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# GETTING MORE ‘CARBON BANG’ FOR YOUR ‘BUCK’ IN ACRE STATE, BRAZIL[1]

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## ABSTRACT

Acre State in Brazil is at the forefront of efforts to institutionalize jurisdictional-scale policies that aim to reduce emissions from deforestation and forest degradation (REDD+). Given limited REDD+ funds and uncertain returns from alternative land uses, this paper estimates the minimum incentive payment Acre’s government would have to pay forest landowners in each of its 22 municipalities to ensure forest conservation. Despite lower profits but with lower conversion costs and more stable returns over time relative to corn and coffee production, cattle pasture generates the highest returns in 19 municipalities. Municipalities are ranked according to their relative policy costs, a ranking which is compared to the distribution of forest carbon stocks across Acre. Finally, the relative cost per tonne of carbon is derived, which enables the identification of a group of 13 municipalities with the greatest potential for ‘carbon bang’ for a given ‘buck’.

**Keywords:** Acre; Cost-effectiveness; Forest Conservation; Option Value; Payments for Environmental Services; Reducing Emissions from Deforestation and Degradation (REDD+); Uncertainty

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## 1. INTRODUCTION

In order to reduce emissions from deforestation and forest degradation (REDD+), policies could either attempt to reduce the profitability of agriculture, e.g. by removing agricultural subsidies, or offer positive incentives such as payment for environmental services (PES) that aim to put a price on forest externalities (Angelsen, 2010; Palmer, 2011). The latter have come to dominate both project and nascent jurisdictional-scale REDD+ strategies (see e.g. Mahanty et al., 2013; Sills et al., 2014). Acre State in Brazil, the setting for our paper, is currently at the forefront of efforts to institutionalize jurisdictional-scale REDD+. At an estimated cost of US$260 million, the State government's objective is to reduce deforestation by 80% by 2020, thus conserving 5.5 million hectares of forest in order to prevent the release of 62.5 Mt of $CO_2$ emissions (Herbert, 2010). To this end, Acre has established a 'PES-like' scheme known as the Incentive System for Environmental Services (SISA) framework. Its objective is to internalize values associated with forest carbon, as well as biodiversity and hydrological services, by incentivizing landowners to conserve forest on their landholdings.

In this paper, we model a hypothetical SISA payment in order to address two related questions. First, given the extent of uncertainty in land-use returns from forest conversion, what is the minimum level of payment that Acre's government should pay to landowners to ensure forest conservation with a 90% probability? Reflecting the common practice of Latin American incentive payment schemes, our payment is held constant over time. The '90% probability' is illustrative of a setting in which there is a relatively strong commitment on the part of the policymaker to enforce conservation contracts and hence, keep land in forest. That said, should alternative land uses become more profitable, e.g. due to rising commodity prices, it may not be possible to prevent contract breach altogether thus reflecting imperfect enforcement of conservation contracts (e.g. Engel and Palmer, 2008; MacKenzie et al., 2012; Jayachandran, 2013).

Our model is applied to municipality-scale, publicly-available data, which allows us to estimate the uncertain returns of an 'average' landowner within each municipality, one faced with the decision of whether to keep land in forest or convert it to an alternative land use. For each of Acre's municipalities, we estimate the uncertain returns for three alternative land uses: cattle, corn, and coffee. These three land uses are among the most popular ones adopted in Acre and have relatively good data availability. We then identify the minimum per hectare cost to the policymaker of conserving forest in each of Acre's 22 municipalities before ranking the municipalities according to ascending payment levels, i.e. moving from the municipalities with the lowest opportunity costs to those with the highest ones. The second question we ask is whether and (if so) how this ranking of municipalities changes when we consider their carbon stocks. Finally, our estimates of policy costs are combined with carbon stock data to give a novel measure of municipality-scale environmental cost-effectiveness: the minimum relative cost, in terms of the forgone profits from alternative land uses under uncertainty, per tonne of carbon.

In studies that evaluate the cost-effectiveness and efficiency of PES, two key assumptions are typically made. First, it is often assumed that future returns from forest conversion are known with certainty (e.g. Ferraro and Simpson, 2002; Börner et al., 2010; Groom and Palmer, 2010; Palmer and Silber, 2012; Curran et al., 2016). Yet, up-front investments combined with greater uncertainty in agricultural returns create incentives to delay the decision to convert forest to an alternative use (Schatzki, 2003). This implies that a lower level of incentive would be required to prevent forest conversion. In general, a failure to consider uncertainty in future agricultural returns results in estimates of the opportunity costs of forest conservation that are biased upwards. The consequence is that payment levels would be set higher than necessary in order to incentivize forest conservation.

Second, it is also commonly assumed that the environmental benefits from conserving forest are homogenous across space. However, it has become increasingly clear that this assumption is erroneous. For example, Saatchi et al. (2011) demonstrate wide variation in forest carbon stocks, even at the local scale, e.g. within municipalities. A failure to consider heterogeneity in forests and their corresponding eco-system services can thus lead to under- or over-estimates of benefits from conservation (see Vincent, 2016).

In Acre, funds for SISA remain dependent on public sources of funding despite a Memorandum of Understanding signed in 2010 with the US State of California to provide REDD+ credits. There is currently little scope for the use of carbon markets and offsetting to augment Acre’s conservation budget. Given this limited budget, the basic idea behind our analysis is to identify municipalities in Acre where it might be possible to conserve a lot of carbon at relatively low cost. Our paper contributes to Acre’s ongoing efforts to design an efficient and effective set of forest conservation institutions, particularly with respect to jurisdictional REDD+, which are described in Section 2. We do so by adapting the model of uncertain land-use returns by Engel et al. (2015), in Section 3. First, we adapt their model so that it is more consistent with most Latin American PES schemes, namely by changing the incentive from a variable to a fixed, area-based payment and by creating a shorter payments period (five years instead of 30). Second, in examining three different land uses and with 22 different starting points, i.e. one for each municipality in Acre, we move away from their focus on a single alternative land use and a single starting point for estimating policy costs.

We exploit spatial heterogeneity in land-use returns and model these returns over time using publicly available data, which are described in Section 4. Since similar data are increasingly available for other tropical countries, in addition to other Brazilian States, our model can easily be applied to other settings and land uses. Further, we exploit the spatial variation in forest carbon stocks across the State and by comparing these with the relative land use returns, provide an economic rationale for the targeting of REDD+ payments. Building upon Engel et al. (2015), our analysis therefore not only estimates the spatial variation in the cost of keeping forests standing but also integrates these costs with forest carbon stock data in order to derive a measure of cost-effectiveness across municipalities. In sum, our model offers a novel and straightforward way of allocating scarce conservation resources and while our focus is on forest climate benefits, it can easily be expanded to accommodate other ecosystem services and biodiversity.

Presented in Section 5 and discussed in Section 6, our results suggest that although pasture and cattle ranching is not particularly profitable, it is the land use which results in the highest (relative) returns to landowners under uncertainty, in 19 out of 22 municipalities. With relatively low conversion costs and little volatility in its returns process, pasture determines the minimum payment level in these areas. Upon ranking municipalities by payment level and by carbon stock, we find that cheaper municipalities tend not to have higher stocks. However, this type of ranking masks wide differences among municipalities. Our empirical exercise demonstrates evidence of substantial, economically-meaningful and policy-relevant variation among municipalities. On the basis of cost per tonne of carbon, we identify 13 municipalities in which it might be possible to obtain a substantially larger 'carbon bang' for one's 'buck' in contrast to the other nine municipalities.

## 2. BACKGROUND TO ACRE STATE, BRAZIL

Acre in western Brazil has become a world leader in reducing deforestation while growing its economy (Schwartzman, 2015). The State is home to around 750,000 people. Almost half live in the capital, Rio Branco, while the remainder reside among its 22 municipalities. Since the election of The Acre Workers Party and their allies The Popular Front in 1998, the State government has followed the vision of legendary rubber tapper and environmental activist Chico Mendes towards a sustainable development pathway for the State.

About 14.3 million hectares (143,000km$^2$) of intact, richly diverse forest, approximately 87% of its total area, is found within State borders. Primary forest makes up over 85% of forest cover. The majority of this forest is covered by some form of protection, whether indigenous territory, parks or reserves. Deforestation has fallen over recent years, from an average annual deforestation rate of 60,200 hectares (602 km$^2$) per year between 1996 and 2005, to 49,600 hectares (496 km$^2$) per year between 2001 and 2010.

Acre State set itself two main deforestation goals, to reduce levels by 60% of the 1990-2005 average by 2012, and by 80% by 2020. Total emissions for the State were estimated at 22.7 Mt CO2e in 2010, of which 97% came from deforestation and land degradation. The reduction in deforestation rates has meant that Acre has managed to move forward in issuing verified emission reduction credits to the tune of 11.5 Mt CO2e through the Markit registry (Forest Trends, 2015). In order to meet the State's deforestation goals and achieve verifiable emission reductions it has created the SISA framework, along with operational principles for a system of incentives, not only for forest carbon but also biodiversity and hydrological services.

The majority of deforested lands are now pasture (TerraClass, 2011) and this is representative of the typology of the agricultural sector in Acre. Pasture lands make up approximately 8% of total land area of the State. By contrast, temporary crops take up 1% of total land area, of which cassava and corn account for the greatest share. The acreage of permanent crops is much smaller, just 0.1% of land area. The largest permanent crop is banana, approximately 60% of the total, followed by rubber and coffee, at around 11% each.

Acre has 22 municipalities. A major land-zoning exercise in 2006, focusing on both economic and ecological concerns, created four major land-use zones (Governo do Estado do Acre, 2011): Zone 1 (25% of State land) is private land or agricultural settlements of which approximately half is deforested; Zone 2 (49%) is intact primary or managed forests in indigenous territories, sustainable use reserves, settlement projects, state and national production forests, and strictly protected areas; Zone 3 (26%) has largely intact forest cover but has land tenure that is unclear or where claims overlap; and, Zone 4 (0.2%) is defined as urban.

## 3. MODEL

Engel et al. (2015) developed a general model of a conservation payment scheme with fixed and variable components in which the latter is either indexed to the value of one or more services provided by forest, e.g. carbon, or to the expected net returns from forest conversion, e.g. soya bean production. By tracking carbon or soya prices, this variable component thus allows the payment to vary over time. The scheme's objective is to provide sufficient incentives to keep land in forest rather than convert it to an alternative use. In this paper, we retain their objective and basic model but adapt the latter in three ways.

First, since shorter contracts are typically found in Latin American payment for environmental services (PES) schemes, e.g. in Costa Rica (Pagiola, 2008), we model a conservation contract of five rather than 30 years. Second, also in common with many Latin American PES schemes, we model a payment that is not indexed but instead is fixed and unchanging over time. Finally, although our payment is characterised as an incentive provided by Acre's government to conserve forest carbon stocks (a generic 'REDD+ payment'), it does not reflect the social value of the carbon in a given hectare of forest. Rather, it is calculated as the minimum payment required to keep forest standing when the net returns from alternative land uses are uncertain. Below, we reproduce the model of Engel et al. (2015) and intuitively explain the theory underlying our adaptation of their model.

**Landowner's decision**

For a single hectare of land, profits can be generated from one of two alternative uses: forest (*F*) or agriculture (*A*). For simplicity, we do not specify *A* in this section, although as explained in Section 4 it can be pasture (cattle), corn, or coffee. Whenever land use is changed from *F* to *A*, conversion costs, $CC_{FA}$, are sunk immediately. Profits to a landowner from forest conservation are generated by a REDD+ payment scheme implemented by Acre's State government. This payment is paid annually and is fixed at *F*, i.e. future returns from forest are certain. Net profits from agriculture are generated from crop sales[1] and future returns from agriculture are uncertain.

In theory, the presence of uncertainty in agricultural returns should delay land conversion until the value of non-use benefits equals the value of land in the next-best alternative use plus conversion costs plus an option value. Our aim is to identify an *F* that makes this option value sufficiently large to deter land conversion for a total of five years.

New information about the uncertain returns from agriculture is assumed to become available at various times such that they may be modelled as a stochastic process (e.g. geometric Brownian motion, GBM). The net returns from agriculture to the land owner, *A*, is private information which evolves as a function of the constant trend parameter $\mu_A$ and the (positive) constant uncertainty parameter $\sigma_A$:

$$dA = \mu_A A dt + \sigma_A A dW_A \qquad [1]$$

where $dW_A = \epsilon\sqrt{dt}$ with $\epsilon$ distributed as a standard normal random variable, e.g. $\epsilon \in N(0,1)$. A positive (negative) $\mu_A$ indicates that net agricultural profits are, on average, increasing (decreasing). In Section 5, we parameterize the agricultural returns processes.

On each day, *dt*, a landowner receives *Fdt* if the land is in forest or *Adt* if the land is in agriculture. With a starting point of land in forest, the landowner decides, every six months, whether to continue conserving forest or to convert the forest to agriculture. The decision to change land use generates instantaneous profits net of conversion costs. Alternatively, the landowner can delay the decision to deforest and continue to receive REDD+ payments. Thus, the value of a single hectare of forest is:

$$f(F, A, t) = \max\{\pi^F, \pi^A - CC_{FA}\} \qquad [2]$$

The first term on the right-hand side of equation [2] describes the returns if the land is kept in forest. In this case, the landowner receives a payment of *Fdt* and the discounted future expected returns from forest conservation. Therefore, $\pi^F$ represents the sum of the landowner's returns from non-use benefits of the forest (current land use) and the future value of land in the next-best alternative use (forest or agriculture):

$$\pi^F = Fdt + e^{-r\,dt}E[f(F + dF, A + dA, t + dt)]$$

where *E* is the expectation operator. All returns are valued by discounting their expected values at the constant, continuously compounded, risk-free discount rate *r*. The second term of equation [2] represents the returns when the land is converted from forest to agriculture. The landowner incurs sunk conversion costs equal to $\{CC_{FA}\}$. Using the same line of reasoning and with a starting point of land in agriculture, we can obtain the equation that describes the returns if the land is kept in

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[1] Conversion from forest to agriculture may also generate a one-time timber profit. Such extra profit may be explicitly accounted for by modeling the timber price, the volume of timber extracted from the forest, and the harvest costs. For model tractability, we do not explicitly model these profits. In Section 5, however, we incorporate a one-off timber profit.

agriculture, *g(F,A,t)* and the expression $\pi^A$ that represents the sum of landowner's returns from agricultural use:

$$\pi^A = Adt + e^{-r\,dt}E[g(F + dF, A + dA, t + dt)]$$

To solve the land use change problem, we first evaluate the optimal conversion boundaries as in Engel et al. (2015). These depend upon the parameters of the returns from forest *F* and agriculture A, respectively, the conversion costs $\{CC_{FA}\}$ and the discount rate *r*. We then solve for the optimal land-use change numerically. Instead of modelling the price and crop yield uncertainties separately, the agricultural returns processes are modelled directly. This simplifies our analysis considerably and allows us to utilize existing numerical techniques, used by e.g. Miranda and Fackler (2002), Dangl and Wirl (2004), to solve the optimal land–conversion problem. In practice, the landowner compares two alternative land uses as described below.

**REDD+ payment parameters**

Our model is used to simulate REDD+ payment scenarios in order to estimate the level of incentive needed to ensure that the landowner continues to postpone the decision to switch from forest to agriculture. The landowner's opportunity costs of forest conservation are the forgone returns to agriculture, *A*. Given *A* we estimate the level of the REDD+ payment that ensures forest conservation. We assume that Acre's government seeks to achieve conservation at the lowest possible cost and that the landowner will not always comply with the REDD+ contract. Thus, we introduce the possibility that at some point it might be more profitable for the landowner to convert forest to agriculture. The potential for contract breach is modelled using a probability-based criterion, in which *p* is defined as the probability of avoiding deforestation and (1 − *p*) corresponds to the probability of deforestation.

For a given hectare of forest, we establish an illustrative probability level of *p*=0.9 and a time horizon of *T* = 5 and estimate the REDD+ payment necessary to ensure that the land remains in forest. We argue that a 90% probability of avoiding deforestation reflects Acre's ongoing efforts to build institutional capacity for REDD+ at the jurisdictional level, including institutions for monitoring and enforcement. Thus, this 90% probability is illustrative of a setting in which there is a relatively strong commitment on the part of the policymaker to enforce conservation contracts and hence, keep land in forest.[2] Note that, operationally, we implement the same payment regime as Engel et al. (2015) but identify a constant per-hectare payment *F.*[3] In our adaptation, the landowners' opportunity costs of forest conservation are based on uncertain returns from the production and sale of coffee, corn or cattle.

To determine the REDD+ payment that satisfies this criterion, we first evaluate the optimal conversion boundaries as described above given a specific set of model parameters. For a given REDD+ payment level, we simulate the returns from agriculture. When these returns are below the conversion boundary $C_{FA}$, the landowner prefers to switch land use, converting forest to agriculture. This comparison is assessed every six months. The simulation yields a converted path when agriculture becomes more profitable than forest at any given comparison node. With forest conversion, the contract is breached and REDD+ payments cease, which is equivalent to imposing a conditionality clause on the REDD+ contract. Dividing the total number of non-converted paths by the number of simulations, we compute the likelihood of a land-use change from forest to agriculture not occurring, $\hat{p}$. The probability-based criterion is met when $\hat{p} \geq p = 0.9$.

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[2] A decreasing (increasing) *p* unequivocally decreases (increases) the REDD+ payment necessary to ensure that land remains in forest.

[3] In practice, we implement the payment regime as in Engel et al. (2015) and set the variable leg of the REDD+ payment to be very small. Hence, the REDD+ payment is virtually always constant over time.

## 4. DATA

Our model in Section 3 is based on the land-use decision faced by a landowner. In the absence of landowner-level data, we apply our model to publicly-available agricultural data at the municipality scale. Thus, we compare differences in average net profits for three, different land uses, which are estimated at the municipality scale from data reported by farmers and landowners sampled within municipalities.

Applying the model presented in Section 3 to real-world data requires first identifying the commonest land-use transitions from forest conversion in Acre State over a five-year period. From Section 2, pasture for cattle ranching was clearly more common than any of the other land uses put together. We also select corn as one of the most popular temporary crops and coffee, a permanent crop, which has been gaining in popularity in the region. While there are other, similarly popular crops, e.g. cassava, banana, our choice is also determined by data availability. Municipality-level production data are shown in Appendix 1.

Note that for the five-year duration of contract it was often the case that land once planted, and with conversion costs sunk, would remain either in pasture or coffee for the whole of this time. For corn, however, farmers could switch to a different land use after three years thus incurring another round of conversion costs. We are unable to build another land-use decision into our model simulations for corn and for tractability instead assumed that corn was planted for five years. Switching from corn to beef or coffee within five years would not, however, significantly change the ranking of municipalities by minimum payment level.

**Daily profits**

The returns from converting a hectare of land from forest to agriculture depend upon a variety of factors including production costs, clearance and conversion costs, yields, prices and transportation costs. We combine these factors in order to estimate daily profits, *Adt*. The per-hectare return (in US$) on day *t* from agricultural commodity *x* is given by:

$$\pi_{tx} = (P_{tx}Y_x) - (Fix + L_{tx} + Fe_{tx} + Fu_{tx} + T_{tx}) \qquad [3]$$

where $P$ is the price of commodity *x* in US$/tonne, $Y$ is its yield (tonne/ha), $L$ is its labour cost (US$/ha), $Fe$ is its fertiliser cost (US$/ha), $Fu$ is its fuel cost (US$/ha), $Fix$ is its fixed cost (US$/ha), and $T$ is the cost of transporting *x* to market (US$/ha).

For each of corn, cattle and coffee, we estimate the value of each of these variables for each day in the five-year period between March 31, 2006 and December 30, 2010, before calculating daily returns. Daily agricultural price data are combined with quarterly data on labour costs, annual yield data, and overall costs per hectare for fixed, labour, fertiliser and fuel in order to create daily revenue and cost time-series, with the costs subtracted from the revenue series to give net profits. We draw the majority of data from the Brazilian Agricultural Census of 2006 (IBGE, 2006). More detail on data sources and individual factors, including our measure of carbon stock density, are presented in Appendix 2. Despite relatively good data availability, we face a number of challenges when creating suitable daily price series for our chosen commodities in Acre State.

First, there are gaps in the price data. In order to create a daily price series for each commodity, we converted the daily price series for São Paulo and via benchmarks for prices in Rio Branco created price series for Acre. Since this approach factors in differences in prices due to assumptions about the location of demand for each commodity - and hence, where it is transported - it potentially underestimates transportation costs in more remote regions of Acre state. This is particularly the case for corn and cattle that are not shipped to Rio Branco to be sold.

Second, there are some missing data in the Agricultural Census for some of the cost components of corn and coffee production. Since we have seen no evidence to suggest that there may be, on average, substantial differences in the costs of coffee and corn production at the municipality scale in the Legal Amazon, we filled these gaps by applying regression analysis to municipality-scale data for the whole Legal Amazon. This approach assumes that agricultural production in Acre state follows the same techniques, and utilizes the same mix of inputs, as used by the average Amazonian farmer.

Third, the Agricultural Census reports at the municipality level and is biased towards the sampling of larger farms. At this scale of aggregation, we may therefore overlook important intra-municipality variation in terms of costs and returns. If larger farmers have different yields, mix of inputs and costs in contrast to their smaller counterparts our estimates of average returns may not be perfectly representative, especially in municipalities with greater shares of smaller farmers. We return to the issue of potential variation in profitability among landowners and farmers within municipalities in Section 6.

## 5. RESULTS

We first present our estimates of daily net profits for our three agricultural land uses (pasture (cattle), corn, and coffee) at the municipality scale over a five-year period. These estimates are used to calculate our model parameters, which are then combined with our estimates of up-front clearance costs in order to simulate the returns processes under uncertainty for each land use in each and every municipality in Acre State. The returns are then ranked to give the policymaker's cost of the minimum payment to landowners in each municipality. Cost per municipality is then compared with the distribution of carbon densities across the State. From our estimates of minimum payment and data for mean carbon stock, we derive a novel measure of relative environmental cost-effectiveness: the minimum relative cost, in terms of the forgone profits from alternative land uses under uncertainty, per tonne of carbon.

### Daily net profits

Table 1 presents a summary of patterns in the daily per hectare net profits from pasture, corn and coffee between 2006 and 2010. Only one of these land uses remains profitable over the whole period in 11 municipalities, typically corn. Pasture appears to result in consistent negative net profits in most municipalities.

Negative net profits are obtained due to the use of observable market prices, which proxy for landowners’ returns from alternative land uses. We conjecture that commercial production may simply be unprofitable in much of Acre given remoteness and high costs. For instance, we may be underestimating prices. The São Paulo price, even with adjustment may not reflect higher prices in local markets due to their remoteness.[4] Subsistence agriculture dominates in a lot of municipalities, which is unlikely to be accounted for in government-collected statistics. Sampling in the Brazilian Agricultural Census tends to be biased towards larger farms. Since larger farms are more likely to

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[4] In the Agricultural Census, the prices of corn and coffee sold in Rio Branco are below those quoted in São Paulo but we do not know whether or not higher prices are fetched in the more remote areas of Acre, e.g. due to a relative lack of supply and higher transportation costs (especially in those municipalities with little or no road access).

hire in labour in contrast to smallholders, we may overestimate costs. Finally, we may be underestimating yields and note that our estimates may be missing subsidies that effectively reduce costs or increase profits, e.g. credit subsidies.

Figure 1 illustrates net profits for selected municipalities. Bujari is a good example of one where there is a clearly 'strictly dominant' profitable land use, in this case coffee. There, a rational land owner would convert forest to this land use rather than either of the other two. Feijó, on the other hand, illustrates a case where 'the lines cross' and the relative profitability of one land use changes such that at different times it would be rational to switch from one of corn, coffee or pasture, to one of the other two, and back again at a later date.

**Table 1: Summary of patterns of per hectare daily net profits for pasture (cattle), corn, and coffee for Acre's municipalities, 2006-2010**

**Figure 1: Daily net profits in US$ for Bujari and Feijó, 2006-2010**

In general, and of relevance for modelling returns processes under uncertainty, coffee appears to have the most volatile net profits while beef has the least. Recall that greater volatility in returns is predicted to lead to a greater incentive to delay land-use change, from forest to agriculture. A measure of volatility is more important than the absolute level of profits in determining the relative level of returns under uncertainty, and the likelihood of whether the landowner is likely to stay with forest or convert to an alternative land use. This implies that there are no limitations in using negative net profits to estimate the volatility of the returns process under uncertainty.

### Clearance costs

From net profits, which allow us to estimate the volatility in returns over time, we now turn our attention to the second key component needed to estimate land-use returns under uncertainty: up-front clearance costs. For each municipality, these costs are presented in Table 2.

**Table 2: Clearance costs by municipality for forest-corn, forest-coffee & forest-pasture (US$/ha)**

By a factor of three to four, and often more, Table 2 shows that clearing forest for coffee is more expensive than corn or pasture in all municipalities. Clearance costs of the latter two are broadly equivalent, although those of corn are typically lower. This implies that the decision to delay is likely to be greatest for landowners considering converting forest to coffee, followed by pasture and corn, and indicates that coffee has a lower degree of reversibility than the other two land uses. In sum, given the trends in volatility and clearance costs, the cultivation of coffee would appear to give the greatest incentives to delay the decision to convert forest in comparison to pasture or corn. We now turn to calibrating these variables more precisely in order to estimate landowners' returns under uncertainty.

### Returns under uncertainty and minimum payment levels

The model presented in Section 3, namely the constant trend parameter, $\mu$, and the variance, $\sigma$, is calibrated using the estimated daily profits. Table 3 shows the calibrated parameters for each land use for all of Acre's municipalities. The three columns represent the three alternative land uses from forest conversion, i.e. forest-corn, forest-coffee and forest-pasture. Recall that a positive (negative) $\mu$ indicates that net agricultural profits are, on average, increasing (decreasing); by comparing net profits in Table 1 with the trend parameters in Table 3 this pattern can be clearly discerned.

**Table 3: Calibrated parameters for the three alternative land uses by municipality**

For each municipality, we compare the opportunity costs of forest conservation (for three different alternative land uses: coffee, corn, cattle) under uncertainty with a certain REDD+ payment in order to ensure the land stays in forest with a probability *p* of 90 percent over a time period *T* of five years. Thus, the level of REDD+ payment is 'set' to make forest the preferable 'alternative' 90% of the time/simulations. From this, we can estimate the minimum level of payment Acre's government should make in order to ensure forest conservation with a 90% probability given uncertain land-use returns from forest conversion.

After estimating the uncertain returns for pasture, corn, and coffee in each municipality, we then assume that a rational landowner would choose the one that would earn her the highest returns. This establishes the minimum level at which the REDD+ payment should be set by the policymaker. It is characterised as a cost to the policymaker, highlighted in one of the three 'Cost' columns of Table 4 for each municipality. Note that 'Cost' is given as a relative rather than an absolute number due to the predominance of negative net profits reported in Table 1. Figure 2 displays the data for all three 'Cost' columns' for each municipality and Figure 3 displays the data for the highlighted column (minimum payment) for each municipality in geographic form.

**Table 4: Ranked relative land-use returns under uncertainty ('Cost' per ha; lowest first) and mean carbon stock by municipality (ranking in parentheses, highest first)**

**Figure 2: Relative cost of payment per ha to cover opportunity cost of each land use by municipality**

**Figure 3: Map of the minimum payment required to maintain forest in each municipality.**

### Ranking municipalities and environmental cost-effectiveness

Relative 'Cost' allows for a comparison of minimum REDD+ payments both across land uses within municipalities and across municipalities. Municipalities are ranked according to 'Cost', lowest first, highest last. Thus, Brasiléia has the lowest relative cost of all the municipalities if we assume that landowners in every municipality were to convert forest and choose the agricultural land use with the highest opportunity cost in that municipality in the absence of a payment.

Table 4 shows where a policymaker in Acre might target conservation funds if minimising costs per hectare - thus spreading the budget among as many hectares of forest as possible – is assumed to be the sole aim of policy. The final column of Table 4 presents the data underlying the carbon density map (Figure A1) along with the ranks used to create Figure A2. From this, the most carbon dense municipality, on average, Assis Brasil, is ranked 17 according to policy cost, i.e. one of the more expensive municipalities in which to pay landowners to conserve forest. While there are no clear patterns with regards to cost ranking and carbon ranking, Jordão stands out as a place where a payments scheme may be cheap (ranking #3) and carbon benefits are likely to be high (ranking#2).

Perhaps a more efficient way of targeting payments, at least given the distribution of carbon stocks, is to move away from a ranking based on costs alone. Given wide variation in mean carbon stocks among the municipalities, cheaper areas may not contain as much carbon as some of the more expensive ones. Figure 4 presents the relative cost per tonne of carbon, indexed to the municipality with the lowest cost: Santa Rosa do Purus. On this basis, we can see that Assis Brasil, our most carbon-dense municipality, is ranked second and only just a bit more costly than Santa Rosa do Purus. By contrast, Jordão is over 50 percent more expensive than either of these two municipalities.

The most expensive municipalities by far are Rodrigues Alves and Placido de Castro, which are, respectively, over three and 2.5 times more expensive than Santa Rosa do Purus.

**Figure 4: Relative cost per ton carbon**

## 6. DISCUSSION

In this paper, we estimated the returns under uncertainty from three different, alternative land uses for each and every municipality in Acre State, Brazil. Since these land uses have been shown to drive the decision of whether or not to deforest, addressing them should be central to the formulation of REDD+ policy in the State, in particular, ongoing efforts to design a programme of incentive payments such as SISA. Building upon the model of conservation payments by Engel et al. (2015), we modelled our REDD+ payment on the basis of a fixed financial incentive, which allowed us to estimate the minimum level of payment that might be sufficient to incentivise a five-year delay in the decision to convert forest to pasture, corn or coffee. We then combined the relative cost of the payment with mean amounts of carbon found in each municipality in order to assess how much 'carbon bang' a policy maker might obtain for a given 'buck'.

When conversion costs are sunk and the returns from alternative land uses are uncertain, it is optimal for land owners to delay land use change (Schatzki, 2003; Engel et al., 2015). Land use can be considered a real asset with an attached perpetual option to convert it to another land use at any time. The benefit of waiting rises with the degree of uncertainty: the larger the volatility of the returns from the alternative land uses, the larger the option value to delay land conversion. Equally, the lower is the required REDD+ payment to delay deforestation. Thus, uncertainty about the returns from agriculture and sunk conversion costs lowers the payment needed to make forest conservation more profitable than agricultural production.

Cattle-ranching determines the level of the minimum payment in most municipalities. Despite not being a highly profitable land use, pasture has relatively low up-front costs and generates stable returns over time, certainly in contrast to coffee. The incentive to delay conversion to pasture is often lower than that for coffee thus necessitating a higher payment to a landowner considering the former rather than the latter. In other words, the returns from coffee are subject to greater volatility than pasture (or corn), which lowers the opportunity cost of forest conservation and consequently, generates a larger option value to delay forest conversion. This indicates that coffee has a lower degree of reversibility than the other two land uses.

Looking across Acre, the most expensive municipalities in which to conserve forest are those in the middle of the State, following the main highway, BR364. The cheaper municipalities are mostly located in more remote areas in the North West and the South East. We note that these more remote municipalities are also likely to be at less immediate risk of deforestation than the more centrally located ones. Yet, municipalities identified as having minimum payments at the lower end of the scale tend not to be the ones with the highest carbon stocks. Our ranking of carbon stocks obscures the wide variation among (and within) municipalities. We account for this variation by estimating the cost per tonne of carbon and hence, can identify a group of 13 municipalities in which costs vary by up to 25%. Our estimates imply that these 13 municipalities could be prioritised for cost-effective conservation of forest carbon stock and hence, help determine the allocation of limited REDD+ funds in Acre State. Furthermore, if the policymaker is able to identify the municipalities of greatest deforestation risk in this group then the number of municipalities subject to policy targeting could be further reduced.

In generating our results, we assumed a certain REDD+ payment over time. There remains, however, great uncertainty about the future of REDD+ both in terms of the policy architecture and its funding (Laing et al., 2016). This helps explain why we opted to model five-year contracts in Acre, a State that has already gone some way to positioning itself not only as 'conservation friendly' but also as a jurisdiction for implementing REDD+ policies. That said, our approach is applicable in other settings, where there may be less certainty with respect to REDD+ funding and policy. Indeed, our results hold if the REDD+ payment is uncertain but relatively less uncertain than the returns from agriculture. Our model can easily be extended to accommodate a longer time-scale than five years in settings where policymakers aim to conserve forest carbon stocks over time-scales that are more consistent with broader climate policy. However, over a time scale of say 30 years, as modelled by Engel et al. (2015), we note that there is likely to a much less predictive power in using past data to model future agricultural returns processes. Instead, more up-to-date data could be used to re-calibrate the model and reset minimum payment levels every few years.

Minimum REDD+ payment levels are modelled using estimates of daily net profits and conversion costs. Negative net profits predominate, likely due to data constraints, which are an obstacle to obtaining absolute rather than relative cost estimates. Yet, given that our analysis is determined by the volatility of returns over time, the use of relative profits is sufficient to illustrate the application of our model to Acre State. We find that minimum payment levels are quite similar across municipalities, the calculation of which necessitated the use of aggregate data at the municipality scale rather than more granular data collected at the landowner scale. That said, the extent of heterogeneity in the variability of agricultural returns is arguably better than expected given the granularity of the available data.

The application of our model to data at the municipality scale potentially masks variation not only in the profitability of different farmers, e.g. small-scale farms might be less profitable and hence, have lower opportunity costs than large landowners, but also in the profitability of different land uses within municipalities. But since our analysis is based less on variation in absolute values of net returns and more on differences in the variability of net returns, evidence of sufficient variation in the latter would be needed in order to substantially change our results.

Our model application is meant to be illustrative; it can easily be applied to data collected at the farm and agricultural household scale. Regardless of land use, Delacote et al. (2014) demonstrate relatively little variation in the opportunity costs of forest conservation in a sample of households in the Brazilian Amazon. If this sample is representative then it downplays the extent to which heterogeneity among farms within municipalities might influence our results. A lack of variation, in turn, implies a low level of informational rents. Thus, our municipality-level estimates might be sufficient for setting differentiated SISA payments among municipalities without excessive informational rents accruing to farmers who decide to opt into the scheme. Again, note that it is differences in the variability of net returns over time that drive our results and to our knowledge, we know of no (panel) data collected at the landowner or household scale that can demonstrate how such variability might vary among landowners.

In local settings, where opportunity costs vary greatly and where there are greater differences in the variability of net returns, there is potential for greater informational rents accruing to landowners. This is private information and mechanisms could be applied in order to obtain such information and reduce informational rents, in particular, screening contracts and reverse auctions (see Ferraro, 2008). The extent to which payments ought to become more spatially differentiated in order to reduce informational rents is likely to be at least partially dependent on the additional (transactions) costs, which arise as the complexity of the payment scheme increases.

Given limited conservation budgets, our model offers a novel and straightforward way of utilising publicly-available data – at whatever scale - to target such funds. It can also be easily expanded to incorporate other land-uses within and beyond agriculture. From Section 2 note, however, that around 25% of State land is subject to unclear land tenure, the distribution of which is likely to vary across municipalities. Clear tenure is critical for the successful functioning of any kind of PES scheme. Spatial data on tenure at the local level could be used to help identify areas with targeted land uses and where tenure is already reasonably secure. Regarding forest benefits, our application of the model focused on carbon stocks but it can be extended to incorporate other ecosystem services and biodiversity. Indeed, the mapping of policy costs and different forest benefits would help to address the potential for so-called 'win-win' strategies with respect to REDD+ and biodiversity conservation (e.g. see Phelps et al., 2012). Our model could help understand the extent to which potential 'win-wins' may also be cost-effective in the design of schemes such as SISA, which aim to cover multiple environmental benefits of forests, and not just forest carbon alone.

While our analysis is motivated by the fact of limited forest conservation budgets in Acre, we have little information on the precise nature of these budgets. Money is received from a variety of public sources and there may be potential for future funding from more diverse sources, perhaps depending on the future trajectory of federal REDD+ policy. So, while there is a possibility for a domestic federal REDD+ programme leading to inter-state financial transfers in the future, it remains to be seen whether there will be much scope for finance from international sources like California's cap and trade system and multinational firms, especially given the recent withdrawal of the US from the Paris Agreement. Thus, the extent of future finance for Acre's REDD+ strategy remains unknown. Either way, our modelling exercise remains relevant, more so if we are able to improve upon our net profit estimates and scale up our per hectare estimates of policy costs in order to quantify aggregate costs both within municipalities and across Acre as a whole. Finally, we could build into our analysis the possibility of trading per reforms to Brazil's Forest Code. This would allow us to model the potential impacts of trading vis-à-vis REDD+ policy goals.

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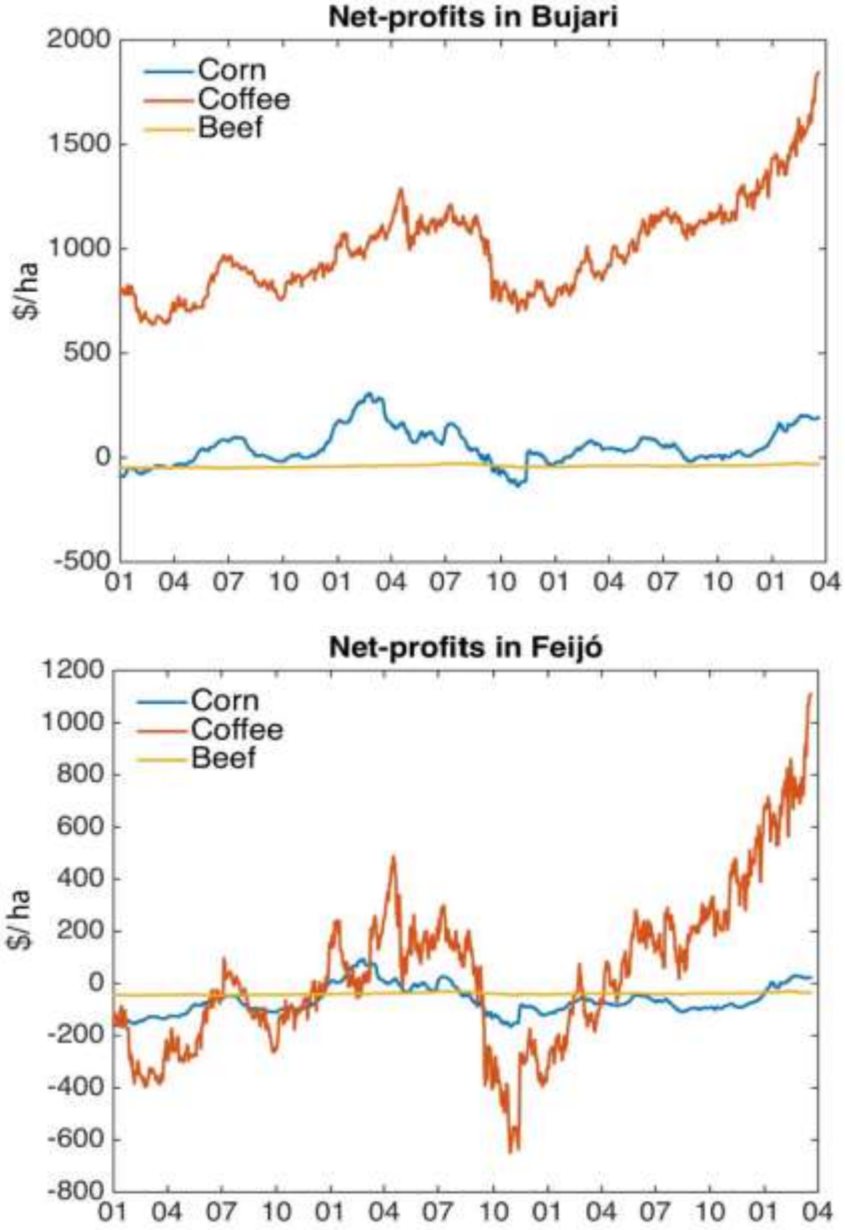
## FIGURES & TABLES

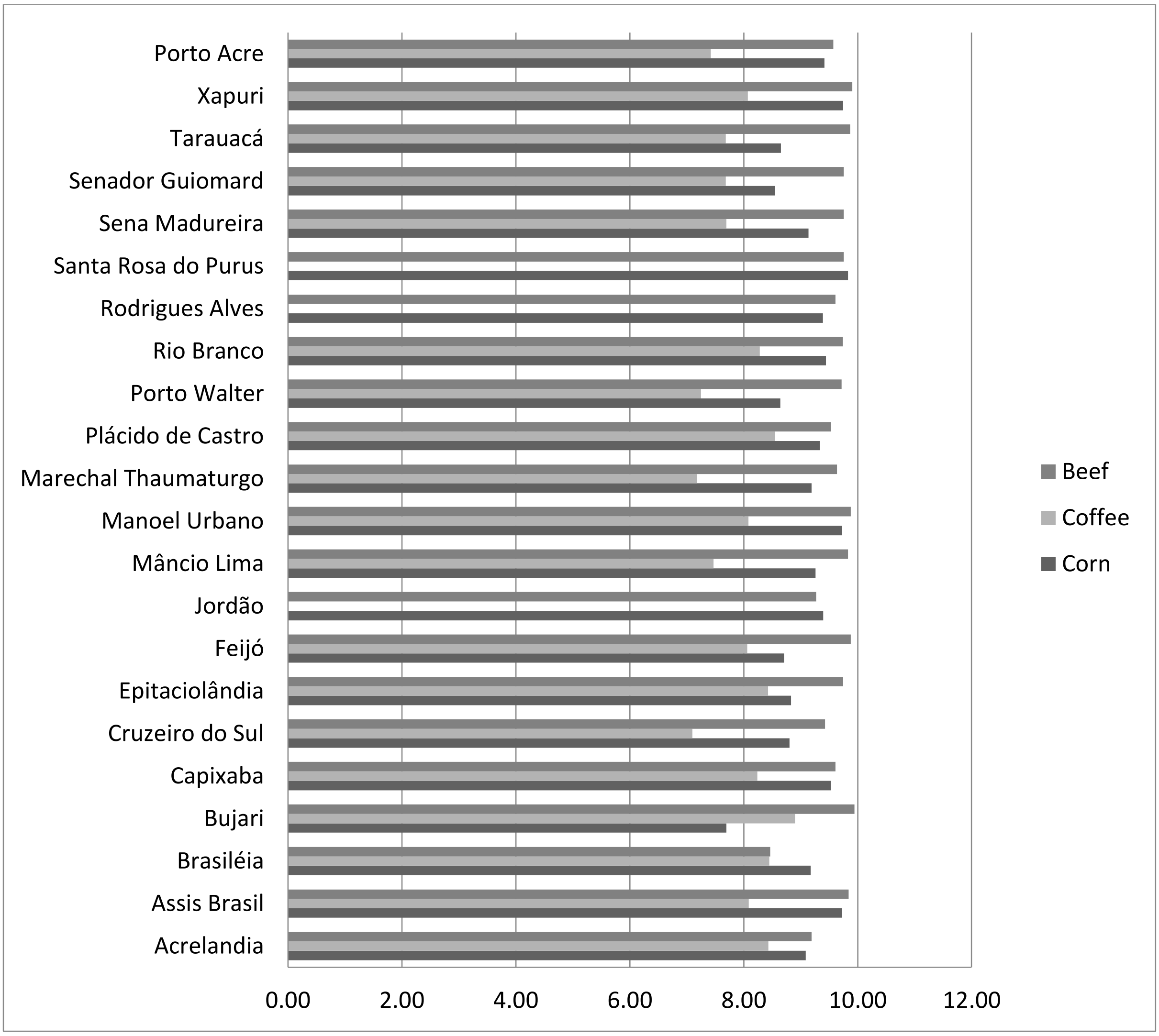
**Figure 1: Daily net profits in US$ per ha for Bujari and Feijó, 2006-2010**



**Source: Authors**

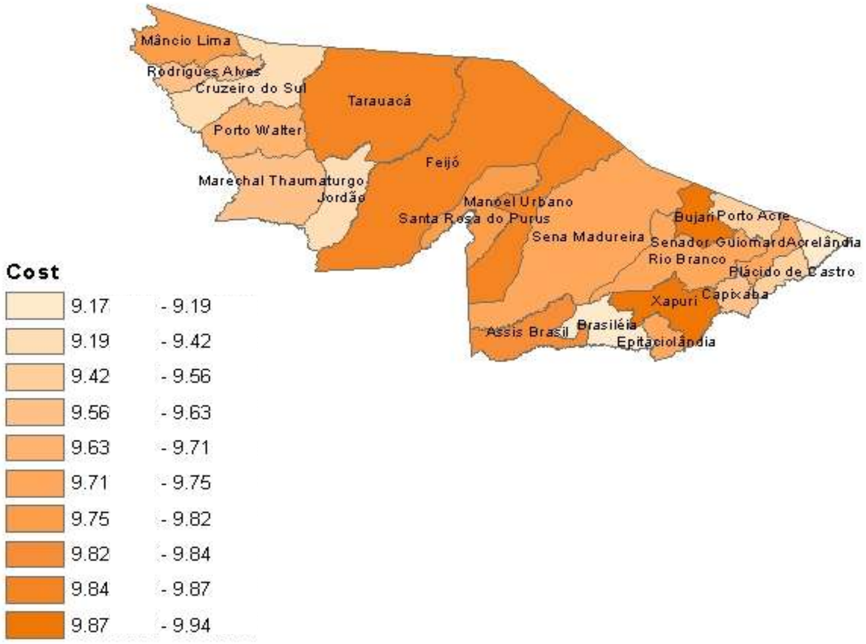
**Note: ‘01’ denotes January; ‘04’ April; ‘07’ July; ‘10’ October**

**Figure 2: Relative cost of payment per ha to cover opportunity cost of each land use by municipality**



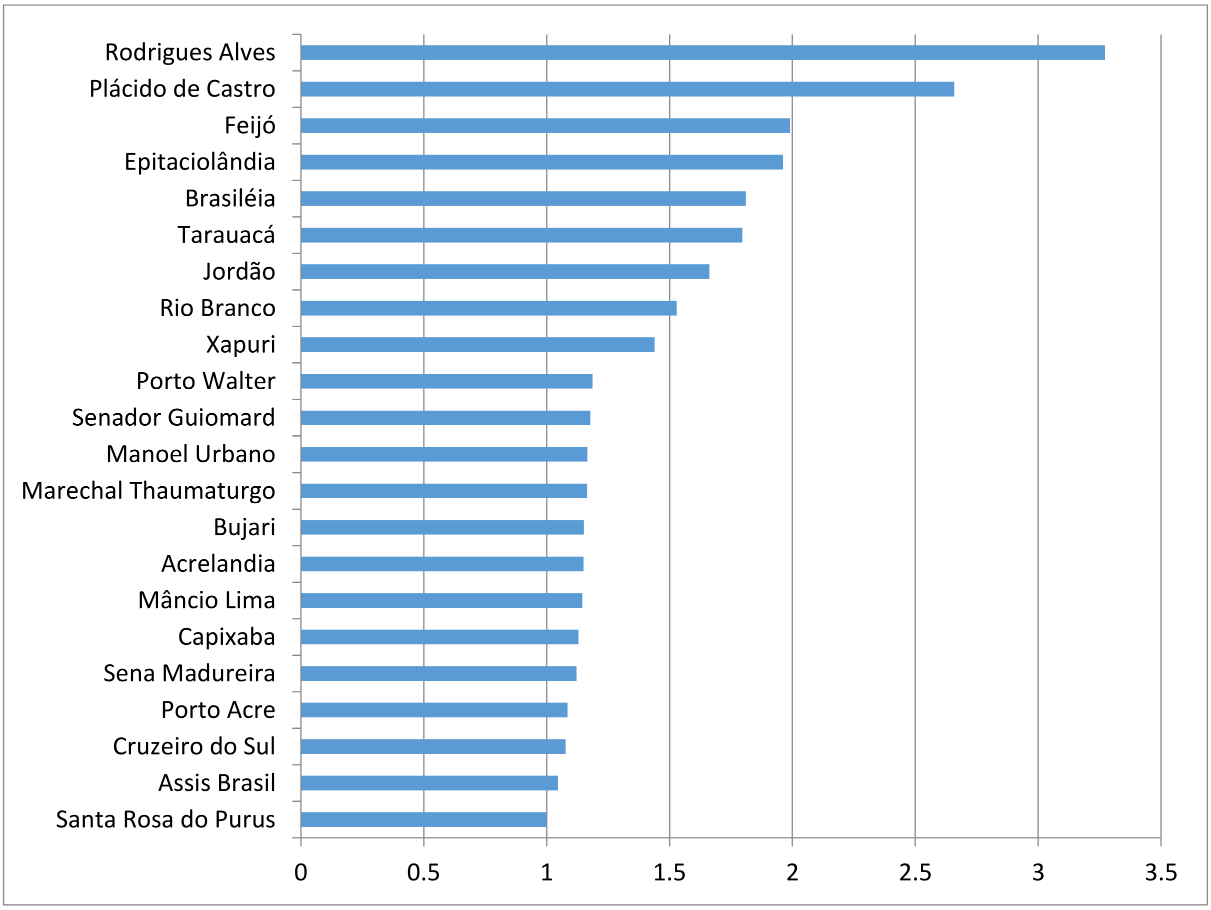
**Source: Authors**

Figure 3: Map of the minimum payment required to maintain forest in each municipality.



Source: Authors

**Figure 4: Relative cost per tonne carbon**



**Source: Authors**

**Note: Cost per tonne carbon is relative to value for the lowest cost municipality Santa Rosa do Purus (indexed at 1)**

**Table 1: Summary of patterns of per hectare daily net profits for pasture (cattle), corn, and coffee for Acre's municipalities, 2006-2010**

| **Municipality** | **Daily net profits are:** | | | **Is there a strictly dominant profitable land use?** |
|---|---|---|---|---|
| | Positive all the time | Positive some of the time, negative otherwise | Negative all the time | |
| Acrelandia | | Coffee | Pasture, corn | No |
| Assis Brasil | Corn | | Pasture, coffee | Yes – corn |
| Brasiléia | Corn | Pasture | Coffee | Yes – corn |
| Bujari | Coffee | Corn | Pasture | Yes – coffee |
| Capixaba | Corn | | Pasture, coffee | Yes – corn |
| Cruzeiro do Sul | | Corn | Pasture, coffee | Yes – corn |
| Epitaciolândia | | Corn | Pasture, coffee | No |
| Feijó | | Coffee, corn | Pasture | No |
| Jordão | Corn | Coffee | Pasture | Yes – corn |
| Mâncio Lima | Coffee | | Pasture, corn | Yes – coffee |
| Manoel Urbano | | | Pasture, coffee, corn | No |
| Marechal Thaumaturgo | Coffee | Corn | Pasture | Yes – coffee |
| Plácido de Castro | Corn | | Pasture, coffee | Yes – corn |
| Porto Walter | | Corn | Pasture, coffee | Yes – corn |
| Rio Branco | | Corn | Pasture, coffee | No |
| Rodrigues Alves | | Coffee | Pasture, corn | Yes – coffee |
| Santa Rosa do Purus | | Coffee | Pasture, corn | Yes – coffee |
| Sena Madureira | Corn | Coffee | Pasture | Yes – corn |
| Senador Guiomard | | Corn | Pasture, coffee | No |
| Tarauacá | | Corn, coffee | Pasture | No |
| Xapuri | Corn | Pasture | Coffee | Yes – corn |
| Porto Acre | Corn | Pasture | Coffee | Yes – corn |

**Source: Authors**

**Table 2: Clearance costs by municipality for forest-corn, forest-coffee & forest-pasture (US$/ha)**

| Municipality | Forest-corn | Forest-coffee | Forest-Pasture |
|---|---|---|---|
| Acrelandia | 1097 | 3714 | 1115 |
| Assis Brasil | 911 | 3528 | 928 |
| Brasiléia | 938 | 3555 | 955 |
| Bujari | 1135 | 3752 | 1152 |
| Capixaba | 929 | 3546 | 946 |
| Cruzeiro do Sul | 441 | 3058 | 459 |
| Epitaciolândia | 929 | 3546 | 946 |
| Feijó | 347 | 2964 | 365 |
| Jordão | 314 | 2931 | 331 |
| Mâncio Lima | 491 | 3108 | 508 |
| Manoel Urbano | 929 | 3546 | 946 |
| Marechal Thaumaturgo | 401 | 3018 | 418 |
| Plácido de Castro | 1097 | 3714 | 1115 |
| Porto Walter | 461 | 3078 | 479 |
| Rio Branco | 929 | 3546 | 946 |
| Rodrigues Alves | 399 | 3016 | 416 |
| Santa Rosa do Purus | 948 | 3565 | 965 |
| Sena Madureira | 929 | 3546 | 946 |
| Senador Guiomard | 1023 | 3640 | 1040 |
| Tarauacá | 348 | 2965 | 365 |
| Xapuri | 948 | 3565 | 965 |
| Porto Acre | 1060 | 3677 | 1077 |

**Source: Authors' own calculations from data described in text**

**Table 3: Calibrated parameters for the three land uses by municipality**

| **Municipality** | **Corn** | | **Coffee** | | **Beef** | |
|---|---|---|---|---|---|---|
| | ***μ*** | ***σ*** | ***μ*** | ***σ*** | ***μ*** | ***σ*** |
| Acrelandia | -0.0003 | 0.0276 | 0.0005 | 0.379 | -0.0003 | 0.0118 |
| Assis Brasil | 0.0011 | 0.0205 | -0.0017 | 0.0431 | 0.0001 | 0.0115 |
| Brasiléia | 0.0015 | 0.0248 | -0.0003 | 0.0109 | 0.0024 | 0.414 |
| Bujari | 0.0006 | 0.5255 | 0.0007 | 0.0218 | -0.0004 | 0.0097 |
| Capixaba | 0.0014 | 0.0233 | -0.0014 | 0.0402 | 0 | 0.0043 |
| Cruzeiro do Sul | -0.0003 | 0.402 | -0.0016 | 0.0426 | 0 | 0.0031 |
| Epitaciolândia | -0.0003 | 0.277 | -0.0013 | 0.0381 | -0.0008 | 0.0197 |
| Feijó | -0.0016 | 0.4148 | 0.0017 | 0.637 | -0.0002 | 0.0073 |
| Jordão | 0.0015 | 0.0237 | 0 | 0 | -0.0017 | 0.152 |
| Mâncio Lima | -0.0018 | 0.1958 | 0.0007 | 0.0225 | -0.0001 | 0.0099 |
| Manoel Urbano | 0.0002 | 0.0204 | -0.0023 | 0.0435 | -0.0001 | 0.0107 |
| Marechal Thaumaturgo | -0.0017 | 0.2401 | 0.0008 | 0.023 | 0.0001 | 0.0064 |
| Plácido de Castro | 0.0025 | 0.0551 | -0.0014 | 0.0404 | -0.0001 | 0.0054 |
| Porto Walter | 0.0006 | 0.4496 | -0.0018 | 0.0444 | 0.0001 | 0.0095 |
| Rio Branco | -0.0013 | 0.1318 | 0.0019 | 0.0462 | 0.0002 | 0.0144 |
| Rodrigues Alves | 0 | 0.0012 | 0 | 0 | 0 | 0.0042 |
| Santa Rosa do Purus | 0 | 0.0117 | 0 | 0 | 0 | 0.0089 |
| Sena Madureira | 0.0014 | 0.0274 | -0.0002 | 0.2923 | -0.0001 | 0.0088 |
| Senador Guiomard | -0.0017 | 0.5053 | -0.0001 | 0.007 | -0.0001 | 0.0087 |
| Tarauacá | 0.001 | 0.4021 | -0.0001 | 0 | 0 | 0.0145 |
| Xapuri | 0.0011 | 0.0201 | -0.0017 | 0.0438 | -0.0001 | 0.0113 |
| Porto Acre | 0.001 | 0.0512 | -0.0002 | 0.0077 | -0.0001 | 0.030 |

**Source: Authors**

**Table 4: Ranked relative land-use returns under uncertainty ('Cost' per ha; lowest first) and mean carbon stock by municipality (ranking in parentheses, highest first)**

| Rank | Municipality | Cost (per ha) | | | Mean carbon density |
|---|---|---|---|---|---|
| | | Corn | Coffee | Pasture | (Mg C / ha) |
| 1 | Brasiléia | **9.17** | **8.45** | **8.46** | 158.49 (13) |
| 2 | Acrelandia | **9.09** | **8.44** | **9.19** | 102.13 (18) |
| 3 | Jordão | **9.40** | **0.00** | **9.27** | 188.99 (2) |
| 4 | Cruzeiro do Sul | **8.81** | **7.10** | **9.43** | 161.05 (12) |
| 5 | Plácido de Castro | **9.34** | **8.55** | **9.53** | 72.13 (21) |
| 6 | Porto Acre | **9.41** | **7.42** | **9.57** | 138.40 (14) |
| 7 | Rodrigues Alves | **9.39** | **0.00** | **9.61** | 168.12 (10) |
| 8 | Capixaba | **9.53** | **8.24** | **9.61** | 98.57 (19) |
| 9 | Marechal Thaumaturgo | **9.19** | **7.18** | **9.64** | 170.32 (9) |
| 10 | Porto Walter | **8.64** | **7.25** | **9.72** | 96.69 (10) |
| 11 | Rio Branco | **9.44** | **8.28** | **9.74** | 164.70 (11) |
| 12 | Epitaciolândia | **8.83** | **8.43** | **9.75** | 117.95 (16) |
| 13 | Sena Madureira | **9.14** | **7.69** | **9.76** | 183.53 (3) |
| 14 | Senador Guiomard | **8.55** | **7.69** | **9.76** | 171.28 (8) |
| 15 | Mâncio Lima | **9.26** | **7.47** | **9.83** | 171.58 (7) |
| 16 | Santa Rosa do Purus | **9.83** | **0.00** | **9.76** | 128.10 (15) |
| 17 | Assis Brasil | **9.72** | **8.09** | **9.84** | 189.24 (1) |
| 18 | Tarauacá | **8.66** | **7.69** | **9.87** | 59.99 (22) |
| 19 | Manoel Urbano | **9.73** | **8.08** | **9.88** | 178.56 (4) |
| 20 | Feijó | **8.71** | **8.06** | **9.88** | 177.01 (5) |
| 21 | Xapuri | **9.75** | **8.07** | **9.91** | 175.78 (6) |
| 22 | Bujari | **7.69** | **8.90** | **9.94** | 111.29 (17) |

**Source: Authors**

**Note:** Although we use 90% (p = 0.9), there are a number of cases in which the variability of the alternative land use (corn, coffee, pasture) was so small that it was numerically challenging to identify the fixed REDD+ payment (see footnote 6) in order to ensure that forest was preferred by the landowner exactly 90 times out of 100.

## APPENDIX

### 1. Production data

**Table A1: Municipality-scale area and production for pasture/cattle, corn, and coffee, 2006**

### 2. Data used to estimate daily profits

*Prices (P)*

Prices for corn, coffee and cattle are obtained from CEPEA.[5] These data are for daily prices recorded on exchanges in São Paulo. Given the remoteness of Acre state to this market the prices that farmers receive for their product is likely to differ from those offered in São Paulo. Factors such as transportation costs and the extent of local demand are likely to cause a variation in prices. We convert the daily price series into an estimation of Acre-level prices. The difference between the prices in Rio Branco (obtained from quantity and value data provided by IBGE, 2006) and São Paulo on January 1, 2006 is calculated. This gives a relative difference in prices on that date, which are then applied to the time series as a whole. Three different price series resulted: a São Paulo price for which transportation to São Paulo must be added; a Rio Branco price that is a relative amendment of the São Paulo price; and, a Rio Branco price that is an absolute level amendment of the São Paulo price. For the latter two, transportation costs to Rio Branco are added. Based on the nature of the commodities and markets the price series for corn and cattle are taken from Rio Branco with the relative amendment, given the likelihood that much of this production is consumed within the State. For coffee, we use the São Paulo price given that much of this product is transported out of the State for export.

*Yields (Y)*

Municipality level annual yields for coffee and corn are drawn directly from the Brazilian Agricultural Census.[6] Cattle yield is estimated using data on head of cattle and area of pasture from the Census.[7] An average weight of 450kg per head of cattle and an annual offtake of 8.5% are assumed based on Bowman et al. (2012).

*Labour, fertiliser and fuel costs (L, Fe, Fu)*

We draw upon municipality-level cost data for labour, fertiliser and fuel for corn, cattle and coffee from the 2006 Brazilian Agricultural Census.[8] This gives total municipality-level production expenditure for a variety of different inputs for the year 2006. Costs per hectare are calculated using municipality acreage, also drawn from the Brazilian Agricultural Census.[9]

For corn and coffee some missing cost data are estimated by the authors. We drew inference from the data that are available in order to estimate substitute observations for the areas where data are missing. Thus, we estimate substitutes for missing observations based on the rationale that costs per hectare are a function of yield and production inputs. Our implicit assumption is that there is a fixed mix of production inputs suitable for growing these crops across the Legal Amazon, and

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[5] Data were obtained from http://cepea.esalq.usp.br/english/

[6] Yields are calculated using quantity and acreage from Table 949 of the 2006 census. The entry 'Milho em grão' is used for corn.

[7] Head of cattle from Table 73 of the 2006 census and area of pasture from Table 1031.

[8] Table 5445 of the 2006 census. Data for 'Cultibatio de cereais' and coffee was used..

[9] Table 949 of the 2006 census for Corn and Coffee, and Table 1031 for Cattle.

acknowledge that this assumption neglects intra-regional variation in farming techniques and unit costs of inputs.

Knowing the level of one input we can estimate the costs of other key inputs. For corn, we find a significant relationship between fertiliser and salary costs and hence, estimate missing fertiliser costs using coefficients from a regression of fertiliser costs on salary costs for all municipalities in the Legal Amazon. For coffee, data are estimated for total, fertiliser, salary and fuel costs. We find a significant relationship between fuel costs and yield and yield-squared and use this relationship to estimate fuel costs – again based on a regression that uses data across all municipalities in the Legal Amazon. Fuel costs are then found to be a significant predictor of each of total, fertiliser and salary costs, which allows us to estimate the remaining costs, yet again based on a regression using data across all municipalities in the Legal Amazon. Details of variables used and the regression results can be seen in Tables A1 and A2.

**Table A2: Variables used in regressions**

**Table A3: Regression results**

We use these cost data to create a March 31, 2006 benchmark for labour, fuel and fertiliser before scaling each one of these factors with a relevant price index in order to obtain daily prices. Gasoline and fertiliser prices are scaled using, respectively, monthly gasoline prices from Reuters for the Central-West region of Brazil, and a weekly time series for the price of Monoammonium Phosphate in Brazil from the CRU group, i.e. used as a proxy for all fertilisers. Labour costs are converted into daily costs across the time series using the industrial labour wages index for North and Central-West Brazil (IBGE, 2006).

*Fixed costs (Fix)*

Agricultural production requires a variety of other costs beyond labour, fuel and fertiliser costs. The Brazilian Agricultural Census reports costs in a number of other categories including lease costs of the land, seeds, packaging, pesticides, taxes and machine rental. As the prices of these items are unlikely to vary on a daily basis we aggregate them together into a fixed costs item at the level reported in the 2006 Census. This level is assumed fixed for the entire five-year time period.

*Transportation Costs (T)*

Transportation costs are calculated using cost per unit per km obtained from SIFRECA's Anuario 2010 (SIFRECA, 2010). Mid-term costs per km for 2010 were used for each of the three commodities and converted into US$ using an exchange rate of 1:2.135 (obtained from Oanda[10]). For each municipality, the shortest distance by road to Rio Branco and Sao Paulo is estimated from Google maps. For those municipalities with no road access, fixed distances of 4500km to Sao Paulo and 1000km to Rio Branco are used. Cost per unit per km is converted into cost per hectare using our yield data. We note that *T* is a crude measure of transportation costs in that it may not reflect the proximity of farms to roads. Yet, it is commonly observed that proximity to roads is associated with deforestation (see Ferretti-Gallon and Busch, 2014). In many parts of the Brazilian Amazon, farms are often found near roads, e.g. those established by the Federal government's resettlement programs (see Caviglia-Harris and Harris, 2011).

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[10] See: http://www.oanda.com/currency/converter/

Daily, total net profits are calculated by multiplying daily prices by yield per hectare to generate total revenue per hectare. These production costs are then subtracted from net revenue to give net profits per hectare per day.

### Other data

*Clearance and conversion costs*

Crucial to the decision to convert forest to agriculture is the cost of clearing forest and converting the remaining land so that it is suitable for agriculture. Clearance and conversion costs are composed of three components that differ depending on the type of conversion. For conversion from standing forest there is a cost of clearing the trees and potential revenue from selling some of the cleared timber. For establishment of each of the different commodities there are various infrastructural costs.

The costs of clearing forest are drawn from estimates of forest management in Acre by d'Oliveira et al. (2005), which are given as US$48.4 per $m^3$ of harvested timber. Revenues from selling cleared timber are calculated given an estimated volume of commercial timber per ha for Acre of 20 $m^3$/ha (ibid). Timber prices are drawn from roundwood timber prices calculated from quantity produced and value reported by IBGE. These are converted to US$ using the January 2006 exchange rate from Oanda.

Infrastructure costs are sourced from de Almedia and Uhl (1995). Estimates for slash and burn annual crops are used for corn infrastructure, intensive agriculture/perennial crops are used for coffee and unimproved pastures are used for cattle. The 1995 estimates are converted to 2006 estimates by first converting the figures into Brazilian Real using the 1995 exchange rate from Oanda, applying the World Bank GDP deflator, and then converting back to US$ using the 2006 exchange rate.

*Carbon density*

Carbon density data are extracted from the underlying 1km x 1km carbon map in Saatchi et al. (2011). Mean carbon density per hectare (MgC per ha) is estimated for each municipality. These are mapped onto Figure A1, with the municipalities ranked in Figure A2 as box plots that show the distribution of carbon density within each municipality. From Figure A1, it can be seen that the lowest mean carbon densities are to be found in municipalities near the State capital, Rio Branco. These municipalities also display greater variation around the mean values in the form of larger boxes, which suggests the presence of a greater diversity of forest in different stages of transition, from pristine, primary forest to heavily degraded forest, in contrast to some of the more remote municipalities.

**Figure A1: Map of mean carbon density (MgC/ha) for each municipality in Acre State**

**Figure A2: Ranking of mean carbon density (in MgC/ha, lowest to highest) by municipality in Acre State**

# APPENDIX FIGURES AND TABLES

**Table A1: Municipality-scale area and production for pasture/cattle, corn, and coffee, 2006**

| **Municipality** | **Coffee** | | **Corn** | | **Pasture** | |
|---|---|---|---|---|---|---|
| | Area (ha) | Production (tonnes) | Area (ha) | Production (tonnes) | Area (ha) | Production (head cattle) |
| Acrelândia | 382 | 548 | 1040 | 5140 | 23939 | 178905 |
| Assis Brasil | 37 | 35 | 142 | 525 | 4692 | 26398 |
| Brasiléia | 132 | 144 | 1538 | 5700 | 27308 | 171864 |
| Bujari | 2 | 2 | 890 | 3080 | 37519 | 208766 |
| Capixabaa | 13 | 11 | 834 | 3377 | 19195 | 118943 |
| Cruzeiro do Sul | 32 | 40 | 1221 | 2413 | 10416 | 42394 |
| Epitaciolândia | 42 | 21 | 1190 | 4410 | 15088 | 71324 |
| Feijó | 9 | 16 | 921 | 3415 | 14912 | 60600 |
| Jordão | 0 | 0 | 284 | 983 | 1913 | 4509 |
| Mâncio Lima | 2 | 2 | 180 | 401 | 1945 | 16035 |
| Manoel Urbano | 40 | 14 | 162 | 600 | 3004 | 22839 |
| Marechal Thaumaturgo | 6 | 10 | 422 | 1113 | 847 | 4957 |
| Plácido de Castro | 62 | 56 | 550 | 2702 | 28650 | 163166 |
| Porto Walter | 0 | 0 | 194 | 479 | 990 | 4431 |
| Rio Branco | 28 | 33 | 524 | 1944 | 52926 | 454728 |
| Rodrigues Alves | 28 | 35 | 236 | 584 | 3987 | 11553 |
| Santa Rosa do Purus | 0 | 0 | 12 | 36 | 730 | 2189 |
| Senador Guiomard | 65 | 64 | 736 | 3960 | 38584 | 257518 |
| Sena Madureira | 150 | 48 | 1303 | 4830 | 39587 | 186642 |
| Tarauacá | 0 | 0 | 1560 | 5781 | 22177 | 97552 |
| Xapuri | 17 | 16 | 579 | 2145 | 31546 | 204163 |
| Porto Acre | 38 | 36 | 808 | 2994 | 37855 | 143439 |

**Source: IBGE (2006)**

**Table A2: Variables used in regressions**

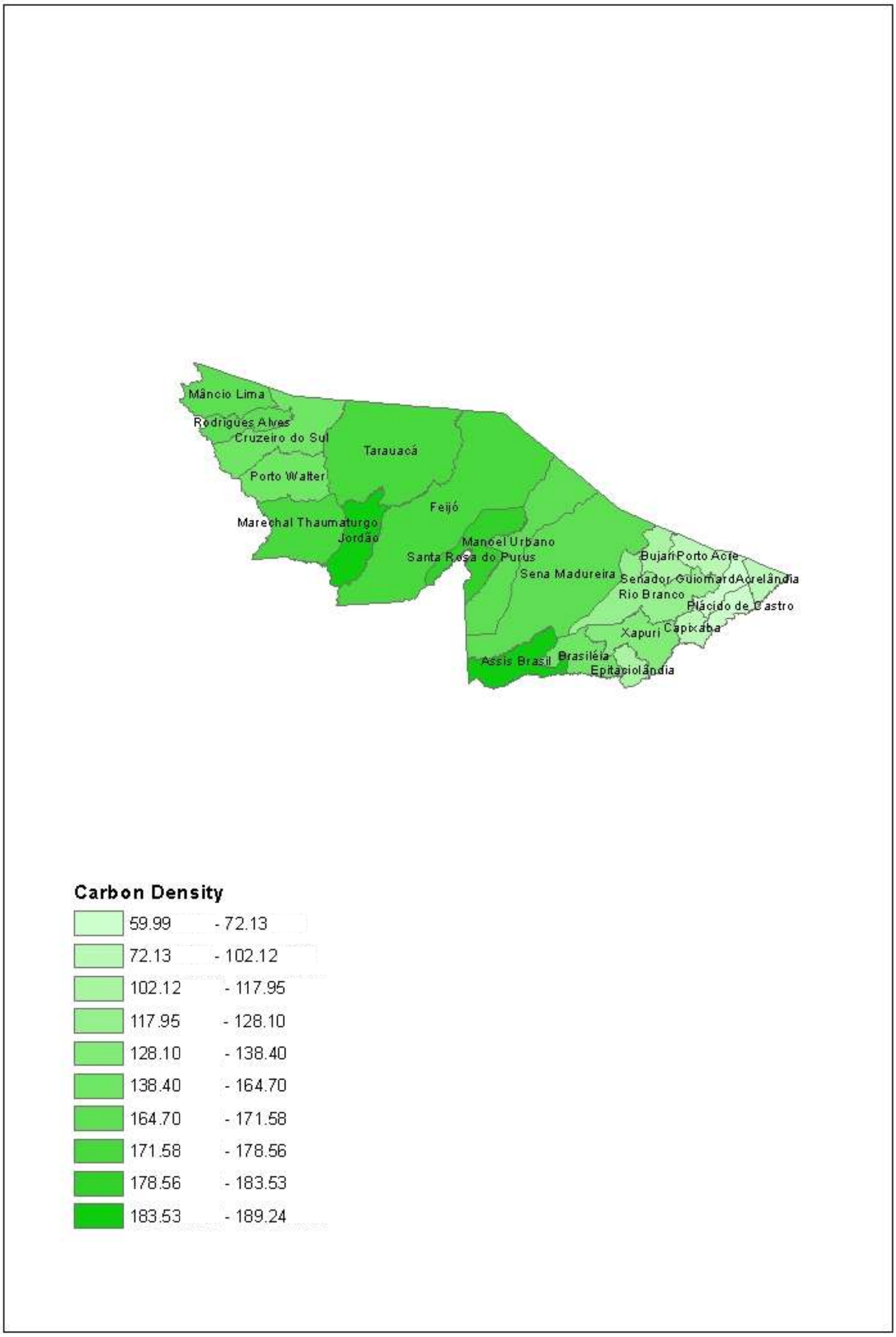
| Variable | Description | Source |
|---|---|---|
| Corn Fertiliser | Fertiliser costs per hectare for corn production per annum at the municipality level | IBGE |
| Corn Salary | Salary costs per hectare for corn production per annum at the municipality level | IBGE |
| Coffee Fuel | Fuel costs per hectare for coffee production per annum at the municipality level | IBGE |
| Coffee Salary | Salary costs per hectare for coffee production per annum at the municipality level | IBGE |
| Coffee Fertiliser | Fertiliser costs per hectare for coffee production per annum at the municipality level | IBGE |
| Coffee Total | Total costs per hectare for coffee production per annum at the municipality level | IBGE |
| Coffee Yield | Yield in tonnes per hectare of coffee production per annum at the municipality level | IBGE |
| Coffee Yield squared | Yield in tonnes per hectare of coffee production per annum at the municipality level squared | IBGE |

**Table A3: Regression results**

| VARIABLES | (1) Corn Fertiliser | (2) Coffee Fuel | (3) Coffee Fertiliser | (4) Coffee Salary | (5) Coffee Total |
|---|---|---|---|---|---|
| Corn Salary | 1.7096*** | | | | |
| | (0.13203) | | | | |
| Coffee Yield | | 0.0005346*** | | | |
| | | (0.000184) | | | |
| Coffee Yield-squared | | -1.54e-08*** | | | |
| | | (5.53e-09) | | | |
| Coffee Fuel | | | 0.1473*** | 1.1895*** | 10.489*** |
| | | | (0.01884) | (0.04618) | (0.5866) |
| Constant | -0.00699 | 0.2849 | -0.01154 | -0.0363 | -2.3230 |
| | (0.2576) | (0.2534) | (0.02746) | (0.05306) | (1.2678) |
| Observations | 302 | 86 | 76 | 64 | 76 |

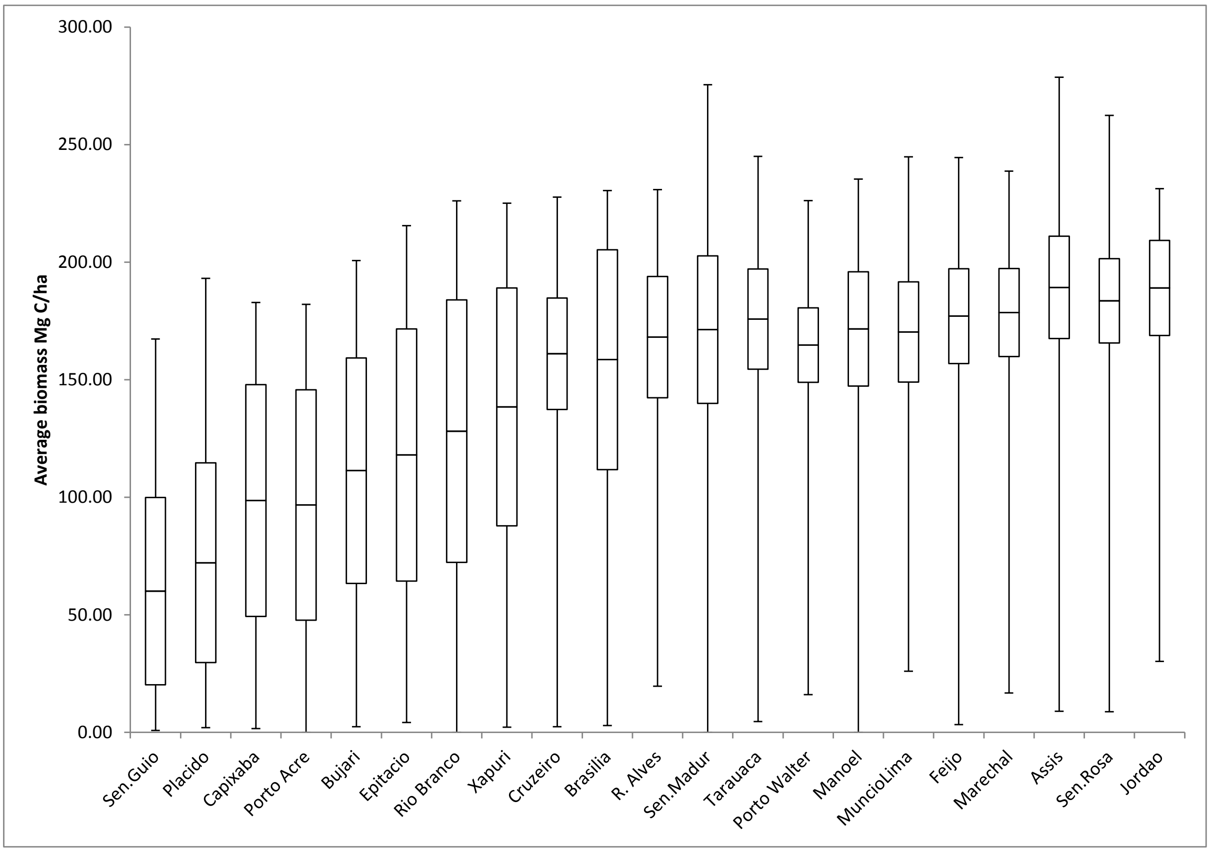
**Source: Authors**

**Figure A1: Map of mean carbon density (MgC/ha) for each municipality in Acre State**



**Source: Authors; data from Saatchi et al. (2011)**

**Figure A2: Ranking of mean carbon density (in MgC/ha, lowest to highest) by municipality in Acre State**



**Source: Authors; data from Saatchi et al. (2011)**

**Note: the centre of each box is the mean value; the extent of each box denotes one standard deviation around the mean.**