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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 low profits but with relatively low conversion costs and stable returns over time, 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 ton 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

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). Although largely not 'results-based', 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 million tons of CO_2 emissions (Herbert, 2010). To this end, Acre has established a 'PES-like' scheme known as the Incentive System

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for Environmental Services (SISA) framework, which aims at conserving forest carbon as well as biodiversity and hydrological services.

When evaluating the cost-effectiveness and efficiency of PES, 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 the level of incentives required to prevent forest conversion may need to be higher when faced by alternative land uses that have relatively low up-front conversion costs and stable returns over time. In general, a failure to consider uncertainty in future agricultural returns results in biased estimates of the opportunity costs of forest conservation, the interpretation of which can lead to potentially misleading policy implications. Indeed, the Stern Review (Stern, 2007) endorsed REDD+ as a cost-effective climate change mitigation strategy based on such estimates. It is also commonly assumed that the environmental benefits from conserving forest are homogenous across space. Yet, 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 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 Acre’s government should pay to landowners in order 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 an acknowledgement that should alternative land uses become highly profitable, e.g. due to rising commodity prices, it may not be possible to prevent contract breach thus reflecting imperfect enforcement of conservation contracts (e.g. Engel and Palmer, 2008; Jayachandran, 2013). For each of Acre’s municipalities, we estimate the uncertain returns for three alternative land uses: cattle, corn, and coffee. From these, we 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 measure of environmental cost-effectiveness at the municipality scale.

Against a backdrop of falling deforestation rates in Acre, around 50,000 hectares of forest were lost annually between 2001 and 2010, mainly to accommodate the expansion of cattle pasture. Thus, any policies that aim to reduce deforestation further, including SISA, would need to target farmers and private landowners. 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. In general, there is currently little scope for the use of carbon markets and offsetting to augment Acre’s conservation budget. Given limited funds, a rational policymaker may seek to minimise the level of incentive while ensuring that it achieves the aim of slowing deforestation, i.e. by equalling or exceeding the opportunity costs of conserving forests. But even if the policymaker could somehow access private information on opportunity costs, there is then the problem of ensuring compliance over the duration of the conservation contract given changing and uncertain returns from forest conversion. In other words, opportunity costs are essentially a moving target for policymakers. Not only do prices of agricultural commodities change over time but also those of various inputs, like fertilizers and labour.

Given a limited conservation budget, the basic idea behind our analysis is to identify any parts of Acre where it might be possible to conserve a lot of carbon but at relatively low cost. With this paper, we aim to contribute 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 collected and thus 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 processes, 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 tends to mask the wide differences found among municipalities. Our empirical exercise demonstrates that there is a 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 with almost half of these living in the capital, Rio Branco, with the remainder spread among its 22 municipalities (Figure 1). 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.

Figure 1: Municipalities of Acre State, Brazil

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. The 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 22,683,000 tCO2e 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 11.5mt 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 Incentive System for Environmental Services (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 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 payment 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 returns from alternative land uses are uncertain. Below, we intuitively explain the theory underlying our adaptation of the model, a formal presentation of which can be found in Engel et al. (2015).

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 the 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[5] 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 and (partially) evolves as a function of the constant trend parameter μ_A the (positive) constant uncertainty parameter σ_A. A positive (negative) μ_A indicates that net agricultural profits are, on average, increasing (decreasing).

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. In the latter case, the landowner receives a payment of *Fdt* and the discounted future expected returns from forest conservation. Therefore, π^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). All returns are valued by discounting their expected values at the constant, continuously compounded, risk-free discount rate *r*.

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 a 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.[6]

[5] 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.

[6] 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.

Note that, operationally, we implement the same payment regime as Engel et al. (2015), $= c + \alpha . I$, where *c* is a constant per-hectare payment and *I* is a per-hectare indexed component scaled by a pre-set coefficient α. In our adaptation, the landowners' opportunity costs of forest conservation are based on uncertain coffee/corn/beef returns and the REDD+ payment has (virtually) zero volatility. However, for technical reasons, we cannot set this to zero. Instead, with the (very small) REDD+ payment variability we calibrate the policy via α and set *c* to zero. The REDD+ payment is virtually constant (α = 0.005).

To determine the REDD+ payment that satisfies this criterion, we first evaluate the optimal conversion boundaries given a specific set of model parameters. Specifically, these boundaries depend upon the values of the: parameters of the returns from forest F_t and agriculture A_t, respectively; conversion costs CC_{FA}; and, 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 Section 5, we parameterize the returns processes.

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, *S*, we compute the likelihood of a land-use change from forest to agriculture not occurring, $\hat{p}$. The probability-based criterion is met when $\hat{p} \geq p = 0.9$.

4. DATA

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 3, 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. Municipality-level production data are shown in Appendix 1. Simplified transitions for these three land uses are shown in Figure 2 below.

Figure 2: Land use transition for pasture, corn and coffee, in Acre State

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 often switched 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 to give daily profits that help us to generate *Adt*. The per-hectare return (in US$) on day *t* from agricultural commodity *x* is given by:

$$\pi_{tx} = (P_{tx}Y_x) - (Fix + L_{tx} + Fe_{tx} + Fu_{tx} + T_{tx}) \qquad [1]$$

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).

Prices (P)

Prices for corn, coffee and cattle are obtained from CEPEA.[7] 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.[8] Cattle yield is estimated using data on head of cattle and area of pasture from the Census.[9] 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.[10] This gives total municipality-level production

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

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

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

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

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.[11]

For corn and coffee some missing cost data are estimated by the authors. For corn, missing data for fertiliser costs are estimated 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. Fuel costs are estimated using the coefficients from a regression of fuel costs on yield and yield-squared, again for all municipalities in the Legal Amazon. In turn, fertiliser, salary and total costs are estimated using coefficients from a regression of these costs upon fuel costs, once more for all municipalities in the Legal Amazon. Details of variables used and the regression results can be found in Appendix 2 and 3.

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[12]). For each of the municipalities, 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.

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

[11] Table 949 of the 2006 census for Corn and Coffee, and Table 1031 for Cattle.
[12] See: http://www.oanda.com/currency/converter/

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 3, with the municipalities ranked in Figure 4 as box plots that show the distribution of carbon density within each municipality. From Figure 3, 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 3: Map of mean carbon density (MgC/ha) for each municipality in Acre State

Figure 4: Ranking of mean carbon density (in MgC/ha, lowest to highest) by municipality in Acre State

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.

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. We obtain negative net profits due to basing our calculations on observable market prices, which proxy for landowners' returns from alternative land uses. Pasture appears to result in consistent negative net profits in most municipalities. Figure 5 illustrates these patterns 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 5: 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 negative net profits can be used to estimate volatility and model returns processes 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, clearance costs are given 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 corn is typically the cheapest. 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 trends more precisely in order to estimate landowners' returns under uncertainty.

Returns under uncertainty

The model presented in Section 3, namely the constant trend parameter, μ, and the variance, σ, is calibrated using the estimated daily profits. The calibrated parameters are presented in Table 3 for each land use and 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) μ 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, beef) 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 times/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, and is characterised as a cost to the policymaker. It is the number which is 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 6 displays the data for all three 'Cost' columns' for each municipality and Figure 7 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 6: Relative cost of payment per ha to cover opportunity cost of each land use by municipality

Figure 7: Map of the minimum payment required to maintain the forest for each municipality.

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 3) along with the ranks used to create Figure 4. 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 for paying landowners to keep land in 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 areas. Figure 8 presents the relative cost per ton 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 8: 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. Following, 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'.

Given that up-front investments combined with greater uncertainty in agricultural returns creates incentives to delay the decision to convert forest to an alternative land use, it is perhaps unsurprising that cattle-ranching determines the level of the minimum payment for 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 the landowner. 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. However, 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 tried to account for this variation by estimating the cost per ton of carbon and hence, can identify a group of 13 municipalities in which costs vary by up to 25%. From Figure 8, this group comprises Porto Walter to Santa Rosa do Purus. Our estimates imply that it is these municipalities that might be prioritised for cost-effective conservation of forest carbon stocks.

Our estimates of minimum payment levels are quite similar across municipalities yet are dependent on the quality and quantity of publicly-available data. There is a predominance of negative net profits, which are an obstacle to obtaining absolute rather than relative cost estimates. 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. Subsistence agriculture dominates in a lot of municipalities, which is unlikely to be accounted for in government-collected statistics. Given that the survey from which IBGE draws data only captures a few large-scale farmers, when most farms tend to utilise more own labour on farm, we may be overestimating 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.

In generating our results, we assume 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.

Given limited conservation budgets, our model offers a novel and straightforward way of utilising publicly-available data to target such funds. It can also be easily expanded to incorporate other ecosystem services and biodiversity. Indeed, the mapping of policy costs and 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). Thus, once we factor in the distribution of biodiversity over space our results could potentially favour some of the cheaper municipalities where carbon may not be so abundant. This could assist in the targeting and design of a policy such as SISA, which aims 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. 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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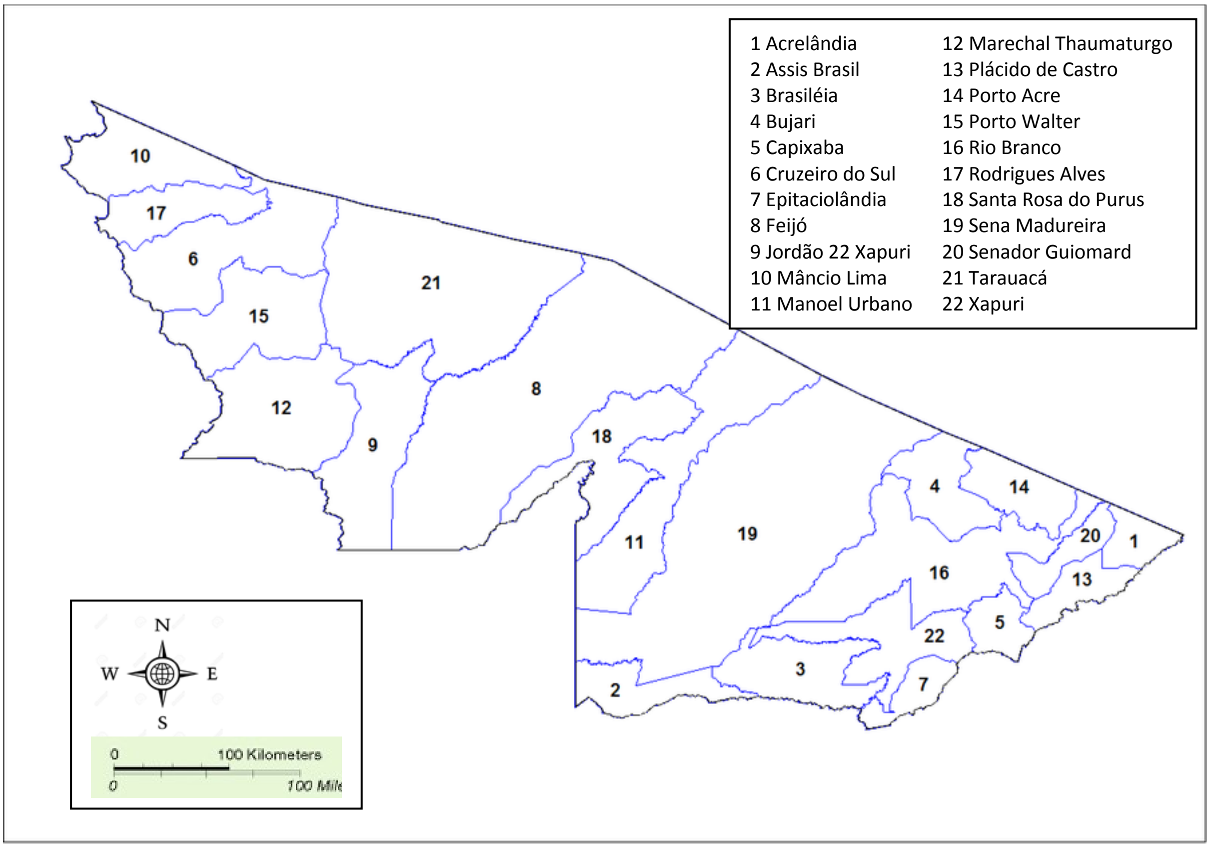
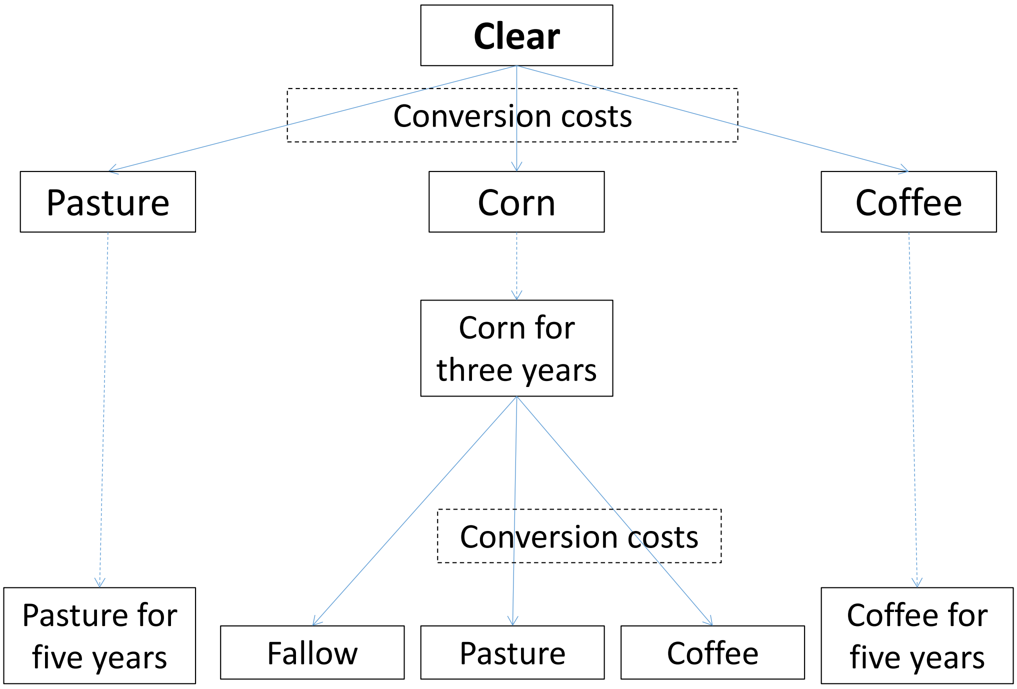
FIGURES & TABLES

Figure 1: Municipalities of Acre State, Brazil



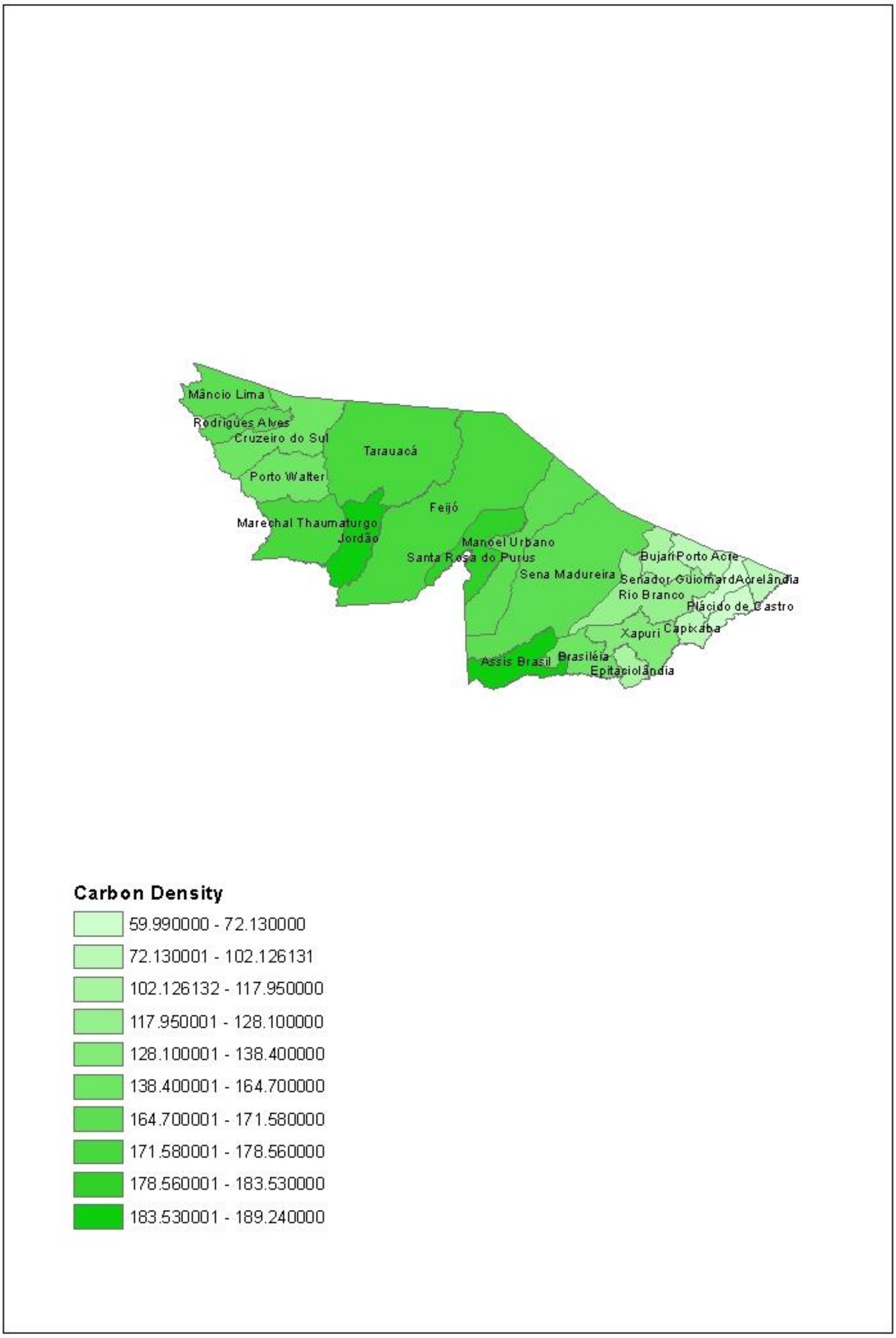
Source: Authors adapted from Wikipedia (2015)

Figure 2: Land use transition for pasture, corn and coffee, in Acre State



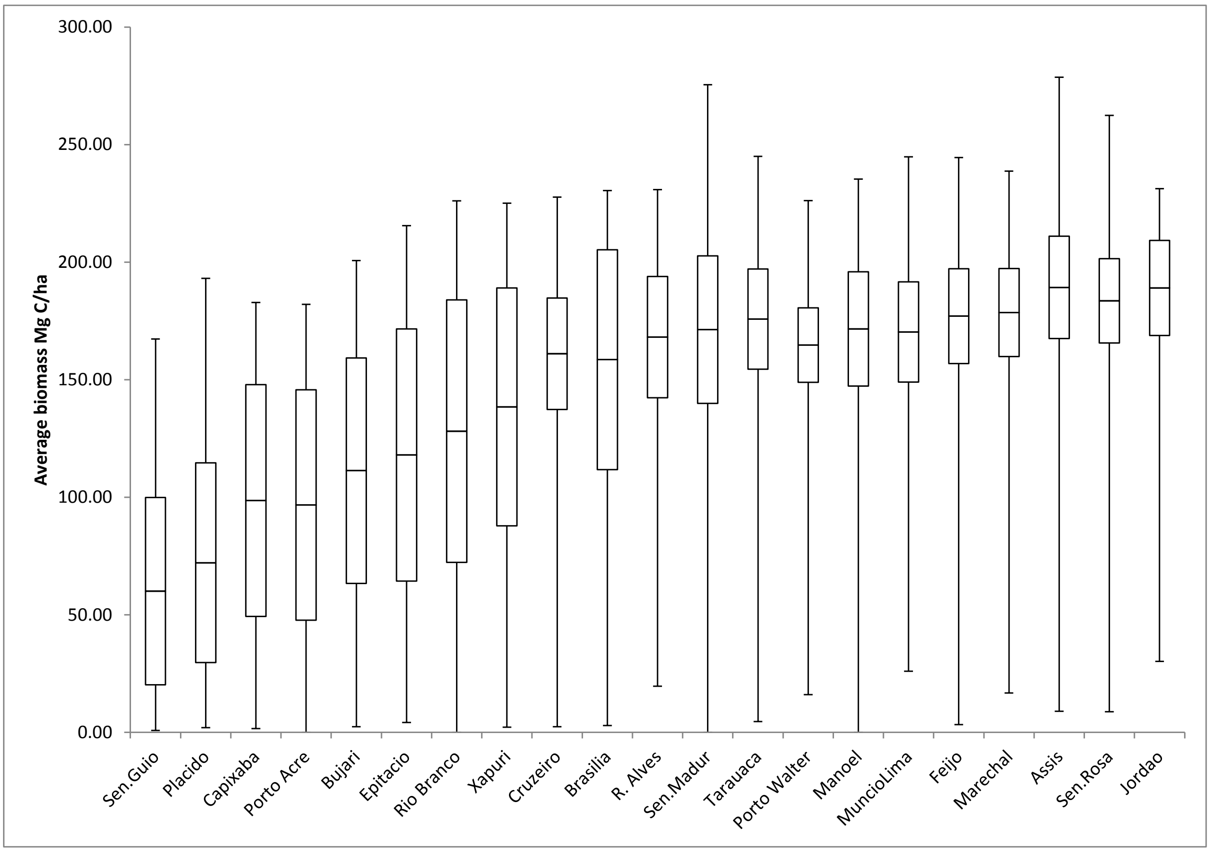
Source: Authors

Figure 3: Map of mean carbon density (MgC/ha) for each municipality in Acre State



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

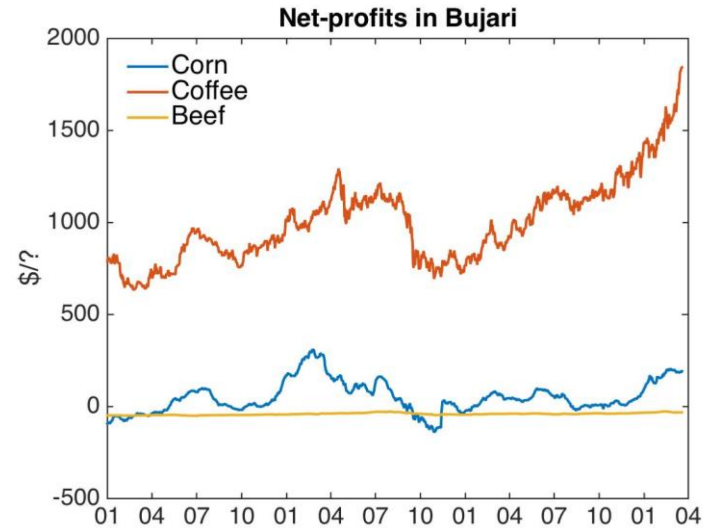
Figure 4: Ranking of mean carbon density (in MgC/ha, lowest to highest) by municipality in Acre State

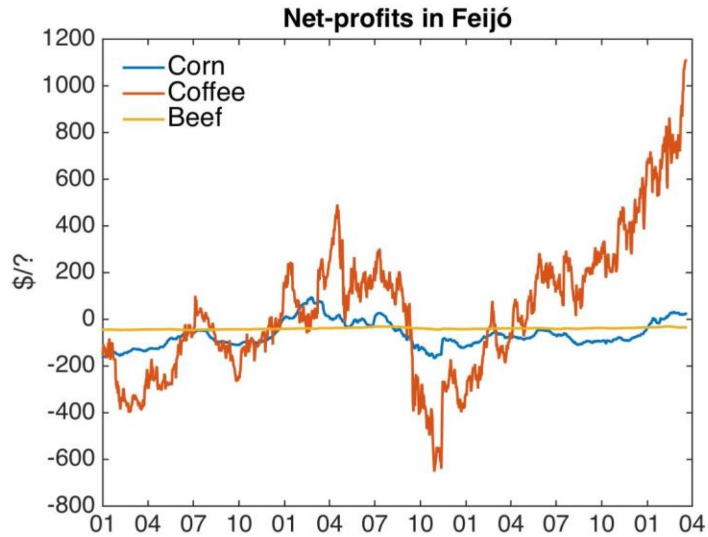


Source: Authors; data from Saatchi et al. (2011)

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

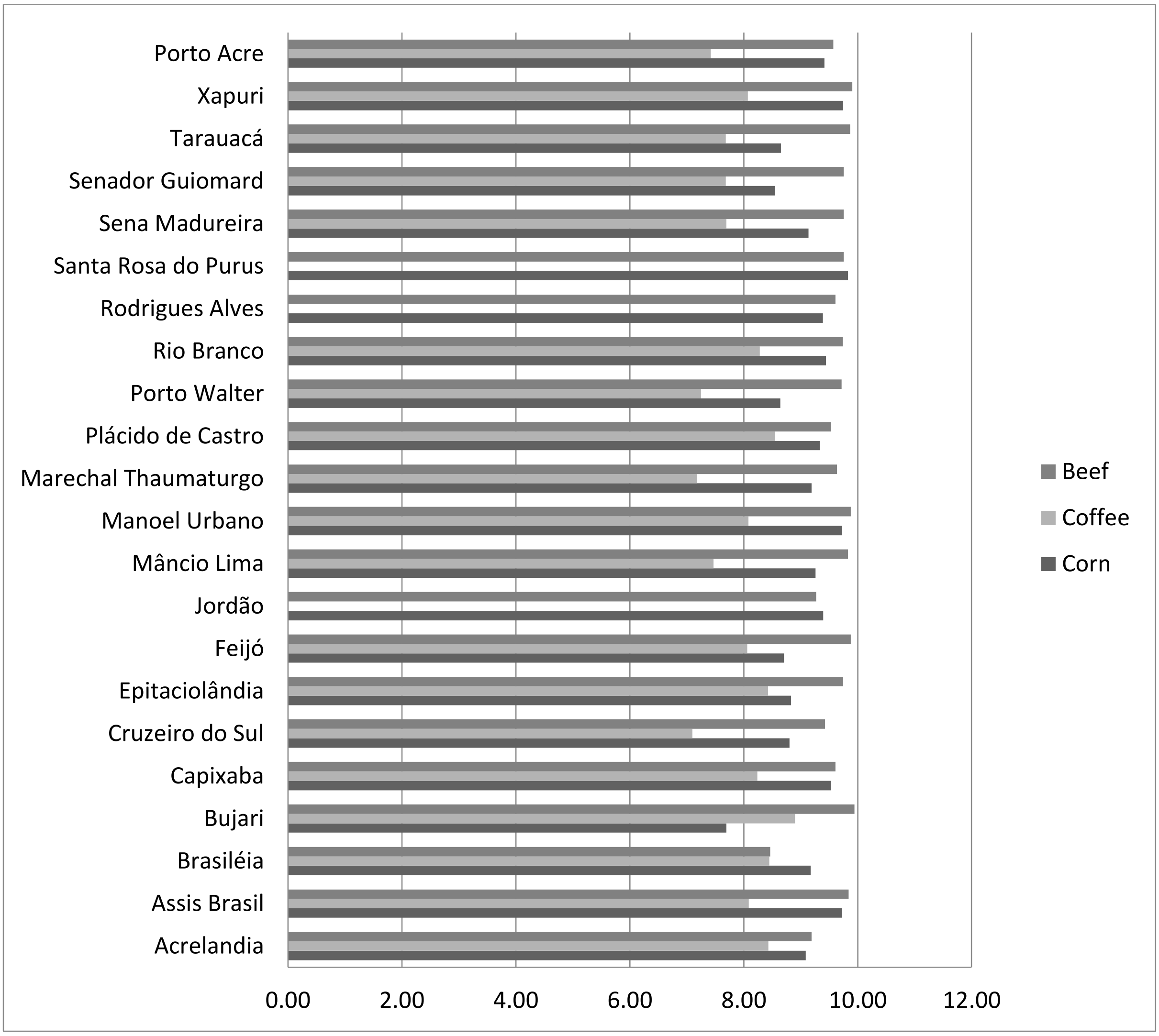
Figure 5: Daily net profits in US$ per ha for Bujari and Feijó, 2006-2010





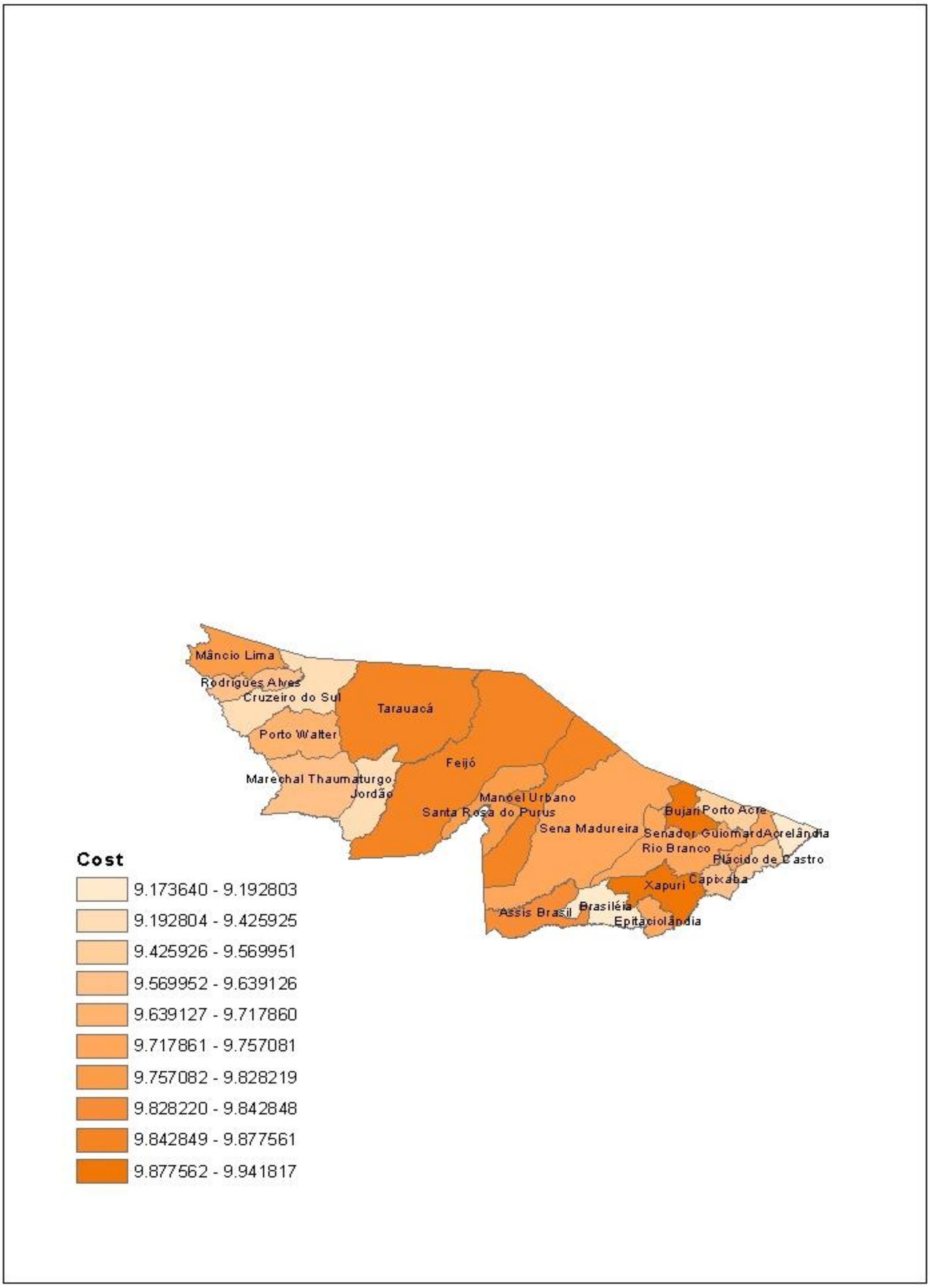
Source: Authors

Figure 6: Relative cost of payment per ha to cover opportunity cost of each land use by municipality



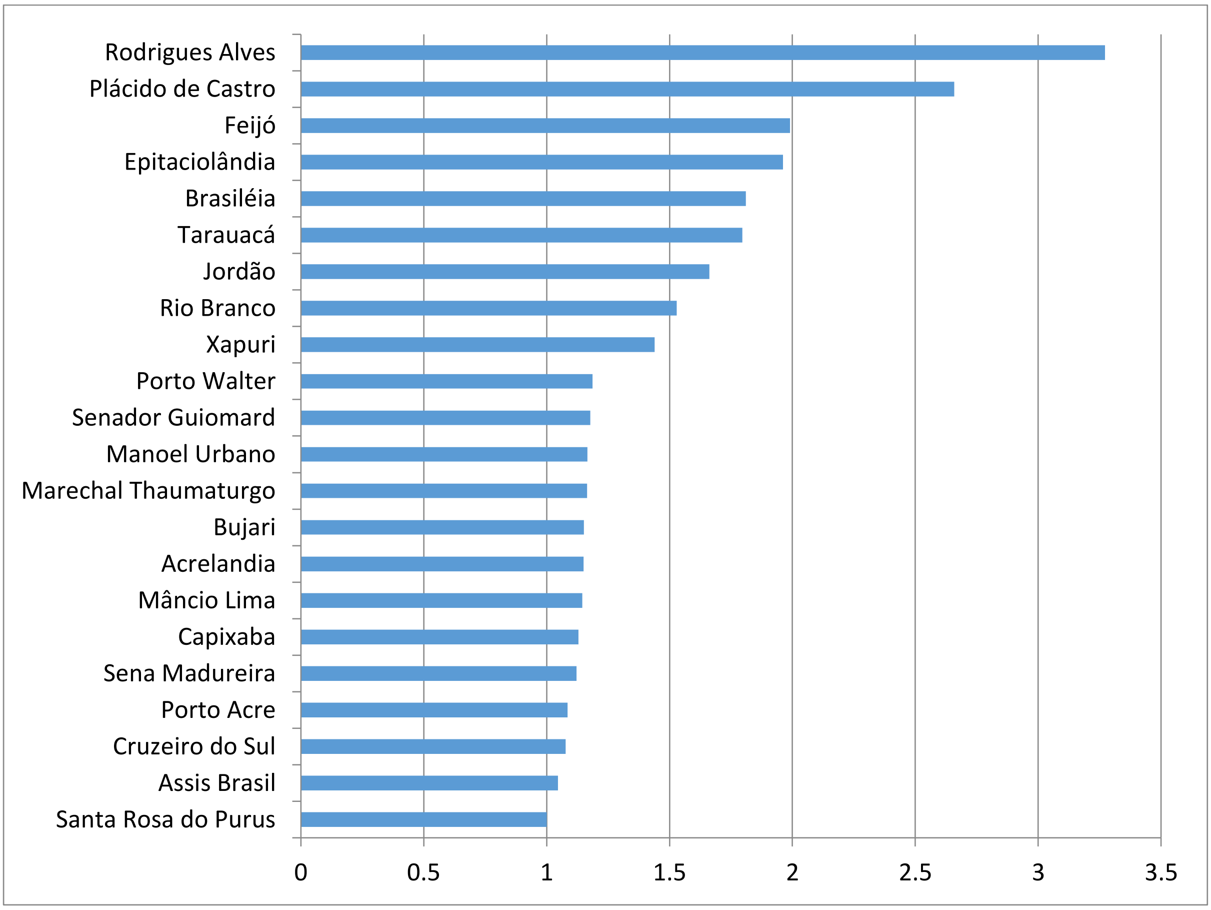
Source: Authors

Figure 7: Map of the minimum payment required to maintain the forest for each municipality.



Source: Authors

Figure 8: Relative cost per ton carbon



Source: Authors

Note: Cost per ton 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. **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)

2. 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

3. 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