m$ for $(g_y \neq 0)$.[21] After optimization, changes in quantity variables are converted back to their natural levels. Table 2 reports descriptive statistics.

[18] We measure deforestation using the data available at INPE, which is able to identify deforested areas of at least 6.25 ha. We recognize that it may or may not include areas of selective logging, depending on whether the logging was sufficient for the area to be identified as deforested. However, we believe that selective logging areas represent a small proportion of deforested area and that selectively logged areas cannot be used during the logged year to commercially produce any of the desirable outputs considered here. We suspect that timber sales from this activity are not reported to IBGE (the source of our data for timber production). Underreporting deforested land biases our estimates upward, while underreporting output from deforestation biases them downward.

[19] A reviewer noted the wide range in the size of municipalities, which range from 28,188 ha to 1,581,759 ha. As there is no reason for us to believe there are economies of size in production at the municipality level, this should not affect our estimate of the production technology.

[20] Here we follow the procedure proposed by Färe et al. (2005) to avoid convergence problems.

[21] For a hypothetical municipality that uses mean inputs and produces mean outputs, the input and output variables would be $(x, y, b) = (1, 1, -1)$. This implies that Figure 2 is in normalized values. Thus, observation k (illustrated in Figure 2) is simultaneously expanded by $\beta\bar{y}$ and contracted by $\beta\bar{b}$.

Table 3. Estimated Average Directional Distances by State in the Arc of Deforestation, Legal Amazon, Brazil, 2006

	Models (described in Table 1)		
State/Region	**A**	**Y**	**E**
Rondônia	0.21	0.28	0.76
Acre	0.12	0.15	0.21
Amazonas	0.07	0.06	0.6
Roraima	0.14	0.15	0.59
Para	0.19	0.22	1.09
Maranhão	0.16	0.17	0.33
Mato Grosso	0.18	0.23	0.59
Arc of Deforestation	**0.18**	**0.22**	**0.75**

Notes: All models are described in Table 1. Model A uses $D^A\left(\boldsymbol{y^k}, b^k, \boldsymbol{x^k}; \mathbf{1}, -1\right)$, model Y uses $D^Y\left(\boldsymbol{y^k}, b^k, \boldsymbol{x^k}; \mathbf{1}, 0\right)$, and model E uses $D^E\left(\boldsymbol{y^k}, b^k, \boldsymbol{x^k}; \mathbf{0}, -1\right)$.

Table 4. Average Revenue Forgone per Hectare of Forest Preserved and per Ton of CO_2 Abated Obtained Using Equation (4), Arc of Deforestation, Legal Amazon, Brazil, 2006

State	**Forest ($/ha) Shadow Prices**	**CO_2 ($/Mg) Shadow Prices**
Rondônia	1,138.95	18.12
Acre	1,962.46	37.66
Amazonas	363.34	7.13
Roraima	1,203.71	18.67
Pará	776.00	12.88
Maranhão	1,550.75	27.55
Mato Grosso	1,198.85	20.23
Arc of Deforestation	**979.12**	**16.36**

Results and Discussion

In this section, we present results for the models described in Table 1, which use the linear program in equation (3) to estimate the directional distance functions. Livestock, grain, and timber production are the three desirable outputs, deforestation is the undesirable output, and we include six inputs as described previously. Table 3 reports the averages of distances (inefficiencies) for municipalities by state obtained for the three models.

The average measured distance using model A is 0.18, indicating that on average an 18% increase in outputs and an 18% decrease in deforestation could have been achieved if it were possible to eliminate the observed inefficiency. Because resources for any one municipality are not in fact identical to those of the others, the inefficiency estimates are at least in part an indicator of resource heterogeneity across these municipalities not captured by the variables included in our model. Figure 3 displays the results by municipality. For models A and Y, which measure potential expansion of all three desirable outputs, 25% of municipalities were efficient, which means that they establish the frontier of the production set.

The main objective of this paper is to evaluate the trade-off between the value of agricultural commodities and forest preservation as an estimate of the cost of forest preservation and thus the cost of carbon sequestration by forest preservation. Table 4 summarizes the trade-offs as determined by equation (4). As previously described, these results are obtained by comparing models Y [$\boldsymbol{g^Y} = (\mathbf{1}, 0)$] and E [$\boldsymbol{g^E} = (\mathbf{0}, -1)$].

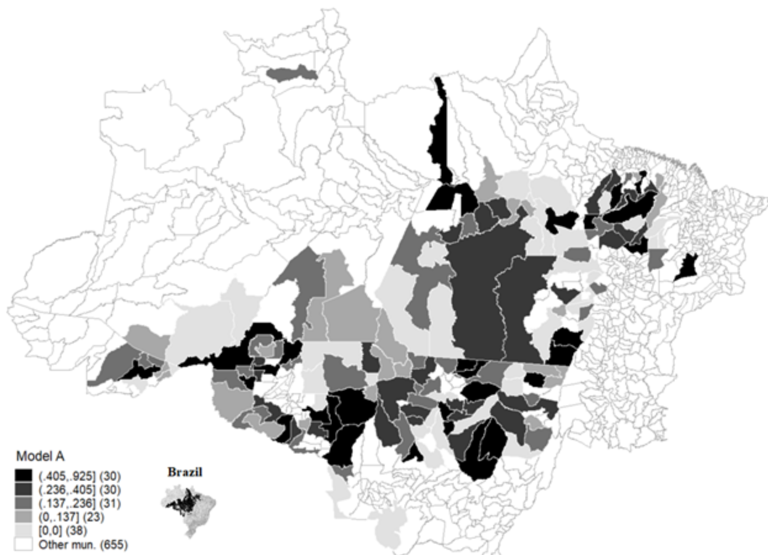

Figure 3. Geographic Distribution of Inefficiency Using Model A for the Arc of Deforestation, Legal Amazon, Brazil, 2006

Notes: Model A uses $D^A\left(y^k, b^k, x^k; 1, -1\right)$. "Other mun." are municipalities not included in the analysis.
Source: Inefficiency is estimated using equation (3) and data from the Brazilian Institute of Geography and Statistics (IBGE) (2014) and the National Institute for Space Research (INPE) (2014).

Using equation (4), we find that on average, \$979.12[22] in revenue from livestock, grain, and timber is given up for every hectare of deforestation reduced.[23,24] Several previous studies report comparable estimates of returns within a year of deforesting: Vera-Diaz and Schwartzman (2005) estimate an average first year return of \$838, a simple average of results from Börner and Wunder (2008) amounts to \$473, and Ickowitz, Sills, and de Sassi (2017) report an average of \$596 across five sites in Brazil.

Figure 4 shows the geographic pattern of this trade-off, with higher shadow prices of forest preservation in the outer border of the arc of deforestation. This reflects the higher per hectare revenues from agriculture in this area.

The Shadow Price of Carbon Dioxide (CO_2) Sequestration

The Brazilian government estimates that, on average, 1 hectare of the Brazilian Amazon Forest sequesters 132.2 t of carbon (Brazilian Ministry of Environment (MMA), 2011; Amazon Fund, 2015) [25]. We use this estimate, which implies that 1 average hectare of Brazilian forest sequesters 485.17 t of CO_2. The government has been using these conversion measures and a price of \$5.00/t of CO_2 to raise funds to preserve the Amazon forest (Amazon Fund, 2015). Between 2009 and

[22] These estimates change slightly with the threshold used for including municipalities in the study. For the 8,173 ha threshold we found an average opportunity cost of \$813.86, for the10,022 ha threshold, \$967.00/ha; and for the 15,000 ha, \$779.46. We also ran an alternative model that included "total area of land in the municipality" in addition to "total cleared land". The average opportunity cost so calculated was \$14.35/t CO_2, compared to \$16.36/t CO_2 calculated here.

[23] An increase in the price of desirable outputs would lead to a higher estimate of this trade-off. For example, a uniform increase of 10% in the price of livestock, grain, and timber would lead to the same percentage increase (10%, or \$97.91) in the opportunity cost of preserving the forest.

[24] When we use average regional prices rather than prices at the municipality level, our estimate increases to \$985.31 from \$979.12.

[25] The Amazon Fund (2015) raises funds to preserve the forest using this carbon content, based on the Technical Committee of the Amazon Fund (CTFA), but states that it is a conservative measure considering that the carbon content in the Amazon Forest ranges from 130 t/ha to 320 t/ha. A higher CO_2 density would lead to a lower CO_2 price.

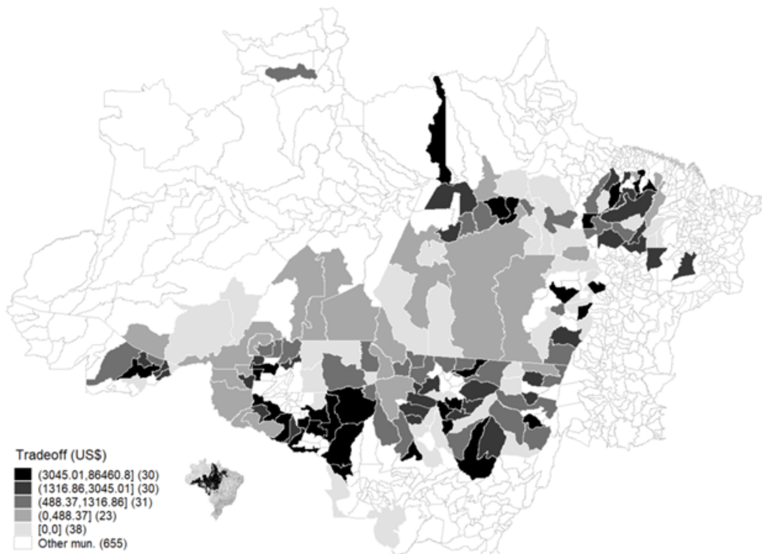

Figure 4. Agricultural Revenue Forgone per Hectare of Forest Preserved in the Arc of Deforestation, Legal Amazon, Brazil, 2006 (equation 4 and Table 4)

Notes: "Other mun." are municipalities not included in the analysis.
Source: Forgone revenue is estimated using equation (3) and data from the Brazilian Institute of Geography and Statistics (IBGE) (2014) and the National Institute for Space Research (INPE) (2014).

2016, Norway has contracted with Brazil for more than $1,000,000,000,[26] under these conditions, to preserve the forest.

At a discount rate of 10%, the present value of revenues forgone to preserve one average hectare of forest in perpetuity is $7,937.29 (using equation 4).[27] Given the official estimate of an average 485.17 t/ha of CO_2 sequestered, this is equivalent to a present value of $16.36/t of CO_2 sequestered. These values will vary depending on what is assumed for the CO_2 conversion factor, the discount rate, length of time, output prices, exchange rates and yields. We comment further on this later.

Using a more standard approach, Vera-Diaz and Schwartzman (2005) estimated this opportunity cost at $6.10/t of CO_2, considering revenue from cattle, soybeans, and timber and using a 10% discount rate for a 30-year period. They assumed a higher carbon density of 155 t/ha of carbon (568 t/ha of CO_2). Using their assumptions, our estimate is reduced from $16.36/t to $13.17,[28] still more than twice the $5.00 used by Brazil to raise funds to preserve the Amazon forest. Our estimate is also much higher than Nepstad et al.'s (2007) average $1.54/ton estimate ($1.08 when adjusted to our assumptions). However, they find higher prices of up to $27.2/t of CO_2 in the southeastern region of the Amazon forest, which includes Mato Grosso, consistent with our estimate of $20.23/t for that state (Table 4). The average price we estimate for a ton of CO_2 is about 50% higher than the average of $10.13/t obtained by Ickowitz, Sills, and de Sassi (2017) for different areas of the Amazon when we adjust their results for the carbon content, the discount rate, the length of the period, and the exchange rate that we use.

Our estimates are a *ceteris paribus* analysis of future income forgone rather than a prediction. They would vary with different carbon content, discount rate, length of time, output prices, and yields. The Amazon Fund (2015) indicates that carbon content in the Amazon forest ranges from

[26] Germany's government and the Brazilian company Petrobras also have contracts. More details can be found at http://www.amazonfund.gov.br/FundoAmazonia/fam/site_en/Esquerdo/doacoes/.

[27] For this calculation, $\sum_{k=1}^{152} p_1^k \Delta y_1^k$ = $234,065.45 for livestock, $\sum_{k=1}^{152} p_2^k \Delta y_2^k$ = $304,212.16 for grain, and $\sum_{k=1}^{152} p_3^k \Delta y_3^k$ = $143,413.90 for timber (values in $thousands). For deforestation, $\sum_{k=1}^{152} \Delta b^k$ = 696,231.23 ha.

[28] The shorter length of time reduces our estimate by 5.6% and the higher carbon intensity by an additional 15%.

130 t to 320 t of carbon per ha of forest biomass. This range would adjust our estimates of the average shadow price to a range of \$6.76/t to \$16.64/t of CO_2. A higher discount rate and a shorter length of time would decrease our estimate. Higher output prices and higher yields would increase our estimates. Our study seems to indicate that the rate of compensation Brazil receives is lower than the lowest reasonable estimate of average opportunity costs for reducing deforestation.

Conclusions

Preservation of the Amazon forest brings many benefits—it sequesters carbon and thus reduces potential climate change, it contributes to preservation of many plant and animal species with unknown value—and people intrinsically value its existence. However, these are benefits to mankind as a whole, while the opportunity costs of preserving the forest fall upon Brazilians themselves, who forgo agricultural income to preserve the forest.

In this paper, we use a radically different approach to estimating forgone income from preserving the forest. We use aggregate municipality-level census data to estimate the potential production frontier, which at the boundary identifies the trade-off between reduced deforestation and income from agricultural products: livestock, grain, and timber. Other studies have mostly depended in some way on budget constructs for estimating the farm-level returns from various agriculture enterprises—income that would be forgone if the forest were preserved rather than deforested. These micro-level approaches are subject to errors in budgeting out farm enterprises for any given location and to errors in selecting locations and enterprises that are representative of the larger regions. Our approach offers a more direct measure of the aggregate trade-offs experienced at the municipality level between deforestation and agricultural production.

Overall, we find that across the arc of deforestation, an average of almost \$1,000 in revenue from livestock, grain, and timber must be forgone for every hectare of deforestation reduced. Using an average carbon content of 132.2 t/ha of carbon sequestered and a 10% discount rate, our results imply that, *ceteris paribus*, the present value of the cost of permanent sequestration averages \$16.36/t of CO_2. This is higher than most of the previous estimates of average cost reported in the literature. It is much higher than the \$5.00 used by the Amazon Fund to raise funds to preserve the forest but lower than the mid-2019 European Emission Allowances average auction price of \$28/t.[29]

Our estimates of the opportunity cost of sequestering carbon in the Amazon forest are higher than other estimates. Most previous studies estimated the opportunity cost using an inductive approach, which consists of estimating the per hectare revenue streams from timber and agricultural enterprises for a few locations, assuming them to represent the social trade-off at the regional level. In contrast, we examine aggregate levels of agricultural production and deforestation across municipalities in the "arc of deforestation" to identify the income forgone if deforestation were reduced. This approach does not suffer from errors in constructing enterprise budgets for enterprises and locations that may or may not be representative, but it is conditional on the quality of the data as well as on actual yields, prices, discount rate, carbon content, and exchange rates. Nevertheless, our results provide useful alternative estimates of the cost of sequestering carbon.

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[29] We used an exchange rate of €1 = US\$1.12 . European Emission Allowances auction prices of CO_2 from 2009 can be found at https://markets.businessinsider.com/commodities/CO2-european-emission-allowances.

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