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The Impact of Climate Change on the Brazilian Agriculture: A Ricardian Study at Microregion Level

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SUMMARY We use at microregion level from the Brazilian Census years 1975, 1985, 1995 and 2006 to assess the impact of climate change on Brazilian agriculture using a Ricardian model. We estimate the Ricardian model using repeated cross sections for each Census Year, a pooled model and a two-stage model based on Hsiao 2003. Results show that a marginal increase of temperature is harmful for agriculture in all regions of Brazil, with the exception of the South. The most negative impacts are felt in the North and in the North-East. There is mixed evidence on the effect of a marginal impact of precipitation. Additional rainfall is beneficial in South, South-East and in the Center-West. It is harmful in other regions. Impact estimates with three GCM scenarios generated using the A2 SRES emission scenario show that climate change is expected to be generally harmful in 2060. In 2100 only the climate change scenario generated by the Hadley HADCM3 model predicts negative impacts; the MIMR model predicts that climate change will not significantly affect land values while the NCPCM model predicts significant beneficial effects using the Hsiao model and non-significant beneficial effects using the pooled model. Among Brazilian regions, only the South and some cases the South-East are expected to benefit from climate change.

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1 INTRODUCTION

Brazil is one of the largest global producers of agricultural commodities. In 2010 Brazil was the third world producer of maize and the second producer of soybeans, two among the most important agricultural commodities. Brazil was the second global producer of tobacco, dry beans and papayas; the first producer of coffee, sugar cane, pineapples and oranges.[1]Animals production is also important. Brazil hosts large cattle, chicken and pigs operations. What will be the impact of climate change on this tropical agriculture powerhouse?

We exploit a unique panel of agricultural land values, socio-economic characteristics, soil and climatic data in Brazilian micro-regions from 1975 to 2006 to estimate how climate affects agricultural land values (Mendelsohn, Nordhaus, and Shaw 1994). We adopt a Ricardian framework. Land values are regressed on climate and other control variables to estimate the relationship between climate (the long-term average of weather) and land values. The method relies on the idea that land values reflect the long-term productivity of land if markets are well-developed. Changes of land values reflect welfare gains or welfare losses of the agricultural sector. Thus, by estimating how climate affects land values it is possible to derive the long-term impact of climate change on agriculture, assuming that all other factors that determine land values remain unchanged.

The Ricardian method assumes that farmers have adapted to different climatic conditions to maximize net revenues. Land values reflect the highest possible level of productivity that can be achieved at that climate, for any particular combination of soil characteristics, geography and other socio-economic variables. Thus, the method also assumes that farmers will efficiently adapt as climate changes. Farmers will adopt crops and methods that are now used by farmers that already face the climate that they will face in the future. The method does not provide information on what farmers actually do to adapt.

In this paper we provide a broad range of estimates of Brazilian agriculture to future climate change. We start by estimating the impact of marginal variations of temperature and precipitations. We then provide estimates of the marginal impact of future climate change on agriculture using three representative climate change scenarios for 2050 and 2100.

Agriculture has gone through remarkable transformations in Brazil. In a deliberate process to increase agricultural production and productivity new methods have been adopted, new crops with high productivity have substituted subsistence crops, new

[1]Source: FAO.

crop varieties have been expressly engineered with the intent to withstand high temperatures and thus allowing the expansion of agriculture in otherwise unproductive areas. The most visible result of this transformation is the revolutionary emergence of Mato Grosso (the Center-West of the country) as a major agriculture production area, a process started in the 1970s and still in progress. From the relatively areas of the Sul (South) and the Sudeste (South-East) the center of gravity of Brazilian agriculture has moved towards a hotter climate with a dry winter season.

We show how climate sensitivity of Brazilian agriculture has evolved over time by estimating four separate cross-sections of Brazilian agriculture for 1975, 1985, 1995 and 2006. These are snapshots of the Brazilian agriculture taken during a period of rapid socio-economic transformation. Land values have changed because agricultural productivity has increased but also because of changes in the distribution of population and because of economic growth. In order to control for these time trends and for specific factors that may have affected agriculture over time, we replicate the analysis exploiting both the cross-section and the intertemporal dimension of our panel. We follow Massetti and Mendelsohn (2011) and we estimate a two-stages model in which we separate the time varying from the time invariant variables and a pooled model in which all cross-sections are used to estimate a single set of climate coefficients.

The rest of the paper is structured as follows. Section 2 presents an overview of the transformations that have radically changed Brazilian agriculture since the 1970's. Section 3 presents the Ricardian model and illustrates how marginal and non-marginal impacts of climate change are calculated. Section 4 describes the dataset used for the analysis. Section 5 presents estimates of the Ricardian equation and marginal impacts of temperature and precipitations changes while Section6 presents non-marginal climate change impacts using three representative climate change scenarios. Conclusions follow.

2 THE TRANSFORMATIONS OF BRAZILIAN AGRICULTURE FROM 1975 TO 2006

The rapid change of productivity and of agricultural land extension in Brazil from 1975 to 1990 has deep roots. The modernization of Brazilian agriculture started in the 1950's with the import of modern machinery and inputs. The use of fertilizers and pesticides became widespread in large-scale commercial farms. In the 1960's Brazil followed the wave of the "Green Revolution" and further increased the mechanization and the scale of farm operations.

The transformation of Brazilian agriculture was centrally planned as part of the overall effort of industrialization on which the country invested in the 1950's and 1960's (Meyer and Braga, 2000). An industrial sector that provided inputs to and processed output of the agricultural sector was developed as a strategic complement of agricultural development. Subsidized rural credit and a devaluation of the exchange rate, especially in the 1970s, provided further stimulus to agricultural production. In the 1970's agriculture production was purposely separated in domestic and export production, with different subsidies and policies. Most importantly, Brazil invested heavily in agronomic research and in local agricultural extension services to provide technical assistance (Martine and Garcia, 1987).

The modernization process was not sponsored uniformly in all regions and for all crops and farm types. There was a deliberate choice of strategic areas, products and farm types (Silva, 1981; Neto, 1982; Mesquita, 2009). Rural credit was targeted to medium (from 100 to 1,000 hectares) and large farms (more than 1,000 hectares) at the expense of small producers. Medium and large farms accounted for 61% of total rural funding in 1970, 65.6% in 1980 and 50% in 1990 and 1995. Small farmers obtained 39% of funding in 1970 and 25% in 1995. The modernization effort was also geographically uneven. Most of the investments in mechanization were concentrated in Central-Southern Brazil, mainly in the states of Minas Gerais, Goiás, Rio de Janeiro, São Paulo, Paraná, Santa Catarina and Rio Grande do Sul (Neto, 1982). While the national average of fertilizer use in 1978 was 74 kg per hectare, in the state of São Paulo fertilizer use reached 180 kg per hectare. Industrialization and mechanization were also uneven across crops, with some national champions destined to foreign markets. In 1977, coffee, sugar cane and soybean consumed half of the total fertilizer used in the country (Neto, 1982).

2.1 CRISIS OF THE 1980S AND RECOVERY IN THE 1990S.

The global debt crisis at the end of the 1970s and at the beginning of the 1980s put an halt to the export-led, subsidized agricultural development model of Brazil.

From 1983 subsidies were reduced, if not totally eliminated in all sectors. The interest rate on loans became positive in 1984 to reflect the actual cost of credit, for the first time after many years. From an average 7.4% growth rate in the previous three decades Brazil economy slowed down to a mere 1.5% in the 1980s (Castro and Fonseca, 1994).

Agriculture performed relatively better than other sectors of the economy, with an average growth rate equal to 2.6% during the 1980s (Ferreira Filho, 1998). The positive performance of agriculture did not occur by chance. From a policy based on input subsidies in the 1970s Brazil switched to a policy based on price support in the

1990s (Gasques and Villa Verde, 1990; Castro and Fonseca, 1994).The government fixed one single national price for the main crops, covering any transportation cost. Agricultural production in remote regions suddenly become attractive. The expansion of agriculture in the Mato Grosso (Central-Western Brazil) was greatly facilitated by the introduction of the national minimum price.

The macroeconomic adjustment policies in the 1990s, especially the Real Plan in 1994, brought rapid and profound transformations to agricultural policy. The increased openness of the Brazilian economy meant less government intervention and more competition for agricultural producers. The Sugar and Alcohol Institute created in 1933 and the Brazilian Coffee Institute created in 1952 were extinct in 1990. The minimum national price policy was abandoned, many government sponsored initiatives were cancelled. The new policy courseled to a strong reduction of wheat and cotton production. Agriculture was hard-hit, especially in the Centre-East region.

Over the years inflation had skyrocketed in Brazil. The Real substituted the Cruzero as the currency of Brazil in 1994 to rapidly change expectations of consumers and international investors. The exchange rate suddenly switched from being undervalued from being overvalued. With the appreciation of the Real the income of the rural sector – largely in US Dollars – plummeted leading producers to a situation of scarcity (Gonzales and Costs, 1998).

The expansion of Brazilian agriculture at this time was favored by the development of new varieties adapted to the soil and climate of the major regions of the country, especially the savannah and low-latitude areas. Since then production efficiency has been increased with the development of improved cultivars carrying genes capable of expressing high productivity, wide adaptation and good resistance to adverse factors, as high temperatures and diseases.

The process of modernization of agriculture was successful in expanding the cultivated areas, in increasing productivity, in integrating peripheral regions into the national economy and in increasing export. However, this process was not even and without costs. Production was concentrated in South-East and South regions. It seems that the distribution becomes less concentrated with the emergence of the Center-West, in large farms and in a few strategic products.

2.2 REGIONAL DYNAMICS OF AGRICULTURE FROM 1975 TO 2006.

The modernization processes in the last decades lead to an enormous changing in the exploitation of Brazilian agriculture. The main important commodities as soybean, maize, beef cattle, pork meat, poultry, cotton and sugar cane presented accentuated changes not only in terms of yield but also in location, which leads to land use change crop wise as well as between crops and livestock (SANTANA, et al, 2011).

Soybean experienced the biggest expansion in the period 1975-2006. In area it increased 279%, expanding from 5,824 million hectares to 22,047 million hectares. In production the expansion was around 430%, increasing from 9,893 million tonnes to 52,464 million tonnes. Over the period 1970 – 1985 it was attributed to the opening and consolidation of new agricultural areas in the South and Center-West regions. After that the growth was due to replacement of productive areas.

Maize was greatly influenced by soybean expansion. Although the maize production is still concentrated in the Centre-South of the country there was a movement towards the CW up to the 1990's. The expansion of soya farming in the border regions stimulated to growth of the 2nd corn harvest (grown immediately after the harvest of soybeans). This form of land-use intensification has compensating part of the land lost to soybeans in the Centre-West region and in the states of Paraná and São Paulo.

Regards to cotton the external market conditions have always had great influence by expanding or contracting the sector. The control on exports of raw materials in the 70s, especially the prohibition of cotton lint exportation until 1988, along with the pest infestation in traditional growing areas and loss of competitiveness due to imported cotton lint, led to a reduction in area and decrease in national cotton production in the 70s and 80s (Alves et.al., 2008).

Only in the 1990s under free trade policies the restrictions was reduced and national production increased again but now under a quite different production system and towards the savannah regions. The traditional labor-intensive production system practiced in the South and Southeast was replaced by a farming business type, fully mechanized, occupying large areas in the CW of the country (states of Mato Grosso, Goiás and Mato Grosso do Sul), and also in Southeast (state of Minas Gerais) and Northeastern (state of Bahia).

Sugar cane presents a quite different trajectory comparing to the other Brazilian crops. From 1968 to 1984, Brazil adopted policies to promote sugar exportation as a strategy for economic development. The National Alcohol Program (Proalcool) implemented in 1975 in order to replace gasoline with alcohol has deeply impacted the development of the sugarcane sector.

year	Brazil	North	North-East	South-East	South	Center-West	year	North	North-East	South-East	South	Center-West
SOYBEANS												
Area (million ha)							Area (% of total)					
1975	5,8	0,0	0,0	0,5	5,1	0,0	1975	0%	0%	8%	88%	0%
1985	10,2	0,0	0,1	0,9	6,3	2,8	1985	0%	1%	9%	62%	28%
1995	11,7	0,0	0,6	1,1	5,4	4,5	1995	0%	5%	10%	46%	39%
2006	22,0	0,5	1,5	1,7	8,1	10,3	2006	2%	7%	8%	37%	47%
Production (million t)							Production (% of total)					
1975	9,9	0,0	0,0	0,8	8,8	0,3	1975	0%	0%	8%	89%	3%
1985	18,3	0,1	0,1	1,8	10,7	5,6	1985	0%	0%	10%	58%	31%
1995	25,7	0,0	1,3	2,4	12,0	10,0	1995	0%	5%	9%	47%	39%
2006	52,5	1,3	3,5	4,1	17,7	25,9	2006	2%	7%	8%	34%	49%
Yield (t/ha)							Yield (% of national average)					
1975	1,699	0	937	1,639	1,719	1,385	1975	0%	55%	96%	101%	82%
1985	1,800	1,515	1,194	1,949	1,709	1,970	1985	84%	66%	108%	95%	109%
1995	2,200	1,920	2,199	2,110	2,213	2,208	1995	87%	100%	96%	101%	100%
2006	2,380	2,484	2,331	2,469	2,181	2,525	2006	104%	98%	104%	92%	106%
MAYZE												
Area (million ha)							Area (% of total)					
1975	10,9	0,2	2,5	3,0	4,4	0,8	1975	1%	23%	27%	41%	8%
1985	11,8	0,3	2,6	2,8	5,0	1,0	1985	3%	22%	24%	42%	9%
1995	13,9	0,6	3,1	2,8	5,6	1,8	1995	4%	22%	20%	40%	13%
2006	12,6	0,5	2,7	2,3	4,6	2,5	2006	4%	22%	18%	36%	19%
Production (million t)							Production (% of total)					
1975	16,3	0,2	1,6	4,7	8,3	1,6	1975	1%	10%	29%	51%	10%
1985	22,0	0,4	1,5	6,2	11,5	2,3	1985	2%	7%	28%	52%	11%
1995	36,3	0,9	2,4	8,1	18,6	6,2	1995	3%	7%	22%	51%	17%
2006	42,7	1,1	3,2	9,6	18,7	10,1	2006	3%	7%	23%	44%	24%
Yield (t/ha)							Yield (% of national average)					
1975	1,505	1,028	646	1,580	1,890	1,869	1975	68%	43%	105%	126%	124%
1985	1,866	1,282	593	2,197	2,300	2,233	1985	69%	32%	118%	123%	120%
1995	2,600	1,553	798	2,852	3,294	3,438	1995	60%	31%	110%	127%	132%
2006	3,382	2,016	1,163	4,143	4,092	4,108	2006	60%	34%	122%	121%	121%
COTTON												
Area (million ha)							Area (% of total)					
1975	1,5	0,0	0,7	0,5	0,3	0,1	1975	0%	43%	31%	17%	8%
1985	2,3	0,0	1,0	0,5	0,5	0,1	1985	0%	45%	24%	24%	7%
1995	1,1	0,0	0,4	0,2	0,3	0,2	1995	2%	33%	22%	26%	18%
2006	0,9	0,0	0,3	0,1	0,0	0,5	2006	0%	34%	10%	2%	55%
Production (million t)							Production (% of total)					
1975	1,3	0,0	0,2	0,6	0,4	0,2	1975	0%	17%	43%	28%	11%
1985	2,7	0,0	0,5	0,9	1,0	0,2	1985	0%	17%	35%	39%	9%
1995	1,4	0,0	0,2	0,4	0,5	0,4	1995	2%	12%	25%	37%	24%
2006	2,9	0,0	0,9	0,2	0,0	1,7	2006	0%	31%	8%	1%	60%
Yield (t/ha)							Yield (% of national average)					
1975	0,9	0,3	0,3	1,2	1,4	1,2	1975	33%	39%	140%	165%	139%
1985	1,2	0,4	0,5	1,7	1,9	1,7	1985	34%	38%	143%	162%	140%
1995	1,3	1,4	0,5	1,5	1,9	1,8	1995	105%	37%	115%	143%	135%
2006	3,2	2,8	2,9	2,7	1,6	3,6	2006	88%	91%	84%	50%	110%
SUGGAR CANE												
Area (million ha)							Area (% of total)					
1975	1,9	0,0	0,8	1,0	0,1	0,0	1975	0%	41%	53%	4%	1%
1985	3,8	0,0	1,3	2,2	0,2	0,1	1985	0%	33%	57%	6%	4%
1995	4,6	0,0	1,2	2,7	0,3	0,3	1995	0%	27%	60%	6%	6%
2006	6,1	0,0	1,1	3,9	0,5	0,6	2006	0%	18%	64%	8%	10%
Production (million t)							Production (% of total)					
1975	80,0	0,2	31,1	45,4	2,8	0,4	1975	0%	39%	57%	4%	1%
1985	229,9	0,3	62,6	146,7	12,3	8,0	1985	0%	27%	64%	5%	3%
1995	303,7	0,7	60,7	201,1	21,7	19,6	1995	0%	20%	66%	7%	6%
2006	457,2	1,3	63,2	312,4	35,7	44,6	2006	0%	14%	68%	8%	10%
Yield (t/ha)							Yield (% of national average)					
1975	43,0	35,2	40,3	45,7	36,2	35,2	1975	82%	94%	106%	84%	82%
1985	60,5	35,6	49,6	67,8	55,5	57,1	1985	59%	82%	112%	92%	94%
1995	66,6	51,3	48,7	73,7	74,4	70,3	1995	77%	73%	111%	112%	106%
2006	74,4	61,4	56,4	79,5	74,0	75,9	2006	82%	76%	107%	99%	102%

year	Brazil	North	North-East	South-East	South	Center-West	year	North	North-East	South-East	South	Center-West
CATTLE												
Animals (million)							Animal (% of total)					
1975	102,5	4,3	18,3	35,6	21,7	22,7	1975	4%	18%	35%	21%	22%
1985	128,4	8,9	23,0	34,6	24,4	37,5	1985	7%	18%	27%	19%	29%
1995	161,2	19,2	23,2	37,2	26,6	55,1	1995	12%	14%	23%	17%	34%
2006	205,9	41,1	27,9	39,2	27,2	70,5	2006	20%	14%	19%	13%	34%
POULTRY												
Animals (million)							Animal (% of total)					
1975	178,4	8,7	28,5	74,1	59,2	7,9	1975	5%	16%	42%	33%	4%
1985	309,6	11,8	48,4	104,2	133,5	11,6	1985	4%	16%	34%	43%	4%
1995	541,2	22,5	71,1	145,5	273,5	28,5	1995	4%	13%	27%	51%	5%
2006	819,9	18,2	82,1	229,1	408,3	82,3	2006	2%	10%	28%	50%	10%
PORK												
Animals (million)							Animal (% of total)					
1975	37,6	1,3	10,3	7,2	15,4	3,5	1975	3%	27%	19%	41%	9%
1985	32,2	2,2	8,6	5,9	12,0	3,5	1985	7%	27%	18%	37%	11%
1995	36,1	4,6	9,1	6,2	12,6	3,6	1995	13%	25%	17%	35%	10%
2006	35,2	2,0	7,2	6,1	16,0	4,0	2006	6%	20%	17%	45%	11%

Notes: source EMBRAPA.

Table 1. Cultivated area, production and productivity of soybeans, maize, cotton, sugar cane and production of cattle, pork and poultry, 1975-2006.

Over the period 1975-2006 the sugar cane production concentrated in the Center-South of the country, where the industries and research institutes are located. In 2006 the Center-South region accounted for about 85% of national production and the North/North-East produced the remaining 15% (MAPA, 2007). Government incentives and the higher profits through sugar cane production in areas where land was largely used for pasture explain the concentration, especially in the west of São Paulo, east of Mato Grosso do Sul and north of Paraná (Garagorry and Chaib Filho, 2010).

Regarding to meat production - cattle, poultry and pork – the period registered a great expansion. The cattle stock jumped from 102.5 million animals in 1975 to 205.8 million in 2006. Santana et al (2011) point out the major technological developments, economic stabilization of the national economy, greater availability of certified fodder seeds and good marketing opportunities among the factors which contributed to this expansion. North and Centre West regions increased their participation in the total production while South and Southeast had significant fall. The North region had the largest expansion in the number of animals in the country. For many authors the cattle-raising and large-scale production of soybeans in the North region are highlighted the biggest culprits of Amazon deforestation.

The poultry industries have established themselves as a modern segment in the 1970s. Since then the industry has continually been incorporating technological innovations and changing the production process in order to increase productivity and revenue. The poultry production is mainly concentrated in the South region which accounted for 49.8% of the total in 2006. However the largest growth in the period occurred in the Centre-West. The availability of land allows the expansion of the stock of pigs with lower risk of soil and groundwater contamination by waste. According to Roppa (2005), the density of swine stock in Brazil is pig/km2 of 4.34, against 6.46 in the United States, 38.4 and 45.5 in the European Union and China respectively.

Like poultry production, the growth of pig production in the Centre-West did not result in a decrease in the share of production in the South from 1975 to 2006. Both poultry and pork expansion in the CW has been accompanying the increasing production of soybeans and corn in the region. It is justified by the high impact of these grains in the final cost of poultry and pork feed.

3 THE MODEL

We use Ricardian model over cross sections as in Massetti and Mendelsohn (2011).The Ricardian method assumes the value of farmland (V) is equal to the present value of net revenue from farm related activities (Mendelsohn, Nordhaus, and Shaw 1994- MNS). Land values are therefore equal to:

$$V = \int \left[\sum PQ\left(I, C, X, Z\right) - R' I \right] e^{-\delta t} dt \ , \qquad (1)$$

where V is the value of farmland per hectare, P is the market price of output, Q is output, I is a vector of purchased inputs (other than land), C is a vector of climate variables, X is a vector of time varying variables (such as income and population density), Z is a vector of time invariant control variables (such as soils and geographic variables), R is a vector of input prices, t is time and δ is the discount rate. Farmers are assumed to maximize net revenues by choosing I, given climate, soil, geographic variables, market prices, and other exogenous socio-economic conditions.

Solving (1) to maximize net revenue leads to a reduced form model where *V* is strictly a function of the exogenous variables facing a farmer: X, Z, *C, P, R,* and *r.* Folding prices and the interest rate into the vector of time varying variables, the Ricardian model has the general form:

$$V = f(\mathbf{X}, \mathbf{Z}, C) \ . \qquad (2)$$

Traditionally, the Ricardian model is estimated across a single cross section:

$$V_i = X_i \boldsymbol{\beta} + Z_i \boldsymbol{\gamma} + C_i \varphi + u_i \ , \qquad (3)$$

where i varies across space. The relationship between the climate variables and land value is assumed to be quadratic so that the climate vector includes squared terms. The estimated coefficients in the model are β, γ, and φ. We control for heteroscedasticity with Weighted Least Squares (WLS). We use farmland by microregion in each year for a weight.

With panel data, one could estimate the Ricardian model using repeated independent cross sections (Mendelsohn, Nordhaus, and Shaw 1994; Schlenker, Hanemann, and Fisher 2006; Deschênes and Greenstone 2007; Massetti and Mendelsohn 2011). The estimated model would be:

$$V_{i,t} = X'_{i,t}\boldsymbol{\beta}_t + Z'_i\,\boldsymbol{\gamma}_t + C'_i\,\varphi_t + u_{i,t} \ , \tag{4}$$

where the coefficients are all allowed to vary over time: β_t, γ_t, and φ_t.

The repeated cross-section model does not exploit the intertemporal dimension of the panel. A more efficient use of the panel would keep all coefficients stable over time:

$$V_{i,t} = X'_{i,t}\boldsymbol{\beta} + Z'_i\,\boldsymbol{\gamma} + C'_i\,\varphi + u_{i,t} \ , \tag{5}$$

where β,γ, and φ are time invariant vectors. By allowing β and γ to vary over time, the repeated cross section can cause φ to also vary.

Following Massetti and Mendelsohn (2011) we explore two ways to estimate the Ricardian model with panel data. One way is to pool the entire data set and estimate the model above in a single stage using Equation (5).[2] The second approach is to estimate two stages (Hsiao 2008). In the first stage, land value is regressed on the time varying variables using the covariance method with county fixed effects and weights equal to farmland in each county:

$$V_{i,t} = X'_{i,t}\boldsymbol{\beta} + \alpha_i + \varepsilon_{i,t} \ , \tag{6}$$

where $\varepsilon_{i,t}$ is the error term. By including county fixed effects, the first stage in the Hsiao model does a better job (than the pooled model) of controlling for omitted spatial variables. In the second stage, the time-mean residuals are regressed on the time invariant variables using WLS, with weights equal to the average farmland in each county over the Census years:

[2]The method was already employed by Schlenker, Hanemann, and Fisher, but only on counties east of the 100th meridian, using growing season degree days as a climate variable, considering data from 1982 to 1997 instead from 1978 to 2002.

$$\overline{V}_i - \overline{X}_i^{'} \hat{\boldsymbol{\beta}}_{CV} = \alpha_i + \overline{\varepsilon}_i = Z_i^{'} \boldsymbol{\gamma} + C_i^{'} \varphi + \overline{u}_i \ , \qquad (7)$$

with $\overline{V}_i = \frac{1}{T} \sum_t V_{i,t}$ and $X_i = \frac{1}{T} \sum_t X_{i,t}$.[3]

If the error term is caused by unobserved variables correlated with climate, the estimator will be biased. This is a common problem for all empirical studies of natural phenomena. However, by estimating the time-varying coefficients carefully, in the first stage, we reduce the impact of these errors (Hsiao, 2003, p. 53). The Hsiao model also makes the assumption that the errors in the second stage are correlated over time and so assumes that one has only the cross sectional variation to learn from. It consequently assumes there are far fewer observations than the panel model and gives a larger estimate of the standard error in the second stage.

Given the final estimated models, the welfare impact W of climate change on Brazilian agriculture is obtained by computing the difference between the value of farmland under the new climate and the value of farmland under the current climate. We use the estimated coefficients, the average farmland in each county, and the predicted change in climate from C_0 to C_1:

$$W_t = \sum_i \left[V_{i,t}(C_1) - V_{i,t}(C_0) \right] F_i \ . \qquad (10)$$

Of course, the best forecast of welfare effects in the future should rely on the expected value of farmland in the future not the past. This would require modeling not only how farmland is expected to change over time from technological and economic forces but also how it might change in response to climate change (Mendelsohn, Nordhaus, and Shaw 1994). In the present analysis, we employ a less sophisticated approach and we assume that the amount of farmland is exogenous. We use the average farmland observed in each county across the Census years.

[3] The two-step procedure that we follow reduces the correlation between unobserved variables that vary over time and might be correlated with climate. However, as for in all cross-sect

	Mean	Std. Dev.	Min	Max
distance from cities (km)	142	133	1.19	897
distance from ports (km)	457	381	6.80	2202
latitude (DD)	15.24	8.45	-3.48	32.7
elevation (m)	429	281	2.28	1270
elevation std	111	69	2.04	443
pop density ('000/Km2)	0.082	0.414	0.00003	14.6
GDP per capita ('000 R$)	6.71	5.48	0.476	61.77
soil pH	4.82	0.72	2.17	7.38
soil CaCO3 (%)	0.099	0.281	0	3.970
soil sodicity (ESP) (%)	2.19	2.34	0	13.80

Table 2. Descriptive statistics of time invariant control variables.

4 DATA

We build a unique dataset at micro-region level for the years 1975, 1985, 1995 and 2006. The Appendix provides a detailed description of all the variables used. Land values per hectare of farmland are from IBGE. GDP per capita and population density enter both with a squared term. A set of geographic variables controls for distance from cities and ports and for latitude at the centroid of each micro-region. Soil data is from the FAO HWSD dataset.[4] We control for the level of pH, of calcium carbonate ($CaCO_3$) and the exchangeable sodium percentage (ESP). Also soil variables enter with a quadratic term because too much or too little of pH, $CaCO_3$ and ESP are equally detrimental for agriculture.

Brazil is a large tropical country with uniformly high temperatures in the North, Northeast and Center-West regions and warm summers (December-February) and relatively cooler winters (June-August) in the South-East and in the South (see Table 6). Precipitations vary across seasons and across regions. Precipitations in the North are abundant and relatively constant during the year, with a total of about 22 cm/month. The North-East is the driest region, with an annual total of about 10 cm/month. Rainfall is more abundant in Summer and Autumn. Winters are dry in the North-East, the South-East and the Center-West, with about 2 to 3 cm/month.

Land values per hectare are unequally distributed over Brazil but there is moderate convergence over time. Land values have grown substantially in the North and Center-West regions. Land values have declined both in absolute and relative terms in the South-East, the region with the highest land values in Brazil. The overall amount of farmland has remained fairly stable since 1985 in Brazil. The region with

[4] FAO/IIASA/ISRIC/ISS-CAS/JRC. 2008. Harmonized World Soil Database (version 1.0). Rome, Italy and Laxenburg, Austria.: FAO and IIASA.

the largest expansion of land in agriculture is the Center-West. The largest contraction has instead occurred in the South-East. As a result of opposite dynamics of land prices and land in agriculture the Center-West has become the region with the second highest total agricultural land value in Brazil. The North is the region in which total land values have grown most, compared to other regions. Therefore, the value of agriculture production has shifted northward in Brazil. More and more agricultural land values are exposed to higher temperatures. If we apply weights equal to the regional share of total agricultural land values to regional mean annual temperatures over 1961-1990, the mean temperature has increased by from 22.2 °C to 22.8 °C, a remarkable difference of 0.6 °C, roughly equivalent to the average global warming from pre-industrial times. Value-weighted mean annual precipitations have increased from 11.8 to 12.5 cm/month.

Soils tend to be too acid compared to optimal growing conditions, with very low calcium carbonate content and with low to moderate exchangeable sodium percentage.

	agricultural land (million of hectares)	% of national land in the region	value of land (thousands of R$)	value of land (% of national average)	total value of agricultural land (billions of R$)	% of national land value in the region
Sul						
1975	42.6	15%	9.36	151%	399	22%
1985	46.1	13%	13.75	176%	634	23%
1995	41.2	12%	4.59	218%	189	27%
2006	40.6	12%	6.09	196%	247	24%
Sudeste						
1975	69.3	24%	14.88	240%	1032	57%
1985	71.6	21%	17.97	230%	1287	47%
1995	61	18%	4.44	211%	271	38%
2006	54.1	17%	6.27	202%	339	33%
Centro-Oeste						
1975	73.7	25%	2.51	41%	185	10%
1985	95.1	27%	4.53	58%	431	16%
1995	104	31%	1.29	61%	134	19%
2006	104	32%	2.55	82%	265	26%
Nordeste						
1975	64.2	22%	2.64	43%	170	9%
1985	79.9	23%	3.96	51%	316	12%
1995	76.3	23%	1.19	57%	91	13%
2006	76.3	23%	1.58	51%	121	12%
Norte						
1975	42.4	15%	0.58	9%	25	1%
1985	56	16%	1.04	13%	58	2%
1995	54.7	16%	0.46	22%	25	4%
2006	52.6	16%	0.88	28%	46	5%
Brazil						
1975	292		6.19		1810	
1985	349		7.82		2726	
1995	337		2.11		710	
2006	328		3.11		1019	

Table 3. Descriptive statistics of land values and agricultural land.

5 RESULTS – CLIMATE MARGINALS

5.1 REPEATED CROSS SECTION

	1975	1985	1995	2006		1975	1985	1995	2006
t sum (°C)	-0.0660	-0.384	-0.657	1.695**	p sum (mm)	0.00374	-0.0106***	0.00330	-9.98e-05
	[0.961]	[1.015]	[0.874]	[0.819]		[0.00651]	[0.00379]	[0.00272]	[0.00338]
t sum sq (°C)	-0.00541	0.00207	0.00700	-0.0389**	p sum sq (mm)	4.29e-06	2.43e-05***	-7.41e-07	7.17e-06
	[0.0190]	[0.0195]	[0.0169]	[0.0157]		[1.26e-05]	[8.24e-06]	[5.66e-06]	[6.65e-06]
t aut (°C)	-1.494	-4.336***	-1.258	-4.075***	p aut (mm)	0.00778***	0.0126***	0.00393	0.0140***
	[0.913]	[0.902]	[0.872]	[0.736]		[0.00296]	[0.00261]	[0.00243]	[0.00218]
t aut sq (°C)	0.0400**	0.0894***	0.0298*	0.0868***	p aut sq (mm)	-2.36e-05***	-1.96e-05***	-1.65e-05***	-2.60e-05***
	[0.0182]	[0.0183]	[0.0172]	[0.0143]		[5.90e-06]	[4.55e-06]	[4.12e-06]	[3.97e-06]
t win (°C)	0.518	1.676***	0.836*	1.552***	p win (mm)	0.00777**	-0.00355	0.00549**	0.000611
	[0.569]	[0.488]	[0.449]	[0.449]		[0.00304]	[0.00281]	[0.00226]	[0.00273]
t win sq (°C)	-0.0186	-0.0418***	-0.0217**	-0.0383***	p win sq (mm)	-8.67e-06	1.19e-05	-5.88e-06	2.48e-06
	[0.0130]	[0.0111]	[0.00951]	[0.00918]		[7.95e-06]	[7.83e-06]	[6.67e-06]	[7.65e-06]
t spr (°C)	1.770***	2.714***	0.817	1.504***	p spr (mm)	-0.0245**	-0.00501	-0.0287***	0.000495
	[0.680]	[0.639]	[0.526]	[0.483]		[0.0110]	[0.00536]	[0.00503]	[0.00482]
t spr sq (°C)	-0.0333**	-0.0485***	-0.0144	-0.0283***	p spr sq (mm)	4.95e-05	-3.18e-06	0.000108***	-2.49e-05
	[0.0147]	[0.0127]	[0.0108]	[0.00947]		[3.42e-05]	[2.17e-05]	[1.99e-05]	[1.92e-05]
Obs	534	544	552	553	Adj R-sq	0.869	0.874	0.842	0.845

Notes: Standard errors in brakets.*** p<0.01, ** p<0.05, * p<0.1. Summer (December, January, February); Autumn (March, April, May); Winter (June, July, August), Spring (September, October, November).

Table 4. Coefficients of climate variables in the Repeated Cross Section model.

We start presenting the coefficient of temperature and precipitations over the four seasons using the repeated cross-section model (Table 4). We find a stable and significant quadratic relationship between land values and winter and spring temperatures. The linear term of temperature in Autumn is negative but it is significant only in 1985 and 2006. The quadratic term of temperature in Autumn is positive and always significant. This suggests a U-shaped relationship between land values and temperatures in Autumn. However, the minimum of the U-shaped function is above the currently observed average Autumn temperature in Brazil when both coefficients are significant. This implies that warming is actually harmful for the Brazilian agriculture during Autumn. Summer temperature is instead not significant in three out of four cross-sections. Precipitations in Autumn significantly affect land values in Brazil. The optimal level of precipitations in Autumn is generally higher than the current level of precipitations in Brazilian micro-regions. Precipitations in winter have an inverted-U shaped relationship with land values in 1975 and 1995 but not in 1985 and 2006.

The coefficients presented in Table 4 are generally non-stable. They reflect the many ongoing changes occurring over time in Brazilian agriculture. In the 2006 cross-section all the temperature coefficients are significant. Warming in Summer is harmful for all regions (average climate in the region). Warming in Winter is harmful for the North, North-East and the Center-West while it is beneficial for the South and the South-East. Warming in Spring is harmful for the North, the North-East but beneficial for the other regions.

	Pooled	Hsiao		Pooled	Hsiao
t sum (°C)	0.126	-0.125	p sum (mm)	-0.00430	-0.00336
	[0.579]	[0.850]		[0.00263]	[0.00357]
t sum sq (°C)	-0.00865	-0.00595	p sum sq (mm)	1.60e-05***	1.34e-05*
	[0.0112]	[0.0163]		[5.38e-06]	[6.88e-06]
t aut (°C)	-3.301***	-3.681***	p aut (mm)	0.0115***	0.0164***
	[0.533]	[0.939]		[0.00164]	[0.00250]
t aut sq (°C)	0.0711***	0.0808***	p aut sq (mm)	-2.31e-05***	-3.17e-05***
	[0.0106]	[0.0185]		[3.18e-06]	[4.22e-06]
t win (°C)	1.411***	2.036***	p win (mm)	6.66e-05	-0.00121
	[0.289]	[0.501]		[0.00184]	[0.00250]
t win sq (°C)	-0.0360***	-0.0499***	p win sq (mm)	4.50e-06	1.40e-05*
	[0.00624]	[0.0103]		[5.49e-06]	[8.27e-06]
t spr (°C)	1.855***	1.600***	p spr (mm)	-0.0136***	-0.0190***
	[0.361]	[0.571]		[0.00432]	[0.00540]
t spr sq (°C)	-0.0340***	-0.0294***	p spr sq (mm)	2.88e-05*	4.52e-05**
	[0.00721]	[0.0113]		[1.61e-05]	[1.83e-05]
Obs	2,183	2,199	Adj R-sq	0.818	0.799

Notes: Standard errors in brackets. *** p<0.01, ** p<0.05, * p<0.1. Summer (December, January, February); Autumn (March, April, May); Winter (June, July, August), Spring (September, October, November). Hsiao model: number of observations refers to the first stage (553 in second stage), Adjusted R-squared refers to the second stage (0.874 in the first stage).

Table 5. Coefficients of climate variables in the Pooled and Hsiao models.

In Autumn the relationship between temperature and land values follows a U-shaped relationship. However, warming is harmful for 94% of the micro-regions in Brazil.

Only precipitation in Autumn is significant in the 2006 cross-section. The signs of the coefficients reveal a U-shaped relationship but virtually all Brazil as a lower amount of precipitation during Autumn than the optimal one.

5.2 THE POOLED AND HSIAO MODELS

In the pooled and Hsiao models we estimate one single set of coefficients using data from 1975 to 2006. We introduce year dummies to control for time varying factors that affect all Brazilian agriculture. For example, broad political changes, inflation, macroeconomic policy, changes in the price of global commodities are all captured by the time dummies. This reduces the possibility that some unobserved time varying variables that are correlated with climate become part of the error term.

The coefficients of climate variables are presented in Table 5. The coefficients of all control variables are reported in the Appendix. Table 5 reveals that the two panel data methods estimate coefficients that have the same sign and are similar in magnitude.

Summer temperature does not significantly affect land values. In the other seasons the two models reveal instead a significant quadratic relationship. In Winter and Spring the relationship is inverted-U shaped while the opposite is true for Autumn. Precipitations in Winter and in Summer do not significantly affect land values while precipitations in Autumn and in Spring have a significant effect. More rainfall in Autumn is beneficial for virtually all micro-regions in Brazil, while more rainfall in Spring is harmful for all micro-regions.

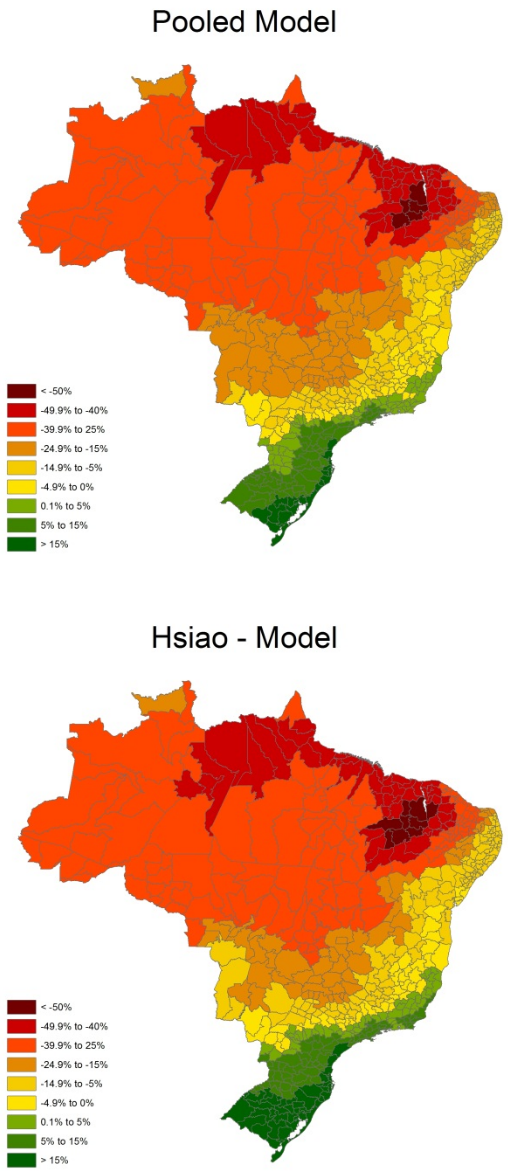
5.3 MARGINAL IMPACTS

The analysis of climate coefficients provides useful information but it is hard to interpret them because the relationship between climate and land values is generally quadratic. The marginal impact of both temperatures and precipitations depends on local climate and are seasonal specific. Figure 1 depicts annual temperature and precipitation marginal effects obtained by summing the seasonal marginals at the average climate of different regions and of Brazil as a whole. Figure 1 immediately reveals that additional warming is harmful for all the regions of Brazil, with the exception of the South region. Warming is most harmful in the North and the North-East regions, the hottest in Brazil. Warming is also harmful in the South-East. Figure 1 also reveals that agriculture in Brazil has become increasingly sensitive to warming over the years. This is especially true for the Center-West. Warming has also become less beneficial in the South. The pooled and the Hsiao models generate very similar temperature marginals. Interestingly, they also indicate that warming is more harmful that the cross-section analysis would suggest.

The impact of a marginal change of precipitations on land values has greater variance across regions and is negligible for Brazil as a whole. More rainfall is beneficial for the South-East, the South and the Center-West. Surprisingly, the North-East has negative precipitation marginals despite being the driest region of Brazil. The changing in the production system into a more resistant to dryness in this region can partially explain this result. The agriculture in the Caatinga biome has been developed in the last decades by using irrigation and modified cultivars to deal with the absence of rain.

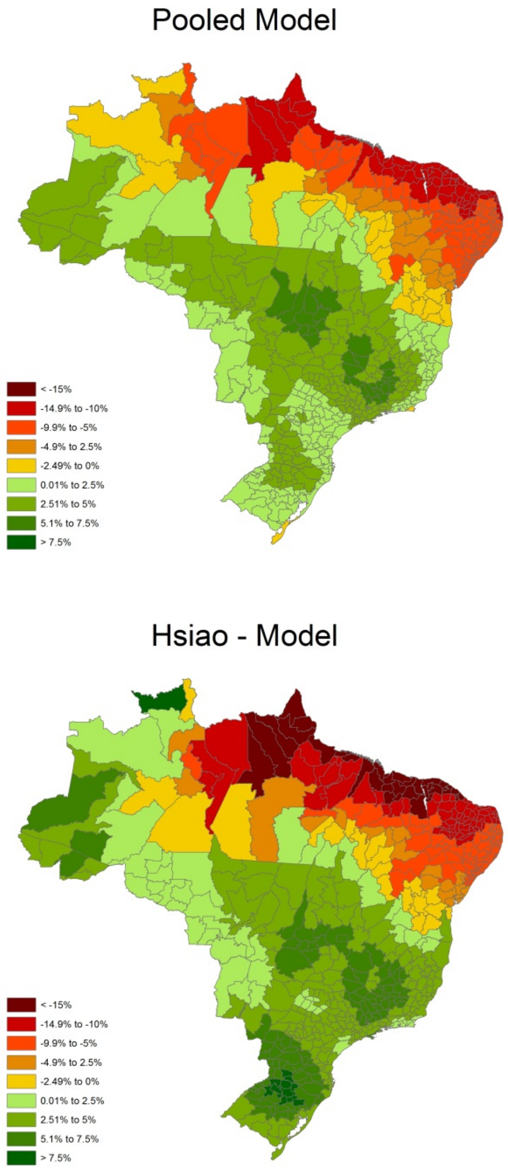
Figure 2 provides more geographically detailed information on the sensitivity of agriculture to warming and to increased precipitations using the pooled and the Hsiao models. Differences in the map are due to differences in present climate. The temperature marginal reveal a very consistent message: warming is going to be harmful for a large part of Brazil. Areas in the North and in the interior are going to suffer more from warming than areas in the South and along the coast. The models suggest that areas near the Southern coastline and near the Uruguay would benefit from warming. However, the overall picture is quite uncomfortable: large parts of the country are expected to suffer large losses from higher temperatures. Marginal precipitation changes are instead beneficial for large parts of the country. The areas that are expected to suffer if rainfall increases are concentrated along the Northeastern coastline. Areas in the center of Brazil are expected to benefit most from a marginal precipitation increases.

Figure 1. Precipitation marginal at macro-regional level, Cross-Sections, Pooled and Hsiao Model.



Notes: Temperature measured in °C.

Figure 2: Temperature marginals, Pooled and Hsiao Model.



Notes: Precipitations measured in cm.

Figure 3. Precipitation marginal at micro-region level, Pooled and Hsiao Model.

6 RESULTS – FORECASTS OF CLIMATE CHANGE IMPACT

In this Section we estimate the impact of non-marginal changes of climate using the cross-sections and the panel data models. We use three General Circulation Models scenarios that use the SRES A2 emissions trajectory (a high global warming scenario). We check what would be the impact of climate on Brazilian agricultural land values ceteris paribus, i.e. assuming that all other factors that affect land values remain unchanged.[5]

Table 7 summarizes present and future climate obtained using historic observations from the CRU dataset over the period 1961-1990 and average conditions over 2046-2065 and over 2080-2099 for the HADCM3, the MIMR and the NCPCM models.

The first striking fact is that while the three GCMs forecast an increase of temperature in Brazil, seasonal and regional changes vary a great deal across climate models. For example, the HADCM3 model of the United Kingdom Meteorological Office (UKMO) forecasts 8.1 °C temperature increase at the end of the century for the North in Winter, while the NCPCM model, for the same season, the same region and over the same period, forecasts only 2.7 °C of warming. While the NCPCM models expects that warming is going to be roughly uniform across seasons and regions in Brazil, the HADCM3 model expects warming to be more intense in the North and in Winter. The HADCM3 model sees a substantial amount of warming already around 2050 while the other models are less pessimistic.

Differences across rainfall scenarios are even larger and models often do not agree on the sign of the change in precipitations.

These differences necessarily translate into wide variations of impact estimates. Figure 3 displays the percentage impact of the three climate scenarios on aggregate Brazilian land values. The figure confirms that Brazilian agriculture has become more and more sensitive to climate change over the years. Using the 1975 and 1985 cross sections climate change is beneficial in 2100. Using the 2006 cross section only climate change appears severely reduce land values. Using the panel data methods climate change is instead harmful, with the exception of the MIMR and the NCPCM scenarios in 2100. Surprisingly, climate change is more harmful using around 2050 than at the end of the century.

Impacts of climate change on aggregate land values hide substantial regional differences, as revealed by Figure 4. All climate models agree on the broad distribution of impacts across different areas of Brazil. The North and the Center of the country are severely hit. The coastline is relatively less affected while the South tends to benefit from climate change. As the most valuable farmland is in the South and along the coastline, the aggregate impact of climate change on Brazil agriculture is mitigated by some geographically concentrated beneficial effects.

[5]We use 1975-2006 averages of time-varying variables.

However, considering the trajectory of Brazilian agriculture in the last decades growing towards the Center-West and North regions the impact of climate change will be considerable. The potential of agricultural production expansion for the country as a whole will be compromised in a great measure.

Table 6. Present and future climate in Brazil's macroregions.

		Temperature (°C)				Precipitations (cm/month)			
		Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
Norte									
1990	CRU	26.2	26.2	25.9	26.8	24.4	25.1	10.2	13.6
	HADCM3	3.7	3.4	4.2	4.4	-2.8	-1.5	-1.8	-4.3
2060	MIMR	2.8	2.4	2.8	3.1	-0.9	-0.1	-0.6	0.0
	NCPCM	1.2	1.1	1.5	1.3	2.2	1.2	0.1	2.1
	HADCM3	6.5	6.5	8.1	7.5	-5.7	-3.7	-3.4	-7.0
2100	MIMR	4.9	4.7	5.4	5.6	0.4	0.0	-1.0	0.5
	NCPCM	2.2	2.3	2.7	2.4	2.8	0.7	0.3	2.5
Nordeste									
1990	CRU	26.1	25.4	24.4	26.3	13.3	13.9	3.5	5.0
	HADCM3	2.7	2.7	2.4	2.4	-3.2	-2.5	-0.2	-0.9
2060	MIMR	3.0	2.6	2.4	2.6	-6.3	-2.1	-0.3	0.0
	NCPCM	1.1	1.3	1.4	1.5	0.5	0.3	-0.4	0.3
	HADCM3	4.8	4.8	4.2	4.4	-7.2	-4.2	-0.4	-1.6
2100	MIMR	5.1	5.0	4.5	5.0	-7.6	-4.0	-0.5	-0.7
	NCPCM	2.2	2.3	2.3	2.5	0.9	0.5	-0.5	0.0
Sudeste									
1990	CRU	24.1	22.6	19.6	22.7	20.9	8.9	2.5	12.0
	HADCM3	1.9	2.5	2.9	2.7	3.1	-0.4	-0.5	2.3
2060	MIMR	2.3	2.0	1.8	2.5	-2.0	-0.7	-0.2	-1.6
	NCPCM	1.0	1.1	1.2	1.4	0.5	0.3	-0.2	-0.4
	HADCM3	3.7	4.3	5.8	5.2	1.5	0.5	-0.4	1.4
2100	MIMR	4.6	4.6	4.1	4.6	-5.4	-2.1	-0.6	-1.8
	NCPCM	1.8	2.1	2.4	2.6	1.7	0.8	-0.2	-1.0
Sul									
1990	CRU	23.3	19.4	14.8	19.0	15.1	12.7	12.0	14.3
	HADCM3	2.2	2.6	2.9	2.8	-0.9	0.3	-0.2	1.5
2060	MIMR	1.7	1.5	1.4	1.8	0.6	-0.9	0.0	-0.1
	NCPCM	0.9	1.1	1.2	1.1	1.2	-0.4	-0.3	-0.2
	HADCM3	3.9	4.0	4.7	4.7	1.8	0.8	0.3	3.9
2100	MIMR	2.8	3.2	2.7	2.7	1.9	-0.5	-0.4	0.1
	NCPCM	1.6	2.4	2.6	2.0	0.6	-0.8	-0.2	0.0
Centro-Oeste									
1990	CRU	25.8	25.1	23.3	25.9	25.9	14.4	2.0	14.1
	HADCM3	2.7	3.2	3.5	3.8	2.1	-0.8	-0.4	-1.4
2060	MIMR	2.9	2.7	2.5	3.4	-1.2	-1.2	-0.1	-1.1
	NCPCM	1.1	1.2	1.5	1.5	1.3	-0.5	-0.1	-0.1
	HADCM3	5.0	5.8	6.6	6.5	-0.6	0.2	-0.5	-3.3
2100	MIMR	5.3	5.7	5.4	6.0	-2.5	-2.2	-0.1	-2.0
	NCPCM	2.0	2.4	2.9	2.8	2.3	-0.1	-0.2	0.6

Notes: Total land area weighted averages of micro-region level temperature and precipitation data. 1990 indicates 1961-1990 climatologies from CRU model. 2060 indicates 2046-2065 climatology for the SRES

A2 scenario; 2100 is the 2080-2099 climatology. The HDCM3, MIMR and NCPCM are three general circulation models. Temperature (°C): average temperature over the season; precipitations (cm): average monthly rainfall per month during the season.

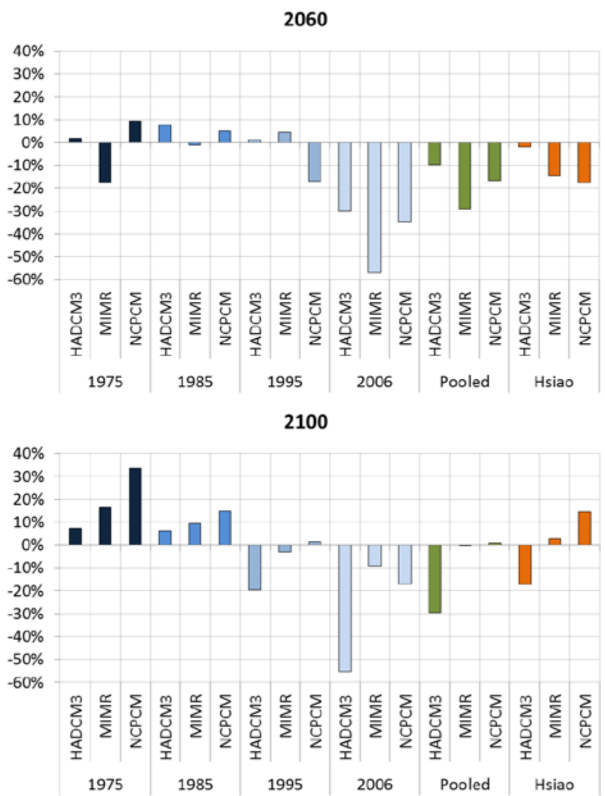


Figure 4. Impacts of climate change on aggregate Brazilian land values.

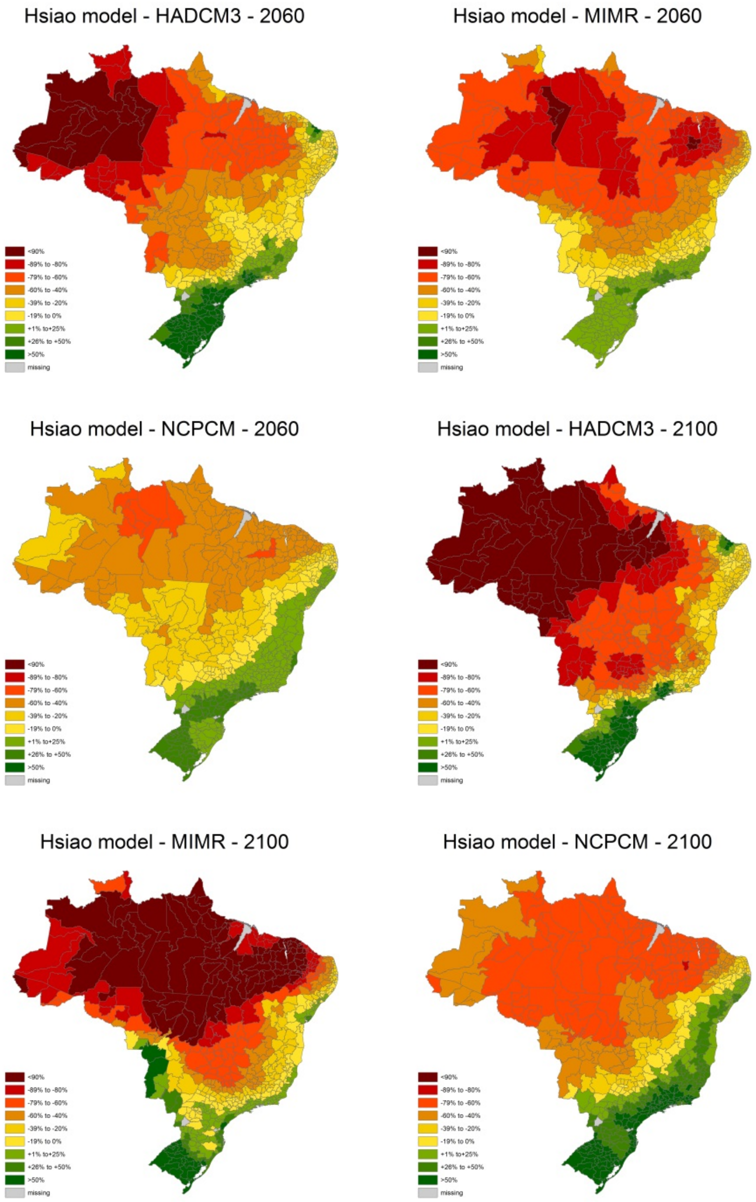


Figure 5. Impact of climate change on land values of Brazilian microregions.

7 CONCLUSIONS

This study uses a Ricardian framework to study the impact of climate change on land values in Brazil. The study relies on a unique panel dataset of land values, socio-economic variables, geographic and climate variables for the years 1975, 1985, 1995 and 2006, for all micro-regions in Brazil.

Brazil has gone through huge transformations since 1975. Agriculture is not an exception. Large parts of the country have been opened to intensive agriculture. New crops have been successfully introduced in previously hostile areas. These transformations have boosted productivity in agriculture and have also changed the sensitivity of agriculture to climate. The agricultural land value weighted average temperature of Brazil has increased over time.

Our estimates reveal that warming is harmful for large parts of the country. Only the South region and other southern coastal areas may benefit from warming. By using different cross-sections we show that the marginal impact of warming has become increasingly negative. Marginal impacts of precipitations are instead more ambiguous.

By using three General Circulation Models scenarios for 2046-2065 and 2080-2099 we have shown that climate change is going to negatively affect agriculture in large parts of the country. However, beneficial effects in the South region and along the southern coastline cannot be excluded. As most of the valuable land is concentrated where the benefits are expected to be beneficial or less harmful, the aggregate impact of climate change on Brazilian agriculture is ambiguous. The impact on Savannah biome which comprehends the majority of Center-West, part of the North and North-East regions is an especial matter of concern. This biome is not only important because of the biodiversity but also for being responsible for the majority of Brazilian agricultural production. All the potential for expansion in Brazilian agriculture is in this area.

Further analysis is needed to check the robustness of our findings to alternative model formulations. In particular, ambiguous impacts of precipitations suggest that controlling for water withdrawals from rivers might be important. The introduction of further soil control variables might increase the accuracy of our estimates. Finally, the study can be enriched by providing accurate confidence intervals for marginal and non-marginal climate change impacts.

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APPENDIX - TABLES

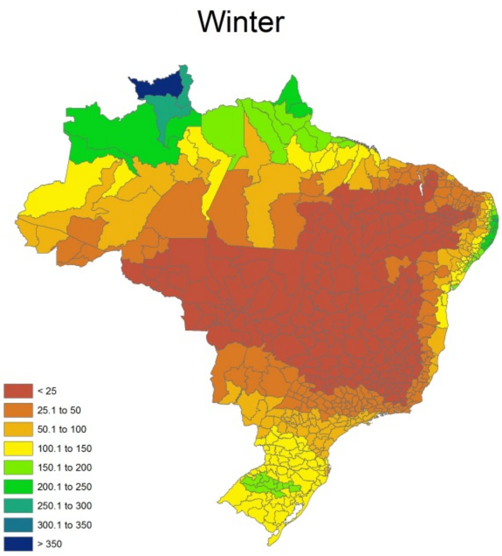
	1975	1985	1995	2006		1975	1985	1995	2006
t sum (°C)	-0.0660	-0.384	-0.657	1.695**	p sum (mm)	0.00374	-0.0106***	0.00330	-9.98e-05
	[0.961]	[1.015]	[0.874]	[0.819]		[0.00651]	[0.00379]	[0.00272]	[0.00338]
t sum sq (°C)	-0.00541	0.00207	0.00700	-0.0389**	p sum sq (mm)	4.29e-06	2.43e-05***	-7.41e-07	7.17e-06
	[0.0190]	[0.0195]	[0.0169]	[0.0157]		[1.26e-05]	[8.24e-06]	[5.66e-06]	[6.65e-06]
t aut (°C)	-1.494	-4.336***	-1.258	-4.075***	p aut (mm)	0.00778***	0.0126***	0.00393	0.0140***
	[0.913]	[0.902]	[0.872]	[0.736]		[0.00296]	[0.00261]	[0.00243]	[0.00218]
t aut sq (°C)	0.0400**	0.0894***	0.0298*	0.0868***	p aut sq (mm)	-2.36e-05***	-1.96e-05***	-1.65e-05***	-2.60e-05***
	[0.0182]	[0.0183]	[0.0172]	[0.0143]		[5.90e-06]	[4.55e-06]	[4.12e-06]	[3.97e-06]
t win (°C)	0.518	1.676***	0.836*	1.552***	p win (mm)	0.00777**	-0.00355	0.00549**	0.000611
	[0.569]	[0.488]	[0.449]	[0.449]		[0.00304]	[0.00281]	[0.00226]	[0.00273]
t win sq (°C)	-0.0186	-0.0418***	-0.0217**	-0.0383***	p win sq (mm)	-8.67e-06	1.19e-05	-5.88e-06	2.48e-06
	[0.0130]	[0.0111]	[0.00951]	[0.00918]		[7.95e-06]	[7.83e-06]	[6.67e-06]	[7.65e-06]
t spr (°C)	1.770***	2.714***	0.817	1.504***	p spr (mm)	-0.0245**	-0.00501	-0.0287***	0.000495
	[0.680]	[0.639]	[0.526]	[0.483]		[0.0110]	[0.00536]	[0.00503]	[0.00482]
t spr sq (°C)	-0.0333**	-0.0485***	-0.0144	-0.0283***	p spr sq (mm)	4.95e-05	-3.18e-06	0.000108***	-2.49e-05
	[0.0147]	[0.0127]	[0.0108]	[0.00947]		[3.42e-05]	[2.17e-05]	[1.99e-05]	[1.92e-05]
pop density	0.00415***	0.00220***	0.000144	0.000864**	elevation	-0.000224	-0.000749***	-0.000451*	-0.000255
	[0.00115]	[0.000620]	[0.000115]	[0.000385]		[0.000331]	[0.000279]	[0.000252]	[0.000246]
po density sq	-1.34e-06**	-6.20e-07*	-7.65e-09	-2.35e-07*	elevation std	-0.000580	-0.000149	-0.000552	-0.000833*
	[6.47e-07]	[3.29e-07]	[7.72e-09]	[1.28e-07]		[0.000614]	[0.000570]	[0.000501]	[0.000452]
gdp cap	0.0803**	0.113***	0.00805	0.0296**	soil ph	0.656**	0.640**	-0.219	0.540*
	[0.0387]	[0.0233]	[0.0137]	[0.0118]		[0.297]	[0.306]	[0.269]	[0.326]
gdp cap sq	-0.00282	-0.00442***	-0.000202	-0.000623***	soil ph sq	-0.0404	-0.0530	0.0264	-0.0542
	[0.00199]	[0.000914]	[0.000278]	[0.000240]		[0.0334]	[0.0341]	[0.0294]	[0.0364]
distance from cities	-0.00104***	-0.000796***	-0.000144	-0.000501***	soil CaCO3	-0.898***	-0.992***	-0.0437	-0.439**
	[0.000353]	[0.000235]	[0.000188]	[0.000178]		[0.260]	[0.207]	[0.174]	[0.206]
distance from ports	-0.000798***	-0.00102***	-0.000402***	-0.000465***	soil CaCO3 sq	0.196***	0.235***	0.0248	0.163**
	[0.000197]	[0.000113]	[0.000105]	[0.000105]		[0.0726]	[0.0652]	[0.0437]	[0.0649]
latitude	0.156***	0.180***	0.143***	0.111***	soil sodicity (ESP)	-0.245***	-0.111***	-0.0157	-0.0605
	[0.0275]	[0.0233]	[0.0193]	[0.0195]		[0.0483]	[0.0397]	[0.0393]	[0.0377]
					soil sodicity (ESP) sq	0.0199***	0.0103***	0.00307	0.00883***
						[0.00405]	[0.00303]	[0.00320]	[0.00339]
Obs	534	544	552	553	Adj R-sq	0.869	0.874	0.842	0.845

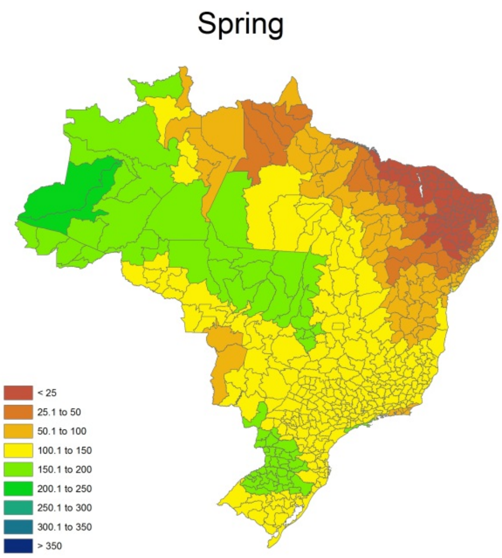
Table A1. Repeated Cross Section model, coefficients.

	Pooled	Hsiao		Pooled	Hsiao
t sum (°C)	0.126	-0.125	p sum (mm)	-0.00430	-0.00336
	[0.579]	[0.850]		[0.00263]	[0.00357]
t sum sq (°C)	-0.00865	-0.00595	p sum sq (mm)	1.60e-05***	1.34e-05*
	[0.0112]	[0.0163]		[5.38e-06]	[6.88e-06]
t aut (°C)	-3.301***	-3.681***	p aut (mm)	0.0115***	0.0164***
	[0.533]	[0.939]		[0.00164]	[0.00250]
t aut sq (°C)	0.0711***	0.0808***	p aut sq (mm)	-2.31e-05***	-3.17e-05***
	[0.0106]	[0.0185]		[3.18e-06]	[4.22e-06]
t win (°C)	1.411***	2.036***	p win (mm)	6.66e-05	-0.00121
	[0.289]	[0.501]		[0.00184]	[0.00250]
t win sq (°C)	-0.0360***	-0.0499***	p win sq (mm)	4.50e-06	1.40e-05*
	[0.00624]	[0.0103]		[5.49e-06]	[8.27e-06]
t spr (°C)	1.855***	1.600***	p spr (mm)	-0.0136***	-0.0190***
	[0.361]	[0.571]		[0.00432]	[0.00540]
t spr sq (°C)	-0.0340***	-0.0294***	p spr sq (mm)	2.88e-05*	4.52e-05**
	[0.00721]	[0.0113]		[1.61e-05]	[1.83e-05]
pop density	0.000158	-0.00356***	soil ph	0.414*	0.535**
	[0.000203]	[0.000408]		[0.219]	[0.268]
po density sq	-1.12e-08	1.76e-07***	soil ph sq	-0.0352	-0.0545*
	[1.38e-08]	[2.12e-08]		[0.0242]	[0.0304]
gdp cap	0.0548***	0.0645***	soil CaCO3	-0.695***	-0.867***
	[0.0107]	[0.0129]		[0.138]	[0.206]
gdp cap sq	-0.00134***	-0.00137***	soil CaCO3 sq	0.189***	0.248***
	[0.000261]	[0.000281]		[0.0429]	[0.0615]
distance from cities	-0.000522***	-0.000669***	soil sodicity (ESP)	-0.0983***	-0.0512
	[0.000171]	[0.000215]		[0.0269]	[0.0405]
distance from ports	-0.000742***	-0.000865***	soil sodicity (ESP) sq	0.0103***	0.00742**
	[8.48e-05]	[0.000110]		[0.00216]	[0.00315]
latitude	0.156***	0.188***	dummy 1985	0.527***	0.496***
	[0.0146]	[0.0234]		[0.0500]	[0.0405]
elevation	-0.000634***	-0.000789***	dummy 1995	-0.413***	-0.440***
	[0.000166]	[0.000246]		[0.0508]	[0.0487]
elevation std	-0.000395	-0.000993*	dummy 2006	-0.0306	-0.0855
	[0.000330]	[0.000535]		[0.0583]	[0.0640]
			constant	0.386	4.195
				[3.846]	[5.600]
Obs	2,183	2,199	Adj R-sq	0.818	0.799

Table A2. Pooled and Hsiao models, coefficients.

APPENDIX - FIGURES





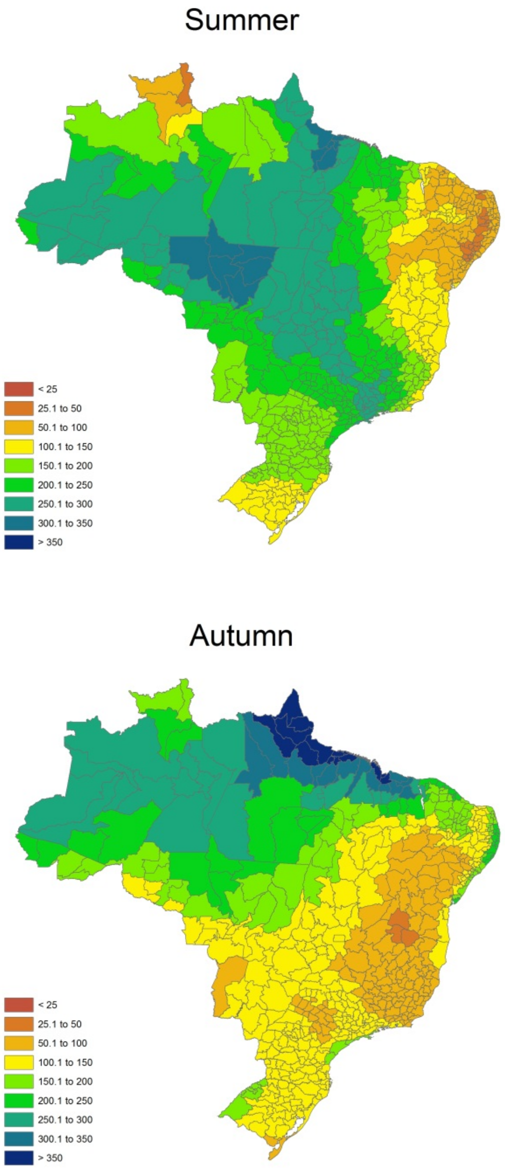


Figure A1. Seasonal precipitations.