The effects of crop-to-beef relative prices on deforestation: evidence from the Tapajós Basin

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ONLINE APPENDIX

Appendix A. Proofs

This appendix presents the proofs of the two propositions presented in the theoretical framework discussed in section 3.

Proof of Proposition 1

Land allocation can be described using the following inequalities:

- Forest $\iff$ $\pi_b(A_i) < 0$ and $\pi_s(A_i) < 0$
- Pasture $\iff$ $\pi_b(A_i) > 0$ and $\pi_b(A_i) > \pi_s(A_i)$
- Cropland $\iff$ $\pi_s(A_i) > 0$ and $\pi_s(A_i) \geq \pi_b(A_i)$

The assumption $1 < \Delta(P_s/P_b) < (wl_s - rk_s)/(wl_b - rk_b)$ ensures that $\pi_s(A_i) < 0$ whenever $\pi_b(A_i) < 0$. It also ensures that $\pi_s(A_i) > 0$ whenever $\pi_s(A_i) \geq \pi_b(A_i)$. Hence, the inequalities above can be reduced to:

- Forest $\iff$ $\pi_b(A_i) < 0$
- Pasture $\iff$ $\pi_b(A_i) > 0$ and $\pi_b(A_i) > \pi_s(A_i)$
- Cropland $\iff$ $\pi_s(A_i) \geq \pi_b(A_i)$

The inequalities above can be expressed as a function of A_i. The first expression can be written as:

$$A_i < \underline{A} = \frac{wl_b + rk_b}{P_b} \tag{A.1}$$

The third expression can be written as:

$$A_i < \overline{A} = \frac{w(l_s - l_b) + r(k_s - k_b)}{\Delta P_s - P_b} \tag{A.2}$$

Notice that the thresholds above can also be used to re-write the second expression. Therefore, these limits determine the land allocation as stated in Proposition 1. Land remains as forest when $A_i < \underline{A}$ and is used as pasture when $\underline{A} \leq A_i < \overline{A}$ and as cropland when $A_i \geq \overline{A}$.

Proof of Proposition 2

Let the relative price be $P = P_s/P_b$. Define the price of beef as the numeraire and write the cost function having a composite input called I with price θ. The input intensities continue to differ across activities with $I_s > I_b$. The thresholds $\underline{A}$ and $\overline{A}$ can be re-written as:

$$\underline{A} = \theta I_b \tag{A.3}$$

$$\overline{A} = \frac{\theta(I_s - I_b)}{\Delta P - 1} \tag{A.4}$$

The effect of an increase in relative prices on land allocation is:

$$\frac{d\underline{A}}{dP} = I_b \frac{d\theta}{dP} \tag{A.5}$$

$$\frac{d\overline{A}}{dP} = -\Delta \frac{\theta(I_s - I_b)}{(\Delta P - 1)^2} + \frac{d\theta}{dP}\frac{I_s - I_b}{\Delta P - 1} \tag{A.6}$$

The equations above make clear that the effect of relative prices on land use depends on its effect on input prices. Let $D(\theta)$ and $S(\theta)$ be the demand and supply of the composite input. Notice that $D(\theta) = I_s A_s + I_b A_b$ and that $S'(\theta) > 0$. Market clearing implies that $D(\theta) = S(\theta)$. Using the implicit function theorem on this equilibrium it is possible to determine the impact of relative prices on input prices:

$$\frac{d\theta}{dP} = \frac{\Delta g(\overline{A})\theta\left(\frac{I_s - I_b}{\Delta P - 1}\right)^2}{S'(\theta) + I_s g(\overline{A})\left(\frac{I_s - I_b}{\Delta P - 1}\right) - I_b g(\overline{A} - \underline{A})\left(\frac{I_s - I_b \Delta P}{\Delta P - 1}\right)} > 0 \tag{A.7}$$

Both the numerator and denominator are greater than zero in the expression above. This result comes from the problem's assumption $1 < \Delta P < I_s / I_b$.

The effect of relative prices on $\overline{A}$ will be negative whenever $d\overline{A}/dP < \Delta\theta/(\Delta P - 1)$. Notice that:

$$\frac{d\theta}{dP} < \frac{\Delta g(\overline{A})\theta((I_s - I_b)/(\Delta P - 1))^2}{I_s g(\overline{A})((I_s - I_b)/(\Delta P - 1))} = \frac{\Delta\theta}{(\Delta P - 1)}(1 - I_b/I_s) < \frac{\Delta\theta}{(\Delta P - 1)} \tag{A.8}$$

Equations (A.7) and (A.8) ensure that $\overline{A}$ will fall as relative prices increase while equation (A.7) proves that $\underline{A}$ will increase as these prices increase. These results prove that an increase in relative prices increases cropland and forest area and reduces pasture area, i.e., it establishes the result in Proposition 2.

Appendix B. Basic Correlations

This appendix presents the bivariate relationships between relative prices and deforestation, soy cultivation, and cattle ranching. These relationships are discussed in subsection 4.3.

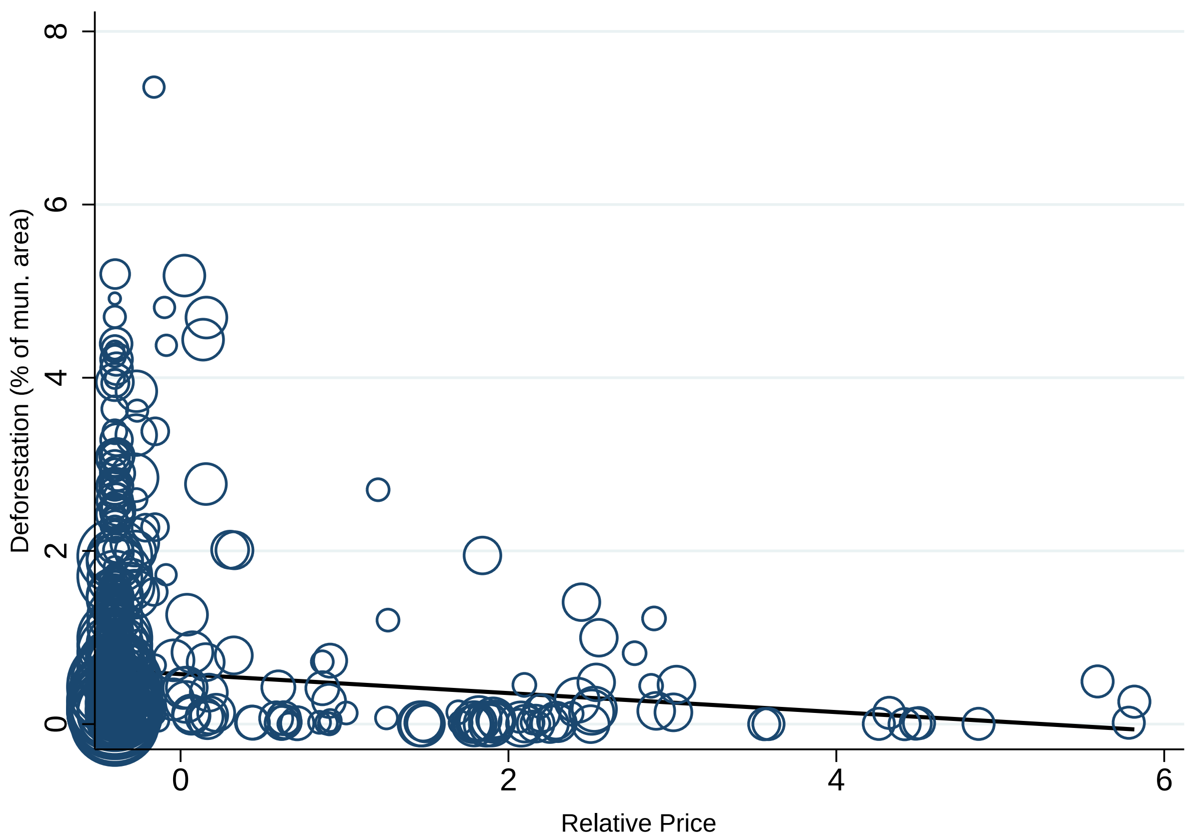

Figure A1. Relative prices and deforestation

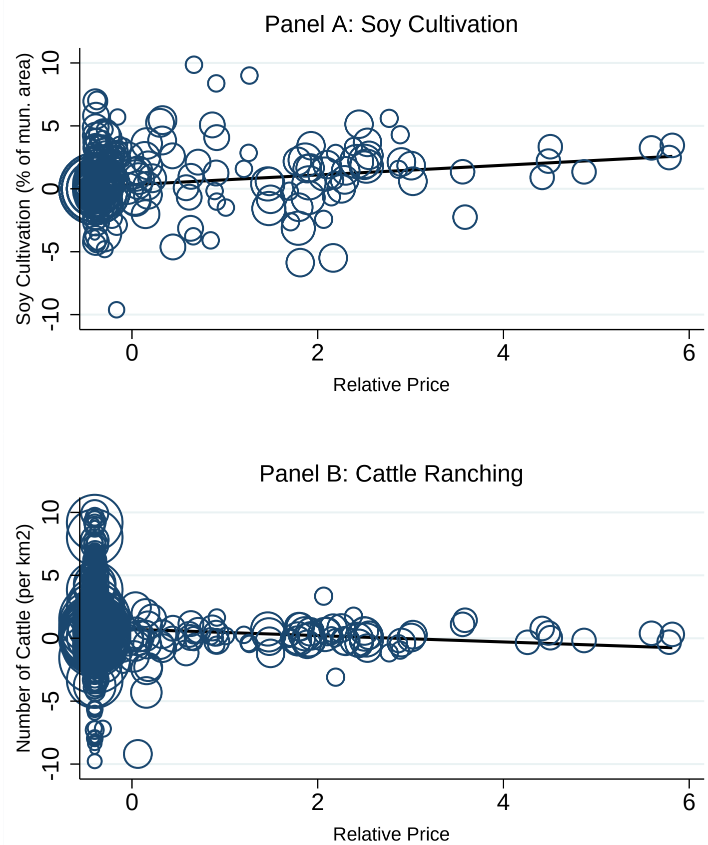

Figure A2. Relative prices and agricultural activities

Appendix C. Robustness to Price Indexes, Weights and Standard Errors

This appendix discusses in detail the robustness of the results to different definitions of the price index, different weighting procedures, and different methods for estimating the standard errors. These robustness tests are briefly discussed in subsection 6.3.

We begin by discussing the robustness of the results to different definitions of the price index. The baseline price indexes combine initial information on soy and beef production with price information to produce local price indexes for these agricultural products. The intuition for these indexes is that price changes will affect more municipalities that are more specialized in a particular product. These indexes can be interpreted as "Laspeyres price indexes" because of the use of initial information. These indexes will typically underestimate (overestimate) the magnitude of the price changes in municipalities in which crop cultivation or cattle ranching are increasing (decreasing). Therefore, it is useful to examine the robustness of the results to using "Paasche price indexes" that use information on soy and beef production at the end of the period under analysis.

Table A1, columns 1-2 report the results of using "Paasche price indexes" instead of "Laspeyres price indexes". Column 1 reports the results of a regression using only municipality fixed effects, year fixed effects, and price levels as controls while column 2 reports the results of a regression using the full set of controls included in the table 3. The effect of relative prices continues negative with comparable magnitudes to the ones estimated in main specification. The effect from column 1 is significant at the 10% level (p-*value* = 0.079) and almost significant at this level in column 2 (p-*value* = 0.102). These results indicate that the results are robust to using information on soy and beef production in the beginning or the end of the period under analysis to construct the price indexes.

The price index will be zero for all municipalities with no production in the baseline. This is not a problem for the beef price index because there is cattle ranching in all municipalities in all periods. However, it is a potential problem for the soy price index because the number of municipalities producing this crop increases in the period. To deal with this issue, initial crop cultivation instead of initial soy cultivation is used in order to calculate local prices. Table A1, columns 3-4 present the results. Column 3 reports the results of a regression using only municipality fixed effects, year fixed effects, and price levels as controls while column 4 reports the results of a regression using the full set of controls included in the table 3. Coefficients and standard errors are similar to the ones obtained in table 3. This suggests that the estimates are robust to the method employed to define soy and beef production.

Furthermore, other potential issue with the price index is that it excludes maize prices in its construction. However, the descriptive statistics indicate that maize cultivation is also relevant in the region both in levels and rate of expansion. This suggests maize prices might also be relevant in determining relative prices across the Tapajós Basin. The analysis addresses this potential problem by using the average between maize and soy prices in the construction of the relative price index. Table A1, columns 5-6 reports the results of regressions using prices indexes constructed using this method. Column 5 reports the results of a regression using only municipality fixed effects, year fixed effects, and price levels as controls while column 6 reports the results of a regression using the full set of controls included in table 3.

The results are quite close to the ones from the main specification both in terms of magnitude and significance of the effect of relative prices. These findings indicate that maize and soy expansion are correlated since there are agronomic benefits to rotating land between these crops (Livingston *et al.*, 2008). The estimates also corroborate the literature on agricultural expansion in Brazil which suggests that maize cultivation is a product of soy cultivation in the Brazilian agricultural frontier (Assunção and Bragança, 2015).

It is also important to examine whether the estimates are robust to the weighting procedure. The baseline weights are constructed using the idea that the statistical analysis should weight more observations in larger municipalities without enabling larger municipalities to drive the results. Table A2 re-estimates our baseline regressions exploring alternative weighting methods: municipal area (columns 1 and 2) and no weights (columns 3 and 4).

Coefficients on relative prices are negative across all specifications in table A2. Columns 1 and 2 provide evidence that magnitudes rise when greater emphasis is placed on larger municipalities. Columns 3 and 4 indicate that magnitudes fall when less emphasis is placed on these municipalities. Nevertheless, standard errors are small in general with estimates significant across all specifications. The overall evidence seems to suggest that the results are not affected by the choice of the weighting scheme.

A final specification test investigates whether inference is robust to allowing spatial dependence in the error term. Table A3 examines this issue and re-estimates standard errors using the Conley (1999) procedure to allow for spatial correlation of the error term. Standard errors have been computed using three different cut-offs: 100 kilometers, 300 kilometers and 500 kilometers. Conley (1999) standard errors are smaller than the baseline standard errors for all distance cut-offs considered and estimates are significant at 5% level. Thus, it is possible to conclude that the main empirical exercise uses a conservative method for estimating the estimators' standard errors.[5]

[5] Hsiang (2010)'s code is used to estimate these spatial standard errors in a panel setting.

Table A1. Relative prices and deforestation in the Tapajós Basin - alternative price indexes

	Annual Deforestation (% of municipal area)					
	Paasche Index		Maize + Soy Area		Maize + Soy Prices	
	(1)	(2)	(3)	(4)	(5)	(6)
Alternative Soy to Beef relative Price Index (t-1)	-0.553*	-0.553	-0.669***	-0.424*	-0.661***	-0.436*
	(0.308)	(0.332)	(0.203)	(0.232)	(0.176)	(0.226)
Price Controls	Yes	Yes	Yes	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Initial Forest Area	No	Yes	No	Yes	No	Yes
State-Specific Trends	No	Yes	No	Yes	No	Yes
Coverage Variables	No	Yes	No	Yes	No	Yes
R-Squared	0.55	0.67	0.55	0.67	0.55	0.66
Number of Municipalities	49	49	49	49	49	49
Number of Observations	539	539	539	539	539	539

Notes: Each column reports the results of regressing annual deforestation on the soy-to-beef relative price index conditional on soy and beef price indexes and a set of additional covariates. Columns 1 and 2 use price indexes constructed combining soy cultivation and beef production in the end of the sample period with aggregate soy and beef price variation. Columns 3 and 4 use price indexes constructed combining soy and maize cultivation and beef production in the beginning of the sample period with aggregate soy and beef price variation. Columns 5 and 6 use price indexes constructed combining soy and maize cultivation and beef production in the beginning of the sample period with aggregate soy, maize, and beef price variation. All estimates use data from the 49 municipalities in the Tapajós Basin during the period 2002 to 2012. Observations are weighted by the square root of the municipal area. Standard errors clustered at the municipality level are reported in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table A2. Relative prices and deforestation - alternative weighting procedures

	Annual Deforestation (% of municipal area)			
	(1)	(4)	(5)	(8)
Soy to Beef Relative Price Index (t-1)	-0.536***	-0.556*	-0.739***	-0.336*
	(0.197)	(0.296)	(0.201)	(0.184)
Price Controls	Yes	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Initial Forest Area	No	Yes	No	Yes
State-Specific Trends	No	Yes	No	Yes
Coverage Variables	No	Yes	No	Yes
Weights	*Area*	*Area*	*None*	*None*
R-Squared	0.54	0.66	0.56	0.66
Number of Municipalities	49	49	49	49
Number of Observations	539	539	539	539

Notes: Each column reports the results of regressing annual deforestation on the soy-to-beef relative price index conditional on soy and beef price indexes and a set of additional co-variates. The soy price index is obtained by combining initial soy cultivation with aggregate price variation while the beef price index is obtained by combining initial number of cattle with aggregate price variation. All estimates use data from the 49 municipalities in the Tapajós Basin during the period 2002 to 2012. Columns 1-2 weight observations using the municipal area and Columns 3-4 do not weight observations. Standard errors clustered at the municipality level are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table A3. Relative prices and deforestation - spatial correlation in the error term

	Dependent Variable: Deforestation (% of mun. area)			
	(1)	(2)	(3)	(4)
Soy to Beef Relative Price (t-1)	-0.656	-0.618	-0.437	-0.441
	(0.117)***	(0.154)***	(0.131)***	(0.133)***
	[0.148]***	[0.171]***	[0.135]***	[0.135]***
	{0.169}***	{0.169}***	{0.136}***	{0.136}***
Price Controls	Yes	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Initial Forest Area	No	Yes	Yes	Yes
State-Specific Trends	No	No	Yes	Yes
Coverage Variables	No	No	No	Yes
R-Squared	0.55	0.55	0.66	0.66
Number of Municipalities	49	49	49	49
Number of Observations	539	539	539	539

Notes: Each column reports the results of regressing annual deforestation on the soy-to-beef relative price index conditional on soy and beef price indexes and a set of additional covariates. The soy price index is obtained by combining initial soy cultivation with aggregate price variation while the beef price index is obtained by combining initial number of cattle with aggregate price variation. All estimates use data from the 49 municipalities in the Tapajós Basin during the period 2002 to 2012. Observations are weighted by the square root of the municipal area. Conley's (1999) standard errors allowing for spatial correlation up to 100, 300 and 500 kilometers are reported in parentheses, brackets and curly brackets, respectively. *** p<0.01, ** p<0.05, * p<0.1.