Deforestation in private lands in Brazil and policy implications for REDD programs: an empirical assessment of land use changes within farms using an econometric model[1]

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SUMMARY

Within the perspective of evolving negotiations for Reduced Emissions from Deforestation and Degradation (REDD), the opportunity costs of deforestation are regarded as the basis for constructing a REDD mitigation cost curve. This paper presents a land-use model that measures the impact of economic and physical variables on farmers' decisions about the allocation of their land among competing uses in Brazil. It is based on a multi-output land allocation model with agricultural land as a fixed input that is to be allocated. For the first time such a land allocation model has been estimated that explicitly separates all main competing uses for forest in Brazil – soybeans, sugarcane and pasture. Our results suggest a clear substitution effect between land allocation for forest and soybeans, and for forest and pasture. The results presented here contribute to the understanding of farmers' land use decisions while providing an estimate of the opportunity costs of deforestation at the county level in Brazil.

Keywords: deforestation, Brazil, land-use model, REDD, mitigation curve.

La déforestation dans les terres privées au Brésil et implications politiques pour les programmes REDD: une évaluation empirique des changements d'usage des terres dans les fermes utilisant un modèle économétrique.

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Dans la perspective des négociations des émissions dues à la déforestation et à la dégradation des forêts (REDD), les coûts d'opportunité de la déforestation sont considérées comme la base pour construire une courbe du coût d'atténuation REDD. Cet article présente un modèle d'utilisation qui mesure l'impact des variables économiques et physiques sur les décisions des agriculteurs concernant l'attribution de leurs terres à des usages concurrents au Brésil. Il est basé sur un modèle multi-sorties répartition des terres et des terres agricoles comme un intrant fixe qui doit être alloué. Pour la première fois un tel modèle d'affectation des terres a été estimé que sépare explicitement toutes les utilisations principales concurrentes de la forêt au Brésil - soja, canne à sucre et de pâturages. Nos résultats suggèrent un effet de substitution claire entre l'allocation des terres pour la forêt et le soja, et pour les forêts et les pâturages. Comme nous le montrons, les résultats présentés ici représentent des informations cruciales pour l'estimation des coûts d'opportunité de la déforestation au niveau des comtés au Brésil.

Deforestación en tierras privadas de Brasil e implicaciones de política para programas REDD: una evaluación empírica de los cambios de uso de suelo en granjas mediante un modelo econométrico.

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Bajo la perspectiva de las negociaciones hacia la Reducción de Emisiones de la Deforestación y la Degradación de los bosques (REDD), los costos de oportunidad por deforestación son considerados la base para construir la curva de mitigación REDD. El presente estudio presenta un modelo de uso de suelo que permite medir el impacto de variables económicas y físicas sobre las decisiones de los agricultores con respecto a la asignación de su tierra entre distintos usos en Brasil. La estrategia empírica se basa en un modelo de asignación de tierra para productos múltiples donde la tierra se considera un insumo fijo pero asignable entre distintos usos. Esta es la primera vez que este tipo de modelo ha sido estimado separando explícitamente los principales usos que compiten con los bosques en Brasil - soya, caña de azúcar y pastizales. Nuestros resultados claramente sugieren un efecto sustitutivo entre la asignación de tierra para bosques y soya, así como entre bosques y pastizales. Los resultados aquí presentados representan información crucial para la estimación de los costos de oportunidad de la deforestación a nivel municipal en Brasil.

INTRODUCTION

According to a number of studies, climate change mitigation opportunities in Brazil have great potential related to reducing emissions from deforestation and degradation (REDD or REDD+[2]) (e.g. Chomitz *et al.* 2007, Mckinsey and Company 2009, Nepstad *et al.* 2007). These reductions are believed to be cheaper to obtain than in other sectors of the economy (Nepstad et al., 2009). Therefore, any national climate change strategy pursued by the Brazilian government should include REDD opportunities as an economic alternative for mitigation, as well as for preserving the country's vast natural capital. Such a strategy, in principle, would compensate farmers for avoiding deforestation of their lands with an amount at least equal to the expected net revenue that they would receive from using the lands for other uses, principally agriculture or pasture. These opportunity costs of deforestation, estimated for each municipality of Brazil, are one of the viable strategies for constructing the REDD mitigation cost curve for Brazil. This paper presents a land-use model that sheds light on the impact of economic and physical variables on the decisions that farmers make regarding the allocation of their land among competing uses, including forest. It is the first time such a land-use model has been developed that includes all significant land-use types driving deforestation in Brazil, such as pasture, soybean and sugar cane plantations in a disaggregated way.[3,4] Therefore, the results presented here represent crucial information for estimating the opportunity costs of deforestation in Brazil.

The paper is organized as follows: section 2 describes the theoretical model that underlies our work; section 3 presents the empirical model and discusses some econometric issues that arise with our data. Section 4 describes the data used in our analysis and section 5 presents our econometric results. Section 6 presents a policy implication example and section 7 concludes.

THEORETICAL MODEL

Multi-crop production models have been widely applied to analyze farmers' behavior and production technologies (Chambers and Just 1989, Just, Zilberman and Hochman 1983, Moore and Negri 1992, Moore, Gollehon and Carey 1994, Moore and Dinar 1995, Shumway 1983, Shumway, Pope, and Nash 1984). These models specify a profit function from which estimable output supply and input demand equations are derived.[5]

As in previous work applying Brazilian land use data (Feres *et al.* 2010), the theoretical model underlying the work presented here is adapted from the multi-output production model (Cambers and Just 1989). The model description below is based mainly on Moore and Negri (1992); the interested reader will find further details in their original work. According to their theoretical model the following three assumptions represent the essential features of agricultural production and provide a tractable approach to the multi-output production, especially of the fixed but allocatable input functions (i.e., land and water in their case, only the former in ours): *(a)* inputs are allocated to specific crop production activities; *(b)* production is technically non-joint in the sense

[2] Currently the discussion is more on REDD+, which includes carbon and forest management more widely and not just deforestation (which was the basis for REDD) when negotiating payments for owners and managers of forested lands. The substance of the analysis of this article can be applied in either case, although additional considerations of forest management in REDD+ could raise more options when looking at trade-offs between conservation and agriculture than are examined here.

[3] Sugarcane has a less straightforward role on the deforestation process of the Brazilian Amazon than the roles of soybean and cattle ranching. Sugarcane plantations traditionally compete with forest, for example, in areas where remnants of the Atlantic Rainforest are (see for example Young, C.E.F. (2006)). A good example regards the São Paulo state and some states in the Northeast Brazil (Alagoas and Pernanbuco). Regarding the Amazon region, some authors observe that although sugarcane is not substituting forest directly, there has been evidence that it is replacing soybean plantations in the Cerrado, pushing soybean plantations further north towards the Amazon's deforestation arch. For example, see Silva, E.B. and L.G. Ferreira Jr. (2010).

[4] Maeda et al., 2011 used a land use model which simulates pasture, forest and cropland transitions but does not work at this level of disaggregation.

[5] Other approaches are related to the random utility maximization framework thus avoiding the choice of functional forms for the profit functions (Hardie and Parks 1997, Lichtenberg 1989, Miller and Plantinga 1999, Parks 1980, Plantinga 1996, Plantinga, Maudlin and Miller 1999, Wu and Segerson 1995). Our approach, however, will allow us and others to derive the opportunity costs in public land in future work.

that the allocation of inputs uniquely determines crop-specific output levels; and *(c)* land is a fixed input that is allocated for different uses. Assumptions *(a)* and *(b)* enable the formation of separate restricted profit functions for each crop, taking land allocations as given; and assumption *(c)* provides the source of joint allocation when maximizing multi-crop profits.

Farmers are assumed to allocate land and other inputs in order to maximize their profits (Π) from different uses, constrained to the total amount of land available. Formally:

$$\underset{n_1 \ldots n_5}{Max} \quad \Sigma_{i=1}^{5} \; \Pi_i\left(p_i, r, n_i, X\right) \, subject \, to \, \Sigma_{i=1}^{5} n_i = N, \qquad (1)$$

where *(n)* is a vector of land allocated for i = 5 uses (sugar cane, soybeans, pasture, forest and "other crops"); *(p)* is a vector of crop prices; *(r)* is a vector of input prices (only labor in our case[6]); *(X)* is a vector of agro-climatic variables that may influence the farmers' decision for allocating land (e.g. temperature; precipitation; soil type and quality; average altitude; distance to markets); and *(N)* is the total farmland available. The Lagrangian function *(L)* is as follows:

$$L = \Sigma_{i=1}^{5} \; \Pi_i\left(p_i, r, n_i, X\right) + \mu\left(N - \Sigma_{i=1}^{5} n_i\right), \qquad (2)$$

where *(μ)* is the shadow price of land constraint. The necessary conditions for an interior solution are:

$$\frac{\partial L}{\partial n_i} = \frac{\partial \Pi}{\partial n_i} - \mu = 0 \quad i = 1 \ldots 5 \qquad (3)$$

$$\Sigma_i^5 n_i = N \qquad (4)$$

Equation (3) allocates land among crops to equate the marginal profit from each crop. The input constraint in (4) is binding assuming an interior solution. Solving equations (3) and (4) yields the optimal solutions to equation (2), denoted $n_i^*(p, r, X, N)$.[7,8] These represent the multi-crop farmer's production equilibrium in land allocations.

ECONOMETRIC MODEL

Normalized quadratic crop-specific profit functions are assumed in our empirical analysis due to their appealing theoretical and empirical properties (Shumway 1983). This form has been adopted in previous empirical work on land-use decisions (Feres *et al.* 2010, Moore and Negri 1992, Moore *et al.* 1994, Moore and Dinar 1995, Shumway 1983) since Lau's series of theoretical works (see for example Lau 1978). The normalized quadratic profit equations give a second order Taylor's approximation to an arbitrary functional form (i.e., flexible functional form) and impose linear homogeneity of degree one in the profit functions in prices (i.e., increasing all input and output prices by the same factor does not change the optimal choice and increases profit by that factor). Furthermore, by applying Hotelling's lemma to these functions, supply and variable input demands that are linear in their parameters are obtained. The primary interest of our study lies on the land allocation functions, which as shown in Moore and Negri (1992), are also linear in their parameters. Importantly, cross-price symmetry conditions are not imposed in the econometric specifications as these do not hold in the case of fixed allocatable inputs (Moore and Negri 1992; n. 8). However, to ensure linear homogeneity of the profit function, *p* and *r* are specified as relative prices with respect to those of other crops. The five land allocation equations to be estimated are:

$$n_i^*\left(p, r, N, X\right) = \beta_0^i + \Sigma_{f=1}^{5} \beta_{1f}^i p_f + \beta_2^i r + \Sigma_{k=1}^{t} \beta_{3k}^i X_k + \beta_4^i N, \qquad (5)$$

It is important to note that the price of land is not included as an explanatory variable in equation (5). Instead, since land is a fixed input, the total land available is included as a regressor.[9,10]

Due to the large number of municipalities in which sugarcane and soybeans are not grown (35% and 75%, respectively), and to a certain degree where there is no forest as well (3%), ordinary least squares (OLS) estimation of those equations would yield inconsistent estimates of the parameters (Cameron and Trivedi 2005). Moore and Negri (1992) solved this issue by applying a Tobit model to their dataset. This model, however, requires the non-censored observations (i.e., those with positive values in those land uses) to be normally distributed for estimates to be consistent. Our data do not comply with that assumption; rather it looks as if the observations have a log normal distribution (see Figure 1). Therefore a Tobit model for lognormal data is applied to the sugarcane, soybeans and forest equations. Equations for other crops and

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6 Variability across municipalities for prices of other inputs such as fertilizers and pesticides is small given the cross-sectional nature of our dataset. We believe that the set of geographical characteristics included in the model can nevertheless proxy for a good part of any price differentials in these inputs. Wages are explicitly included in the model due to the different quality and availability of labor across regions.

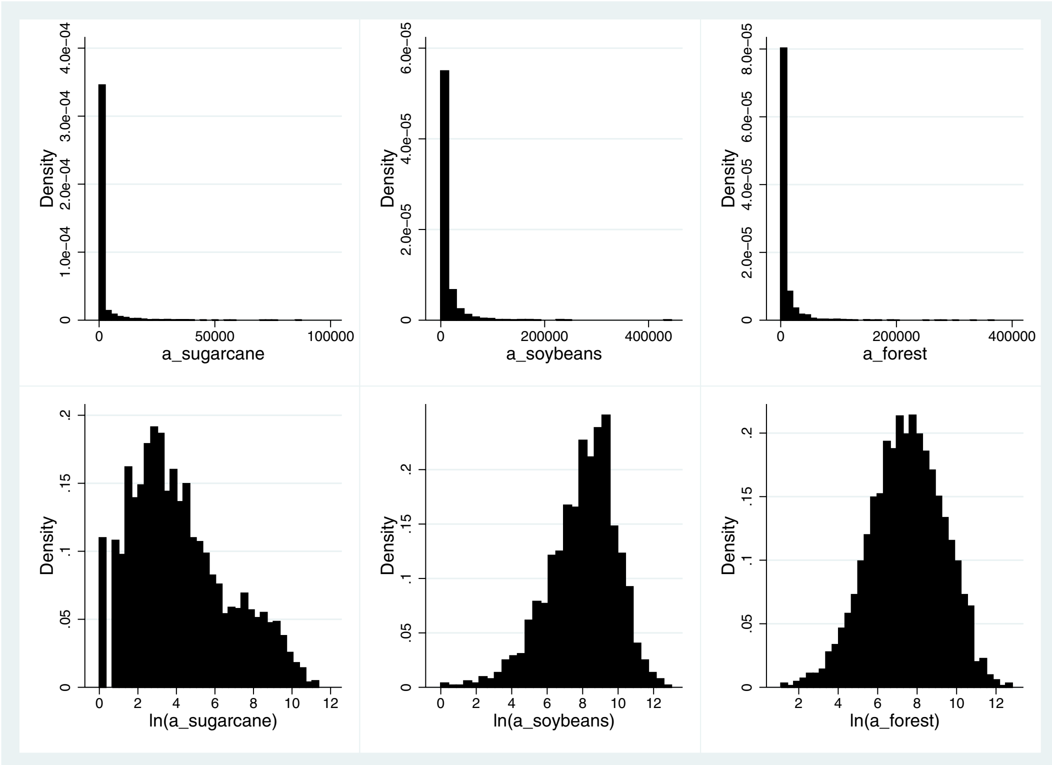
7 The six equations in (3) and (4) give the solutions for n_1 through n_5 as functions of the input and output prices and the agro-climatic variables.

8 Land allocations to sugarcane and soybeans are zero in some municipalities. This would imply that a corner solution is attained in some municipalities and that the shadow price of land for crops receiving zero allocation is less than the shadow price of land for crops produced. As noted in (Chambers and Just 1989), marginal profits are still equal among those uses with non-zero fixed input allocations and optimal solutions n_i^* still hold.

9 By examining regressions in which either the price or the total amount of an input is included, Moore and Dinar (1995) developed statistical tests aimed at discriminating between the fixed or variable assumption of land and water inputs. Here, the common assumption of land being a fixed but allocatable input is adopted.

10 One reviewer has noted that land speculation is an important factor driving the profitability of extensive ranching. To pick up this effect we would need data on expected future land prices, which is not available. Excluding this factor could therefore be a source of uncertainty untreated by the model.

FIGURE 1 *Histograms for sugarcane, soybeans and forest areas in levels and logs*



pasture are estimated through OLS with dependent variable in levels since this method does not require normality for consistency of its estimates and only a negligible number of municipalities have no land in those uses (0.1% and 0.2%, respectively).

It is important to note that the consistency of our estimates is unaffected by the single equation method applied in our study in the presence of potential correlation between error terms across equations. Although in some instances efficiency could be improved due to inter-equation error correlations, there is no efficiency gain in the linear model when regressors are identical across equations as they are in our case. As a separate issue, although our data comes from an agricultural census, it is possible that some estimation gains could be achieved by weighting observations by the importance of agriculture output or number of farms in a county. So-called analytical weights can be attached when variables represent averages. However, although our price variables are averages, our dependent variable is a sum. These two issues are left for future work and Table 3 presents results for the separate un-weighted regressions for the five land use categories.

DATA

Land-use, production and sales data in our analysis were obtained from the latest agricultural census available in Brazil.[11] In this dataset tables correspond to farm data aggregated at the municipality level. Thus, data on land allocation and production were recovered at the municipal level (5,564 municipalities) for sugar cane, soybeans, other crops representing approximately 90% of the rest of the agricultural production in Brazil[12], pasture (planted and natural) and forest (planted and natural).

Prices were estimated from information about the value of production divided by the quantity produced for each commodity in every state. National prices estimates were also calculated and used as a reference price in those municipalities where there was no production of a given crop[13]. For the

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[11] Censo Agropecuário 2006, Instituto Brasileiro de Geografia e Estatística – IBGE; Sistema Automático de Recuperaçao de Dados – SIDRA – www.sidra.ibge.gov.br.

[12] Algodao herbáceo (*cotton*); arroz em casca (*rough rice*); feijao em grao (*beans*) – preto (*black beans*), de cor (*red beans*), fradinho (*black eyed beans*) e verde (*green beans*); fumo em folha (*tobacco leaf*); mandioca (*cassava*); milho em grao (*corn grains*) e forrageiro (*fodder maize*); sorgo em grao (*sorghum*); trigo em grao (*wheat grain*); forrageiras para corte (*fodder*); cacao (*cocoa*); café arábica e canephora (coffee); laranja (*orange*).

[13] By assuming a national average price as a reference price means that the farmer's decision to allocate land is purely economic. As correctly pointed out by a reviewer, the absence of production of a certain crop in a given county may be due to agro-climatic constraints of the area, and in this case the reference price to be used in the model should be zero. In the present model, national prices are used as reference prices when the county does not produce a certain good and control for agro-climatic characteristics by including county-specific dummies for soil type, temperature and precipitation levels in each county.

product "other crops", a price index was estimated as a weighted (quantities produced) average of the representative crops grown in each state. Price for "cattle" was estimated dividing the value of abated and sold herds by the quantities of abated and sold animals, which results in the weighted average price from these goods. A similar procedure was used to estimate the price for forest products in which total value was divided by quantities of timber, wood for paper and wood for other uses.

Wages are the weighted average salaries paid to family and non-family workers divided by number of workers. This is the only input price variable included in our regressions. Capital costs are assumed to be similar across the country where agro-climatic and distance variables capture some of the remaining differences in variable costs. Climatic (average quarterly temperature and precipitation from 1993 to 2002), altitude, and soil type data were provided by IPEA. These data were collected for year 1995 and since then some municipalities in Brazil have been created through emancipation. In other words, the geographical units in 2006 do not match with the geographical units in the agro-climatic dataset. To address this, two assumptions related to the soil data collected in 1995 are made. First, municipalities that had split since then share the same soil characteristics as those in the original municipality. Second, average municipality soil characteristics have not changed during the decade preceding the latest agricultural census. Finally, municipalities that did not exist in 1995 were dropped from the analysis. Future work will incorporate these municipalities as information becomes available regarding their origin.

Finally, macroeconomic data (GDP, GDP per capita, sectoral GDP, population) per municipality were obtained from IPEADATA (www.ipeadata.gov.br). The dataset was complemented with distances from each municipality to the Federal District (Brasilia) and to the nearest sea shore.[14] Tables 1 and 2 respectively describe and summarize the data used in the analysis.

ECONOMETRIC RESULTS

Equations for sugarcane, soybeans and forest were estimated using lognormal Tobit whereas equations for pasture and other crops using ordinary least squares. Therefore the comparison of results across equations based on the regression coefficients is not straightforward. In order to facilitate this comparison across equations the corresponding land allocation elasticities are presented in Table 3 (detailed results from Tobit and OLS models are available from the authors upon request).

From Table 3, goodness of fit of our models is generally satisfactory, with many regressors presenting the expected signs and significance at the usual levels. Pseudo-R-square statistics (R-square in OLS equations) are typical of cross-sectional analysis. The positive exception is the unusually high goodness of fit of the pasture equation, indicating that the explanatory variables in our model explain 92.6% of the observed land allocation for pasture.

Own-price elasticities are positive and statistically significant, as expected, except for the sugarcane equation in which the own-price elasticity is negative but not statistically significant. These results indicate that, except for sugarcane, a marginal increase in output price, all other factors being constant, increases the land allocation of the corresponding output. The observed own-price effect is especially large for soybeans (land allocation elasticity equal to 1.075). The impact of sugarcane price (relative to other crops) is not significant in any equation except forest. The ineffective performance of sugarcane price raises a number of conjectures. It can partially be explained by the multiple use of this crop in some regions in Brazil as sugarcane can be used for ethanol and sugar production, depending on the market prices of these commodities at the time of harvesting. This fact may allow producers to put less importance on sugarcane prices when deciding their land allocation for sugarcane since risks are reduced by the double use characteristic of this crop. In fact, high variability of all of the price estimates is observed, even when aggregated at the state level. This is a limitation of our dataset that perhaps affects the sugarcane equation more than others. Secondly, it is likely that endogeneity may play a negative role in our model, since prices are assumed to determine land allocation and it may be the case that for sugarcane the amount of output (and therefore the amount of land allocated) drives the price of sugarcane. Finally, it may be the case that for sugarcane the appropriate price to be used is the lagged-price, i.e. that farmers determine their land allocation driven by crop prices in the previous year[15].

A particularly relevant result for the objectives of our study is that price of soybeans and cattle affect negatively and significantly land allocation for forest. However, price of timber impacts negatively land allocation for pasture but positively all other land uses, including soybeans. This latter result suggests that cross-price effects are not symmetric in our model, as expected in the case of fixed allocatable inputs.

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[14] Road distance to the capital and road distance to the nearest sea shore are included to approximate the level of access to markets for agricultural goods, cattle and timber. Another good proxy would be the road density in the municipality, as suggested by a reviewer. However, we believe that the two road-distance variables included together with those representing the topography of the area, rain precipitation and soil type, incorporate the most important spatial characteristics of the municipalities in Brazil.

[15] The lagged-price effect is likely to be true for all crops. However, the Agricultural Census is undertaken every five years in Brazil, which makes it impossible to estimate lagged prices in such a large period difference. It is possible, however, to estimate lagged agricultural prices by using a different data source, the Pesquisa Agrícola Municipal – PAM, which is undertaken every year. This may be an interesting improvement for future versions of the model.

TABLE 1 *Data description*

variable	description
p_sugarcane [1]	State-level sugar cane price (R$ 1 000 / ton)
p_soybeans [1]	State-level soybeans price (R$ 1 000 / ton)
p_cattle [1]	State-level cattle price (R$ 1 000 / head)
p_timber [1]	State-level timber and wood price (R$ 1 000 / 1 000 m^3)
wages [1]	State-level average annual salary paid per family and non-family worker (R$ 1 000)
a_sugarcane	Area of the municipality used to grow sugarcane (hectares)
a_soybeans	Area of the municipality used to grow soybeans (hectares)
a_pasture	Area of the municipality that is pasture (hectares)
a_forest	Area of the municipality that is forest (hectares)
a_crops	Area of the municipality used to grow other crops (hectares)
a_municip	Total area of the municipality (hectares, excluding constructed areas)
Aggdp	Share of total GDP from agriculture (%) in the municipality
dist_shore	Distance from municipality to the nearest shore (meters)
dist_captl	Distance from municipality to Brasilia-DF (km)
temp1	1993–2002 municipality average temperature for Dec–Feb (°C)
temp2	1993–2002 municipality average temperature for Mar–May (°C)
temp3	1993–2002 municipality average temperature for Jun–Aug (°C)
temp4	1993–2002 municipality average temperature for Sep–Nov (°C)
prec1	1993–2002 municipality average precipitation for Dec–Feb (millimeters)
prec2	1993–2002 municipality average precipitation for Mar–May (millimeters)
prec3	1993–2002 municipality average precipitation for Jun–Aug (millimeters)
prec4	1993–2002 municipality average precipitation for Sep–Nov (millimeters)
Altitude	Average altitude (meters) in the municipality
perc_alt2	% of municipality area between 100 and 199 meters high
perc_alt3	% of municipality area between 200 and 499 meters high
perc_alt4	% of municipality area between 500 and 799 meters high
perc_alt5	% of municipality area between 800 and 1199 meters high
perc_alt6	% of municipality area between 1200 and 1799 meters high
perc_agpot2	% of municipality classified as level 2 agricultural potential
perc_agpot3	% of municipality classified as level 3 agricultural potential
perc_agpot4	% of municipality classified as level 4 agricultural potential
perc_agpot5	% of municipality classified as level 5 agricultural potential
perc_soil1	% of municipality area with class 1 soil type
perc_soil2	% of municipality area with class 2 soil type
perc_soil3	% of municipality area with class 3 soil type
perc_soil4	% of municipality area with class 4 soil type
perc_soil5	% of municipality area with class 5 soil type
perc_soil6	% of municipality area with class 6 soil type
perc_soil7	% of municipality area with class 7 soil type
perc_soil8	% of municipality area with class 8 soil type
perc_soil9	% of municipality area with class 9 soil type
perc_soil10	% of municipality area with class 10 soil type

Note: (1) Price relative to state-level "other crops" price; all data refer to year 2006.

TABLE 2 *Descriptive summary of data*

Variable	mean	standard deviation	minimum	maximum
p_sugarcane	0.215	0.195	0.028	2.277
p_soybeans	1.294	1.012	0.259	6.336
p_cattle	1.478	0.681	0.363	3.444
p_timber	32.657	19.632	5.042	70.752
wages	4.933	5.834	0.385	18.938
a_sugarcane	969.33	4 552.20	0.00	87 337.00
a_soybeans	2 741.71	13 379.80	0.00	443 921.00
a_pasture	30 120.38	83 146.24	0.00	369 3974.00
a_forest	7 303.04	18 445.32	0.00	368 493.00
a_crops	7 500.59	11 651.47	0.00	266 541.00
a_municip	48 635.05	100 195.20	0.00	4 026 075.00
Aggdp	0.217	0.143	0.00	0.788
dist_shore	346 225.60	352 174.30	0.00	2 494 990.00
dist_captl	1 392.123	623.557	0.00	4 600.000
temp1	25.354	1.713	18.690	28.716
temp2	23.565	2.720	15.552	27.760
temp3	20.998	4.082	11.234	28.494
temp4	23.984	3.229	14.689	30.353
prec1	181.140	79.934	29.070	413.713
prec2	128.300	59.434	29.144	488.084
prec3	61.202	57.623	0.023	424.880
prec4	106.471	54.721	2.258	268.464
Altitude	417.697	293.224	0.00	1 628.000
perc_alt1	0.148	0.320	0.00	1.00
perc_alt2	0.126	0.248	0.00	1.00
perc_alt3	0.356	0.387	0.00	1.00
perc_alt4	0.269	0.342	0.00	1.00
perc_alt5	0.093	0.220	0.00	1.00
perc_alt6	0.007	0.042	0.00	0.50
perc_agpot1	0.075	0.238	0.00	1.00
perc_agpot2	0.108	0.266	0.00	1.00
perc_agpot3	0.004	0.056	0.00	1.00
perc_agpot4	0.567	0.426	0.00	1.00
perc_agpot5	0.246	0.368	0.00	1.00
perc_soil1	0.296	0.389	0.00	1.00
perc_soil2	0.108	0.269	0.00	1.00
perc_soil3	0.008	0.081	0.00	1.00
perc_soil4	0.003	0.047	0.00	1.00
perc_soil5	0.009	0.070	0.00	1.00
perc_soil6	0.321	0.397	0.00	1.00
perc_soil7	0.034	0.159	0.00	1.00
perc_soil8	0.120	0.265	0.00	1.00
perc_soil9	0.030	0.155	0.00	1.00
perc_soil10	0.039	0.165	0.00	1.00

TABLE 3 *Land allocation elasticities*

variable	sugarcane	soybeans	pasture	forest	other crops
p_sugarcane	–0.049 (0.075)	–0.136 (0.220)	–0.008 (0.031)	0.219 (0.037)***	–0.049 (0.035)
p_soybeans	–0.477 (0.116)***	1.075 (0.363)***	0.060 (0.013)***	–0.315 (0.053)***	–0.160 (0.026)***
p_cattle	–0.112 (0.239)	1.592 (0.609)***	0.336 (0.046)***	–1.242 (0.105)***	–0.367 (0.072)***
p_timber	0.556 (0.209)***	0.898 (0.419)**	–0.272 (0.077)***	0.422 (0.116)***	0.211 (0.112)*
wages	0.302 (0.106)***	–0.647 (0.228)***	0.055 (0.038)	–0.215 (0.059)***	0.006 (0.055)
a_municip	0.143 (0.048)***	0.874 (0.110)***	1.279 (0.072)***	0.395 (0.110)***	0.290 (0.111)***
aggdp	–0.302 (0.085)***	1.128 (0.194)***	–0.000 (0.029)	0.074 (0.047)	0.048 (0.048)
dist_shore	0.174 (0.126)	2.254 (0.332)***	–0.017 (0.056)	0.066 (0.084)	0.127 (0.091)
dist_captl	–0.650 (0.279)**	–7.296 (0.738)***	–0.193 (0.100)*	0.343 (0.161)**	–0.061 (0.183)
temp1	–16.603 (4.453)***	24.773 (12.175)**	6.743 (1.216)***	–2.821 (2.122)	–4.978 (1.977)**
temp2	18.119 (4.811)***	–107.048 (11.474)***	–2.303 (1.151)**	–6.396 (2.136)***	–0.277 (1.755)
temp3	–32.034 (3.604)***	–2.865 (9.379)	1.540 (0.710)**	6.793 (1.561)***	–0.731 (1.234)
temp4	33.283 (4.255)***	55.885 (11.769)***	–3.551 (0.867)***	–2.312 (1.913)	2.146 (1.540)
prec1	1.417 (0.454)***	–12.455 (1.205)***	0.843 (0.110)***	–2.235 (0.228)***	–1.437 (0.196)***
prec2	–1.488 (0.399)***	8.420 (1.040)***	–0.480 (0.127)***	1.014 (0.217)***	0.900 (0.219)***
prec3	0.584 (0.184)***	–0.525 (0.516)	0.130 (0.035)***	–0.529 (0.082)***	–0.196 (0.063)***
prec4	–0.961 (0.387)**	8.007 (0.983)***	–0.357 (0.092)***	0.646 (0.169)***	0.081 (0.177)
altitude	0.204 (0.179)	2.030 (0.383)***	–0.060 (0.034)*	–0.066 (0.083)	0.162 (0.058)***
perc_alt2	–0.062 (0.043)	0.092 (0.114)	0.023 (0.005)***	0.084 (0.019)***	–0.066 (0.013)***
perc_alt3	–0.627 (0.109)***	–0.084 (0.297)	0.028 (0.018)	0.291 (0.052)***	–0.230 (0.034)***
perc_alt4	–0.636 (0.107)***	–0.365 (0.262)	–0.012 (0.016)	0.364 (0.052)***	–0.097 (0.031)***
perc_alt5	–0.308 (0.052)***	–0.507 (0.121)***	0.007 (0.007)	0.082 (0.025)***	–0.031 (0.014)**
perc_alt6	–0.040 (0.010)***	–0.173 (0.045)***	0.005 (0.001)***	0.003 (0.004)	–0.017 (0.002)***
perc_agpot2	0.021 (0.034)	–0.260 (0.074)***	0.004 (0.006)	0.049 (0.017)***	–0.019 (0.011)*

TABLE 3 *Continued*

variable	sugarcane	soybeans	pasture	forest	other crops
perc_agpot3	–0.003 (0.004)	–0.044 (0.026)*	0.004 (0.002)*	–0.001 (0.003)	–0.006 (0.003)**
perc_agpot4	–0.515 (0.165)***	–1.224 (0.374)***	0.036 (0.033)	0.284 (0.083)***	–0.099 (0.058)*
perc_agpot5	–0.088 (0.091)	0.240 (0.233)	0.029 (0.013)**	0.021 (0.042)	–0.099 (0.026)***
perc_soil1	0.860 (0.156)***	–0.349 (0.461)	–0.028 (0.032)	–0.335 (0.064)***	–0.123 (0.071)*
perc_soil2	0.189 (0.058)***	0.056 (0.168)	–0.020 (0.011)*	–0.023 (0.024)	–0.020 (0.026)
perc_soil3	–0.020 (0.007)***	0.046 (0.015)***	0.002 (0.001)	–0.008 (0.003)***	–0.005 (0.002)**
perc_soil4	–0.006 (0.006)	–0.529 (0.133)***	0.002 (0.001)	–0.010 (0.004)***	–0.005 (0.002)**
perc_soil5	0.023 (0.009)***	–0.053 (0.041)	–0.000 (0.002)	–0.010 (0.005)*	0.001 (0.005)
perc_soil6	1.051 (0.174)***	1.718 (0.500)***	–0.124 (0.035)***	–0.281 (0.071)***	–0.005 (0.077)
perc_soil7	0.005 (0.022)	–0.156 (0.072)**	–0.007 (0.003)*	0.005 (0.009)	–0.007 (0.008)
perc_soil8	0.104 (0.061)*	0.007 (0.179)	–0.031 (0.013)**	0.013 (0.024)	0.004 (0.031)
perc_soil9	0.049 (0.020)**	0.134 (0.049)***	–0.014 (0.004)***	–0.026 (0.008)***	–0.007 (0.008)
perc_soil10	–0.105 (0.027)***	0.234 (0.072)***	–0.002 (0.004)	–0.035 (0.011)***	–0.004 (0.011)
pseudo-R2	0.072	0.273	0.926	0.115	0.206
N	4 891	4 891	4 891	4 891	4 891
N (y=0)	1 736	3 691	11	125	5

Elasticities calculated at mean values from lognormal Tobit (sugarcane, soybeans and forest) and OLS (pasture and crops). Robust standard errors in parentheses.
Significance at the 1%, 5%, and 10% level denoted by ***, ** and * respectively.

The elasticities of area in a given use with respect to total land are all statistically significant and positive, as expected since they measure the additional allocation in a specific land use given a marginal increase in total land. Our land allocation elasticity results show that pasture and soybeans present a much higher elasticity in regard to total agricultural land than other land uses. For example, an extra hectare of agricultural land corresponds to an increase of 0.7922 hectare of pasture. One especially relevant and positive result of our study concerns the additive property of total land allocation (physical constraint, equation 4). In other words, the coefficients of land constraint should sum up to one when all land uses are accounted for.

Wages have a mixed impact in our land allocation equations. Coefficients for wages (our input price) are not statistically significant for pasture and other crops, perhaps reflecting the lower labor intensity of these activities, especially cattle ranching. However, wages are statistically significant for sugarcane, soybeans and forest. The negative sign of this coefficient in the soybean equation reflects the high level of mechanization in soybean plantations in Brazil. The positive effect of wages in land allocation for sugarcane (a labor intensive activity), may be driven by the fact that sugarcane is mostly produced in the state of São Paulo, a highly industrialized region where wages are certainly above the national level, in all sectors of the economy.

Finally, climate (temperature and precipitation) and soil coefficients are in general statistically significant, confirming that these factors are important for farmers' land allocation among the different land uses. It is difficult, however, to figure out the expected signs of these coefficients because location-specific physical variables in a multi output production model (with fixed, allocatable inputs) measure a municipality's comparative advantage in producing a crop rather than its absolute advantage (Moore and Negri 1992).

POLICY IMPLICATIONS OF ECONOMETRIC RESULTS FOR REDD

The relevance of these results for a program such as REDD are not straightforward. Nevertheless the paper has some important policy implications, which we illustrate in this section. The cross section of data is assumed to represent the current "equilibrium" of land use in Brazil between different crops and forest. In the future, changes in this pattern (in particular a loss of forest) will be driven (inter alia) by expected increases in the prices of soya, cattle, sugarcane and other crops relative to forest. Hence any program that offers an incentive to maintain standing forest in that form has to be judged relative to the incentives that may exist to clear the forest and convert it to agriculture.

It is difficult to know what the incentives are likely to be for clearance but, as an example, the following two are considered: 1) an expected increase in the price of cattle of 10% and 2) an expected increase in the price of soybeans of 10%. The results of applying the elasticities in Table 3 allow us to calculate the change in land areas.[16] To be sure these changes depend on the baseline values of areas in the municipality under each crop. For the purposes of illustration consider a "typical" area with the average values of pasture and of each crop, as given in Table 2[17]. Furthermore, assume three levels of payment for the avoided deforestation in terms of US$ per ton of CO2 avoided: US$5, US$10 and US$20. These payments need to be converted into payments per hectare of forest, which has been done using parameters given in the notes to Table 4. The REDD payments are then compared against the net present value of the return from the land under ranching or soya. The results of changes in land converted are shown in that Table.

The higher prices for soybeans and cattle do indeed result in some clearance in our simulation (around 9 percent in the case of cattle prices and 6 percent in the case of soya prices). At the same time they also result in shifts in other crops (following the results generated in this paper[18]). These impacts can, however, be reduced if there is a REDD premium for holding forest as standing timber. The first set of calculations for the price of cattle shows that a modest price of US$5 would act to reduce the amount of deforestation by 60 percent (from 678 ha. to 272 ha.). Further increases in REDD reduce the amount deforested, so with a US$20 payment the amount cleared is only 5 percent of what it would be without any payment.

In the case of soya the impact of REDD is similar. The US$5 payment reduces the amount of deforestation by about 75 percent and a payment of US$20/ton reduces it by 97 percent[19].

These results can be compared with those of many others who have attempted to estimate the impacts of different REDD programs on deforestation. In the two global models used in the Eliasch Review (Eliasch 2008), the carbon prices that would halve forest emissions are in the range of US$11 and US$15 per ton of CO2, reflecting differences in the costs of components and how the program is designed. In comparison, Börner and Wunder (2008), in a local-empirical study in two states in Brazil, estimate a 'choke price' (that would prevent all deforestation) at US$12.34 in Mato Grosso and US$3.24 in Amazonas. Another study of the whole Brazilian Amazon (Nepstad et al. 2007; Nepstad 2009) produces much lower costs still, finding that 90 per cent of the forest emissions can be abated for less than US$1.4/t CO2 (US$5/t C). At a local level for Brazil, Olsen and Bishop (2009), estimate a range of values for the opportunity cost of land, depending on possible alternative uses. These range from almost nothing for beef cattle production to US$ 2.6 tCO2e and between US$2.5 and $3.4/tCO2e for soybean production. Tree plantations present high returns, but cover only a small area of the Amazon. As approximately 80% of recently deforested land is used for cattle ranching, they argue that the scope for achieving cost-effective reductions in CO2e emissions through avoided deforestation is high.

Our model allows for a somewhat different analysis. As the first model that looks at land use allocations of all significant land-use types driving deforestation in Brazil in an overall profit making structure, it offers the possibility to examine combinations of changes in future incentives for deforestation. The need to look at the problem in a dynamic context is emphasized, in which case deforestation will be driven by expected changes in the prices of crops. Furthermore, few of the researchers have incorporated in their models the wide variations in returns within a region or country. Olsen and Bishop recognize the variability across provinces but as our data shows there are also considerable variations within a province or indeed even within a municipality.

These are of course only just examples, and there could be many other incentives that motivate forest clearance. We should note that price shocks could be much larger such that higher carbon prices would be needed to induce the ameliorating effects that REDD may have on deforestation in Table 4. The purpose of the calculation is to show how the

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16 Since we look at price changes for soya and cattle that affect profitability and therefore land allocation, the shadow price of land is not relevant in our simulations for deforestation occurring in private lands. The shadow price of land could be however relevant as the incentive that squatters have when deciding to move towards public land (forest) expecting to acquire land tenure rights.

17 When designing a REDD program it is important to account for potential leakages if the focus is on a small area only. Landowners may act to reduce deforestation in the areas covered by the agreement but if the price incentives are there, they could increase forest removal in other areas. Thus the examples, while they look at a typical area, would have to be part of a wider national program if such leakages are to be avoided.

18 According to the regressions the net changes in land should be zero. In practice they are not because applying the elasticities results in non-marginal changes; a scaling adjustment factor to bring the net changes to zero has been applied.

19 To capture the very real feature of land use (i.e. that profitability varies widely) a log normal distribution of profit per ha. is assumed, with the mean values as in Table 2 and a plausible standard deviation.

TABLE 4 *Impacts of a REDD Program on a Typical Municipality in Brazil*

Impact of a 10% expected increase in the price of cattle

Price of CO2 Under REDD $/Ton	Gain from REDD R$000/Ha.	Δ Forest Ha.	Δ Pasture Ha.	Δ Other land use Ha.	Net Change Ha.
0	0	–678	1 012	–334	0
5	8.037	–272	606	–334	0
10	16.075	–117	451	–334	0
20	32.149	–34	369	–334	0

Impact of a 10% expected increase in the price of soybeans

Price of CO2 Under REDD $/Ton	Gain from REDD R$000/Ha.	Δ Forest Ha.	Δ Soya Ha.	Δ Other land use Ha.	Net Change Ha.
0	0	–396	295	101	0
5	8.037	–98	–3	101	0
10	16.075	–37	–64	101	0
20	32.149	–10	–91	101	0

Assumptions and Data on which calculations are based:

1.	Mean forest area:	7 303 ha.
2.	Mean area soya:	2 741 ha.
3.	Mean area of pasture:	30 120 ha.
4.	Tons of carbon per cubic meter:	0.7
5.	Tons of CO2 per ton carbon:	3.67
6.	Tons of carbon per Ha of forest:	200 (http://news.mongabay.com/2007/0508-amazon.html)
7.	Price per head of cattle:	1.6258 R$ (000) (10% above figure in table 2)
8.	Cattle per ha.	1.1 (Soares Filho, 2011)
9.	Profit margin per cattle:	0.35 (From Table 2 in Somwaru, A and C. Valdes (2004))
10.	Mean profit per cattle/Year:	0.6259 R$ (000). Based on above assumptions
11.	SD of profit per cattle:	2.72
12.	NPV of Profit from pasture:	Lognormal distribution with mean 1.83 and SD 1.0
13.	Price of soya:	1.4234 R$ (000) (10% above figure in table 2)
14.	Yield of soya:	2.67 Ton/Ha. http://en.mercopress.com/2012/03/20/drought-punishing-soy-crops-and-yields-in-southern-brazil
15.	Profit margin of soya	0.1 (http://www.cpac.embrapa.br/noticias/artigosmidia/publicados/359/)
16.	Mean Profit from Soya/Year	0.38 R$ (000). Based on above assumptions
17.	SD of profit from soya	3.0
18.	NPV of profit from soya/Year	Log normal distribution with mean 1.34 and SD 1.1
19.	Discount rate:	10%

results obtained here may be applied at the municipality level to get some idea of the likely impacts of programs such as REDD and what the main factors are. Other factors not taken into account here are the permanence of the increase in prices or the costs of meeting the REDD conditions and expectations of future carbon prices. Expectations of these price trends can be derived from historic data, as can trends of prices of the key agricultural outputs. These can be built into the models that evaluate the impacts of such programs along the lines we have set out.

CONCLUSIONS

This paper introduces a land-use model that measures the impact of economic and physical variables on farmers' decisions about the allocation of their land among competing uses. It is based on a multi-output land allocation model with agricultural land as fixed and allocatable input. For the first time, to the best of our knowledge, such a land allocation model that explicitly separates all main competing uses for forest in Brazil – soybeans, sugarcane and pasture has been estimated.

Appropriate econometric models were implemented to deal with a large number of zeros and nonlinearities in the dependent variables.

The results suggest a clear substitution effect between land allocation for forest and soybeans, and for forest and pasture. However, a limitation of our model regards the non-significant coefficients obtained for land allocation for sugar-cane; and the high variability observed for our price estimates. A number of possibilities are foreseen to improve this land-use model in the near future and overcome the current limitations: (i) using lagged prices for agricultural goods obtained from complementary data sources available, which leads us to also investigate the possibility of introducing some time dynamics to the model (a panel data analysis); (ii) introducing more relevant county-level characteristics in the model, such as indicators of cattle intensity, historic rate of deforestation and legal constraints (e.g. the Forest Code requirements for Legal Forest Reserve)[20].

Two examples of the kinds of impacts that can be expected from REDD programs in private land were provided. Additionally, simulations with our model can predict the long run land allocation among the five uses in our model given different output prices. The coefficients estimated in our models can also be used to estimate the shadow price of land; i.e. the price that farmers would be willing to pay for an extra hectare of land, corresponding to their expected profit from an extra hectare of (forest) land. These correspond to the opportunity costs of deforestation in Brazil, and can be used to derive a REDD curve for Brazil where an important share of deforestation takes place in public land.

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[20] For example, in the Legal Amazon region the Forest Code requires that 50% of the property has to be covered by forest.

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