Genetic breeding as an adaptive strategy to cope climate change in Brazilian agriculture

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ABSTRACT

An important adaptive strategy to cope climate change is plant breeding through the development of seeds resistant to water stress or high temperature. Therefore, the present paper provides an analysis of adaptation to climate change using genetic breeding on Brazilian farms. This work aims to investigate how climate change will affect the adoption of genetic breeding and the profitability of farmers. Temperature and rainfall projections for the 2010-2099 time periods were used, considering different climate scenarios (A1B and A2), according to IPCC (2007). The used framework was the Treatment Effects model. The results indicate that the probability of using transgenic seeds will grow from 74% in the current period to 86% in 2020, 83% in 2050, and 81% in 2080, in the A1B scenario. The producers who adopt this adaptation strategy will have higher profits. In the areas where genetic breeding is used in agriculture, the land value tends to be higher in both scenarios. Therefore, producers who adopt this adaptation measure will be less exposed to the adverse effects of climate change. Our conclusions corroborate that it is necessary to invest in adaptation strategies so that Brazil can overcome the adverse effects of global climate change.

Keywords: Climate change; adaptation; genetic breeding; Propensity score-matching; Brazil

1. Introduction

World population has been continuously growing since early 13th century. According to projections, the population will continue to increase until approximately 2050, resulting in several environmental problems, such as global warming (Oh et al., 2011). The agricultural sector, which directly depends on temperature and rainfall, is one of the most vulnerable to climate change (Deschênes and Greenstone, 2007). High temperature and water deficit are two important environmental constraints to plant growth and productivity in several countries (Ciais et al., 2005). Global climate change will presumably increase the occurrence and extend the distribution of these constraints, leading to further reduced productivity (Chaves et al., 2002; Lobell and Asner, 2003; Porter, 2005; Thuiller et al., 2005; IPCC, 2007). Temperature rise is expected to cause severe drought stresses in crops and, eventually, food shortages. Hence, it is believed that manipulation of high temperature and drought stress tolerance in plants may alleviate human suffering due to agricultural stresses (Oh et al., 2011).

Temperature and water supply (mainly by rainfall) are critical factors not only for productivity, but also for several physiological processes, such as seed dormancy (breaking and initiation) and germination. Furthermore, seedling emergence is a process synchronized with seasonal changes in the environment (Baskin and Baskin, 2000; Fenner and Thompson, 2005). The germination of some species occurs soon after dispersion, while in other species, it is delayed due to dormancy, until a favorable season, when the seedlings are able to survive, grow and then reproduce (Walck et al., 2011). Thus, climate changes, associated with other environmental changes (e.g. land use) can affect not only the productivity of crop plants, but also the entire production chain.

According to Seo and Mendelsohn (2008a), in order to adequately quantify the impacts of climate change on agriculture, it is necessary to consider adaptation strategies. The analysis cannot simply estimate how a particular culture will be affected, but it should recognize that producers will change their production decisions to maximize profit according to each climate scenario. In this context, studies which assume that producers will continue performing the same activities without changing their production techniques certainly overestimate losses. The main adaptation strategies to the agriculture sector included crop diversification and switching, changes in planting and harvesting seasons, irrigation, use of soil conservation techniques, shading, and use of genetic breeding.

The discovery of recombinant DNA technology allowed the development of transgenic seeds aiming to achieve, among other traits, increased tolerance or resistance to high temperature, drought, pathogens, and specific herbicide groups. Nowadays, both traditional breeding and genetic engineering of crop plants have been used to improve drought and high temperature tolerance or resistance aiming at increasing agricultural productivity in regions affected by global warming (Oh et al., 2011). Plant breeding also allows farmers to employ strategies for more rational use of soil and water, weed management and general inputs that allow increased production and income (Da Silva et al., 2007).

To date, transgenic crops occupy 10% of ~1.5 billion hectares of all cropland in the world (James, 2010). This report showed that developing countries were the main responsible for this amount. Brazil, Argentina, China, India, and South Africa planted 63 million hectares of transgenic crops in 2010, equivalent to 43% of the global total area, and are driving the adoption in developing countries. Further, transgenic soybean is the main transgenic crop, occupying 73.3 million hectares or 50% of global transgenic area, followed by maize (46.8 million hectares, or 31%), cotton (21.0 million hectares, or 14%) and canola (7.0 million hectares, or 5%). Thus, transgenic crops are already contributing to sustainability and can help mitigate the effects of climate change by contributing to food, feed and fiber security, and self sufficiency, including more affordable food, and by increasing productivity and economic benefits to farmer sustainability (James, 2010).

The main studies that analyzed climate change impacts on Brazilian agriculture (Siqueira et al., 1994; Sanghi et al., 1997; Nobre et al., 2005; Ávila et al., 2006; EMBRAPA, 2008) are unanimous in stating that climate change will cause a negative impact on the country. There is also agreement that the regions will be affected differently, which is directly related to the wide variation in climatic conditions throughout the national territory. However, with the exception of the analysis of change in land use of Evenson and Alves (1998), none of the several studies considered adaptation, which may overestimate the impacts. Therefore, the explicit inclusion of the use of genetic breeding as an adaptive strategy provides better understanding about the impacts on the Brazilian agricultural sector, thus contributing more effectively to future public policies aimed at creating strategies to combat the effects of global warming on agriculture.

In this scenario, the present paper aims to analyze climate change effects on Brazilian agriculture, considering genetic breeding as an adaptation strategy. Here we considered the use of transgenic seeds in the Brazilian agriculture as a proxy for genetic breeding. Thus, we investigated how climate variability affects the adoption of transgenic seeds and if this adaptation method will reduce farmers' vulnerability to climate alterations and, in affirmative case, how much producers who do not use these seeds would affected.

The methodology applied is described in Section 2, which explains how propensity score-matching estimators were used to obtain the average effect of the treatment. Section 3 describes the data sources and variables used in this study. The empirical results are presented in Section 4, followed by simulation results of future climate change scenarios. The final section presents a summary, conclusions and policy discussions.

2. Methodology

This study tests the hypothesis that the use of genetic breeding, specifically transgenic seeds, as an adaptive measure tends to mitigate the negative effects of global climate change on Brazilian agricultural sector. In fact, this decision is taken in a process to maximize benefits to ensure that only optimal choices are observed, regardless of which option was selected. The choice is an optimization action, influenced by the environment in which producers dwell (personal characteristics, economic conditions etc.). Transgenic seed adoption is voluntary and may be based on individual self-selection. Therefore, this is a classic nonrandom treatment assignment. In this scenario, the traditional regression analysis may not capture the true effects of the use of transgenic seeds on agricultural profits. This problem can be solved by matching methods, using a class of estimators called propensity score-matching estimators (PSM). This methodology was first developed by Rosenbaum and Rubin (1983). In this study, the standard matching procedure described in Heckman and Robb (1986), Heckman et al. (1997; 1998), and Bento et al. (2007) is adopted.

Following Bento et al. (2007), let Y_1 be the potential outcome in the “treated” state, which is the value of the land of the county that adopted transgenic seeds, and Y_0 is the potential outcome that would have happened in these counties had they not adopted these seeds. The farmer profitability was represented by land values because, according to Mendelsohn et al. (1994), land values are simply the present value of profits (or net revenues). These are called potential outcomes because only one of (Y_0, Y_1) is observed for each county. Let $D = 1$ indicate a county with areas that use transgenic seeds and let $D = 0$ indicate a county without such areas. Finally, let X be a vector of observed covariates affecting both transgenic seed adoption and outcomes. These covariates, such as soil, climatic characteristics and socioeconomic aspects of the counties will be detailed in the next section.

The effect of the use of transgenic seeds on farm profitability, measured by land values, is the parameter of interest. It is calculated by the mean effect of being in a county with areas that use transgenic seeds versus an observationally equivalent county, as measured by X, that does not use transgenic seeds. Formally, the parameter of interest is:

$$\Delta TT = E\left(Y_1 - Y_0 \,|\, D = 1\right) \qquad (1)$$

where ΔTT refers to the average treatment effect on the treated observations.

According to Bento et al. (2007), the matching method consists of finding a "proxy" for Y_0, since Y_0 is not observed for this treated observation (e.g., $D = 1$). This "proxy" is called counterfactual outcome, e. g., the one which would have resulted in case an individual farmer had not used transgenic seeds. Propensity score estimator will be defined as an estimator for $E\left(Y_0 \,|\, D = 1\right)$, using an appropriate subset of the $D = 0$ data. Matching estimators pair each treated observation with one or more observationally similar nontreated observations, using the conditioning variables, *X*, to identify similarity. This methodology is valid if outcomes are not dependent of the selection process, conditional on these *X*'s. As showed by Rosenbaum and Rubin (1983), the independence condition holds conditional on the propensity score $P(X)$ as well, which leads to the propensity score matching method.

The estimation of the model is carried out in three stages. In the first, a probit model of transgenic seed adoption is estimated. The estimated coefficients were used to predict the probability of using transgenic seeds for each observation, e.g., the propensity score. In the second, the data were divided into the treatment group (the counties that used transgenic seeds) and the control group (the counties that did not use transgenic seeds, but presented characteristics similar to those of the areas that adopted them), using the propensity scores. In the last step, it was estimated a counterfactual for each treated observation $\left(Y_1 \,|\, D = 1, P[X]\right)$ based on $\left(Y_0 \,|\, D = 0, P[X]\right)$ the kernel matching. The average effect of the treatment on the treated (the conditional mean difference), e.g., the impact of the use of transgenic seeds on farmers who actually adopted them is:

$$\begin{aligned}\Delta TT &= \left\{Y_1 - Y_0 \mid D = 1\right\} \\ &= E\left[E\left\{Y_1 - Y_0 \mid D = 1, P[X]\right\}\right] \\ &= E\left[E\left\{Y_1 \mid D = 1, P[X]\right\} - E\left\{Y_0 \mid D = 0, P[X]\right\} \mid D = 1\right]\end{aligned} \qquad (2)$$

The main objective of this research was to analyze the medium and long-term effects of climate change on agriculture. Thus, simulations were performed. In these simulations, projections of temperature and rainfall were used for three time periods: 2010-2039, 2040-2069 and 2070-2099. We considered two climate scenarios, A1B and A2, according to the Intergovernmental Panel on Climate Change (IPCC, 2007).

3. Data

Three categories of variables were used to compose the *X* vector: climatic, agronomic and socioeconomic (Table 1). The unit of observation was the Minimum Comparable Area (MCA), which refers to the aggregated area of the smallest number of counties needed to ensure the comparisons of the same geographical area at different time periods. Since MCAs represent county-level observations, we will refer to them as “counties”, to simplify the exposition. The use of farmer-level data for each variable would be ideal. However, the Instituto Brasileiro de Geografia e Estatística (IBGE) only provides these data without identifying geographic coordinates (latitude and longitude) to preserve the privacy of the farmers who answered to the Agricultural Census’ questionnaires. Therefore, it is not possible to assign values of climate variables to each producer. MCA was used to solve this problem.

Socioeconomic variables (aspects related to education, age, income, etc.) and those related to access to water resources were obtained from the 2006 Agricultural Census, published by IBGE. The agronomic aspects used referring to types of soil were provided by IPEADATA. These variables were created by overlaying geo-referenced county boundaries over geo-referenced land-attribute data.

Information about observed temperature and rainfall was extracted from CL 2.0 10' dataset, produced by the Climate Research Unit – CRU/University of East Anglia. The observed climate variables are temperature (°C) and rainfall (mm/month), for the 1961-1990 period. Monthly values were averaged to create two seasonal means: December through February (summer) and June through August (winter). This seasonal specification decreases the information loss associated with the conventional use of one month from each season and, at the same time, maintains a measure of the trends in intra-annual variation. In order to construct the variables, all climate data were converted into arcGIS shapefiles using their XY coordinates, these grid-points were joined to the MCA boundary layer, and the average temperature and rainfall were calculated for each MCA. Unlike the analysis already carried out for Brazil, which included only the first moments of temperature and rainfall distributions, in this study, climate variability was considered and the second moments of these distributions were included.

It is important to highlight that the decision of considering only summer and winter temperature and rainfall, instead of the four seasons, was based on studies by Seo and Mendelsohn (2008b) and Seo (2010, 2011). According to the authors, such specification is more appropriate to studies related to South America, since this region does not present four well defined seasons, differently from the USA. However, several specifications that also included other seasons were tested. The estimated models, with variables related to summer, autumn, winter, and spring, generally present few statistically significant coefficients (data not shown), confirming their low adequacy to the Brazilian case.

For the projected climate values, average data generated by ten General Circulation Models (GCMs) were used. The following models were used: CNRM_cm3, CSIRO_MK3.0, GFDL CM2.1, GISS ER, IPSL_CM4, MIROC3.2_medres, MPI ECHAM5, MRI CGCM2.3.2, UKMO_HADCM3 and UKMO_HadGEM1. The emission scenarios, A1B and

A2, are based on the 4th Assessment Report of IPCC (2007). For each model, climate data for four time series were provided: 1961-1990 (named current), 2010-2039 (2020), 2040-2069 (2050) and 2070-2099 (2080). Time series were used rather than single year projections, in order to prevent the selection of an outlier projection-year. Time series provide a better measure of the overall trend, which is the purpose of this study. Data on projected climate change were provided by the Centro de Previsão de Tempo e Estudos Climáticos/Instituto Nacional de Pesquisas Espaciais (CPTEC/INPE). Table 2 summarizes the climate scenarios of the three models for the years 2020, 2050 and 2080.

Finally, the dependent variable of the Treatment Effect Model is land value. This variable, provided by the IBGE 2006 Agricultural Censuses, is measured in terms of monetary units (1000 R$). Land values represent the best estimations by farmers of the value of their land without any improvements, such as buildings. All statistical procedures were performed using the Stata 11.0 software system (StataCorp LP, College Station, TX, USA).

4. Results and Discussion

First, the descriptive statistics of the variables presented by the two types of agricultural production (Table 3) will be examined. Among the 3123 counties considered in this work, 2039 (~ 65% of the total sample) presented areas where transgenic seeds were adopted. It was observed that the counties that use transgenic seeds were exposed to higher temperatures in both summer and winter. On the other hand, these counties were exposed to a lower volume of rainfall during summer. Both productions are also exposed to high rainfall and low temperature variability. These results are in agreement with the adoption of adaptive strategies, as evidence of the use of seeds tolerant or resistant to high temperatures and water deficit.

High temperatures are expected to cause severe water deficit in crop plant. Thus, transgenic seeds can be used to avoid drought effects. Therefore, drought can also occur due to irregular rainfall patterns among the seasons. These irregular patterns lead to seasonal soil water deficit and decreased productivity. Climate changes may also lead to increased incidence of pathogens, such as diseases caused by *Fusarium*, which are more severe in dry environments (Booth, 1971). Changes in temperature and rainfall patterns may affect the susceptibility of plants to pathogens. Plants growing in optimal temperature, water and nutrient conditions are able to tolerate a certain degree of infection. However, in less favorable environmental conditions, such as those resulting from climate change, plants become less tolerant and more susceptible to pathogen infection. Thus, the use of transgenic seeds resistant or tolerant to drought and pathogens becomes an essential tool for increasing productivity, especially in regions where climate variability is characterized by low rainfall and high temperatures.

Differences can be seen in agronomic and socioeconomic variables as well. Producers that use transgenic seeds had more access to water and were located in counties with high soil quality (Table 3). These data indicate that the use of transgenic seeds is related to the agronomic conditions of crop lands, because it would not be economically viable to adopt this strategy in areas where conditions were not satisfactory. The average of farms that did not receive technical guidance was lower among those that use transgenic seeds; these producers also had more experience than those who did not use transgenic seeds. On the other hand, access to higher education did not present significant differences (Table 3). In general, producers with these characteristics are expected to have good knowledge about genetic breeding technology and therefore are more likely to adopt the strategy.

Finally, the land values of producers that use transgenic seeds were higher than those of producers that have not adopted this strategy (Table 3). This is the first evidence that the use of transgenic seeds to reduce the risk associated with climate variability generates higher income to farmers and is an effective adaptation strategy.

Following the proposed methodology, the first part of the analysis consisted of estimating a probit model in order to obtain the propensity score (Table 4). The dependent variable received the value 1 if there were areas using transgenic seeds in a given county and 0, otherwise. The explanatory variables included were those described in Table 1. The model was highly significant, according to the Likelihood ratio statistics. The parameters are mostly significant at 1 and 10% level, and all climate coefficients are statistically different from zero.

The estimated probit model indicates that agronomic, socioeconomic, and climate conditions affect the use of transgenic seeds in Brazil. Accesses to water resources and availability of land in good conditions for agricultural practice (in terms of soil quality) are important aspects. Farmers' decision is also conditioned by their technical expertise and management capacity, which involves understanding about the potential and limitations of the technique, its operation and functioning. Good income conditions are also important. It was also observed that transgenic seeds have been adopted as a response to temperature changes rather than decreased rainfall. The expectation that the adoption of transgenic seeds is influenced by climate variations and, thus, can effectively be modeled as an adaptive strategy, was confirmed.

After propensity score estimation, it was possible to evaluate the performance of both producers that use and do not use transgenic seeds in the present and future climate change scenarios proposed by IPCC (2007). This analysis was performed by calculating the average effect of the treatment on the treated (ΔTT), for which the variable of interest was land value. Possible benefits of transgenic seeds as adaptive measure were evaluated as well as losses related to the decision of not using these seeds. Table 5 shows mean estimates of land value for each period of time and climate scenario.

Following Mendelsohn et al. (1994) and Seo (2011), simulations were performed by changing the climatic conditions and maintaining socioeconomic and agronomic conditions unchanged. According to Seo (2011), it should be noted that many aspects other than climate will change in the future, e.g. technological factors, economic development, agricultural policy, international trade, regimes etc. However, Seo (2011) explains that this kind of simulation aims to separate the effects of climate from other changes in economic conditions.

Results on Table 5 show that, in future simulations, returns associated to the use of transgenic seeds are always higher than the production systems that do not use these seeds. The P-value indicates that the differences between the two classes of producers are statistically significant at less than 1%. In the counties where transgenic seeds are used, the average land value tends to increase (although there is little reduction in the period 2070-2099, compared to 2040-2069 in A1B scenario). There is a significant reduction in the average land value in the counties where agricultural production is performed exclusively without transgenic seeds. Losses can range from R$ 21.7 million (scenario A1B) in the short term to 15.8 million (scenario A2) in the long term.

According to Schlenker et al. (2005), benefits and costs are capitalized in future land values. Thus, it can be stated that under climate change scenarios, the profits achieved with transgenic seed adoption outweigh its costs. This result is consistent with those presented by Margulis and Dubeux (2010). According to these authors, the relationship between the cost of investment in genetic breeding and the benefit (measured by the losses avoided) seems to be advantageous, ranging from 8% in 2020 to 5% in 2070 for soybean production, and 8% to 11% for rice production.

It can be argued, therefore, that producers who use transgenic seeds will be less exposed to the negative effects of climate changes. Average global temperatures have been continuously growing since the past decades and will continue to increase in coming years, which may present high frequency of extremely hot days (Asseng et al., 2011). Temperature rise is expected to accelerate phenological processes of plant development, resulting in a short growing season. A wide range of crops are vulnerable to thermal stress. Wheat plants exposed to high temperature, for example, show rapid leaf senescence and reduction of about 50% of grain yield (Zhao et al., 2007). Furthermore, the interactions between the predicted increase in air temperature (and, consequently, in soil temperature), dormancy and seed viability could lead to decreased agricultural productivity, especially in developing countries located at lower latitudes. Thus, by adopting transgenic seeds tolerant or resistant to high temperature, farmers will decrease the risk related to changes in the weather pattern, avoiding direct and indirect loss.

Water availability limits the growth and development of plants and this problem tends to worsen in climate change scenarios. About 70% of the water in the planet is used for agricultural purposes; it is estimated that about 3000 liters of water are necessary to feed one person per day. Water use has increased substantially with agricultural productivity improvement, which can lead to depletion of surface and underground water. Drought resulting from climate change can lead to sharp increases in food prices and poverty in developing countries. This trend should persist as a result of changes in weather patterns resulting from climate change (FAO, 2003; Gornall et al., 2010). The use of transgenic crops less vulnerable to drought, obtained from a group of genes that collectively optimize water use, is an economically viable alternative to overcome the predicted impacts of climate change. Thus, addressing temperature and water issues requires the most realistic estimates that are possible of plant response to climate change.

However, there are still legal and cultural barriers against the use of transgenic seeds in Brazil. Much has been said about the dangers to the environment and human health related to genetically modified organisms. Nowadays, there are few transgenic lines approved and commercially available in Brazil. Away of political and speculative issues, this study aimed to simply analyze the cost and benefit of the use of transgenic seeds in a perspective of global climate change. It is known that the use of transgenic seeds involves a series of reductions in production costs, such as demands for water, pesticides and herbicides. Furthermore, transgenic crops have increased their productivity, since annual yields are higher. Thus, it is believed that, given the upcoming effects of climate change, legal and cultural restrictions on the use of transgenic crops will be relieved.

5. Conclusions and Outlooks

The results confirmed prior expectations that the adoption of genetic breeding is influenced by climate variations and, thus, should be modeled as an adaptive strategy. Under current conditions, transgenic seeds have been adopted as a response to temperature variations rather than to reduced rainfall.

It is possible to conclude that the land values of producers that use transgenic seeds tend to be more stable, demonstrating the effectiveness of transgenic seeds as an adaptive measure. Given climate change predictions, transgenic crops may improve agricultural performance of the country, making producers less vulnerable to climate. It is confirmed, thus, the need to include adaptation measures in the estimation, providing good assessment of the actual events. Ignoring the adjustment makes the estimation of impacts overestimate damages, sometimes dramatically.

It is necessary to point out some limitations of this study. The present work did not capture the full range of adjustments that can be performed; in particular, when assuming fixed portions of land, it was not possible to analyze how the pattern of land use for (non) agricultural purposes will change. Since it is a partial equilibrium study, it does not deal with the implications of these results in terms of the effects on other sectors of the economy. It is suggested that future studies should consider these issues. It is also important to note that studies of crosstalk simulations of different adaptive measures, such as an integrative view of the relations between irrigation and genetic breeding, must be of great value to understand the magnitude of the impacts.

Although the results indicate a less pessimistic scenario for the effects of climate change, public policies should seek strategies to combat the effects of global warming in agriculture sector. Moreover, given the importance of genetic breeding to mitigate the effects of climate change, specific credit policies for future research in this area should be encouraged.

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Table 1 – Climatic, agronomic and socioeconomic variables used in this work

Variable	Description
Climatic variable	
Summer temperature	Summer average temperature (°C)
Summer rainfall	Summer total rainfall (mm)
Winter temperature	Winter average temperature (°C)
Winter rainfall	Winter total rainfall (mm)
Temperature variability	Second moment of temperature distribution
Rainfall variability	Second moment of rainfall distribution
Agronomic variable	
Water resources	Number of agricultural establishments with water resources
High agricultural potential	Proportion of land area in the county with high soil quality
Low agricultural potential	Proportion of land area in the county with low soil quality
Socioeconomic variable	
Farm income	Value of income earned by the farms (1000 R$)
Age of head	Number of farms run by someone from 25 to 45 years old
Education of head	Number of farms managed by someone graduated from a university
Without technical guidance	Number of farms which had not received any technical guidance
Seeds costs	Mean value of seed cost per county (R$)
Land value	County land value (1000 R$)

Table 2 – Brazilian average GCM climate scenarios

	Current	2020	2050	2080
Summer temperature (°C)				
A1B	24.5	25.5 (+1.0)	26.4 (+1.9)	27.5 (+3.0)
A2	24.5	25.4 (+0.9)	26.5 (+2.0)	27.9 (+3.4)
Winter temperature (°C)				
A1B	20.2	21.6 (+1.4)	22.6 (+2.4)	23.6 (+3.4)
A2	20.2	21.5 (+1.3)	22.5 (+2.3)	24.1 (+3.9)
Summer rainfall (mm/month)				
A1B	167	164 (-1.8%)	167 (0.0%)	168 (+0.6%)
A2	167	164 (-1.8%)	166 (-0.6%)	168 (+0.6%)
Winter rainfall (mm/month)				
A1B	56	63 (+11.1%)	63 (+11.1%)	63 (+11.1%)
A2	56	64 (+12.5%)	62 (+9.7%)	63 (+11.1%)

Notes: 1) A1B and A2 refer to the Intergovernmental Panel on Climate Change scenarios (IPCC, 2007). 2) "Current" refers to the baseline climate for 1961-1990.

Table 3 – Descriptive statistics on agricultural production in Brazil

Variable	Treated		Control	
	Mean	Std	Mean	Std
Summer temperature	24.64	1.97	24.19	1.96
Summer rainfall	158.41	74.80	190.44	68.47
Winter temperature	20.48	4.00	19.59	3.43
Winter rainfall	56.09	52.10	51.28	50.51
Temperature variability	3.71	3.19	3.80	2.12
Rainfall variability	5,361.03	3,792.87	5,649.12	3,209.85
Water resources	224.93	270.41	81.91	125.05
High agricultural potential	0.13	0.27	0.07	0.22
Low agricultural potential	0.52	0.41	0.64	0.43
Farm income	10,425.38	31,087.42	11,276.70	28,151.00
Age of head	425.01	428.77	176.20	209.08
Education of head	29.11	37.29	31.12	32.91
Without technical guidance	17.88	42.43	39.72	85.78
Seed costs	278.31	1,056.13	335.94	6,842.60
Land value (R$ 1000)	56,531.79	113,714.10	44,516.75	83,516.48
Number of counties	2039	–	1084	–

Note: “Treated” refers to producers who use transgenic seeds and “Control” refers to producers who do not use them.

Table 4 – Probit estimatives of transgenic seed adoption in Brazil

Variable	Estimative	P-value^{HC}
Summer temperature	0.3249874***	0.0000
Summer rainfall	-0.0055190***	0.0000
Winter temperature	0.2428232***	0.0000
Winter rainfall	-0.0041580***	0.0000
Temperature variability	0.2162869***	0.0000
Rainfall variability	0.0000425***	0.0020
Water resources	0.0014623***	0.0030
High agricultural potential	0.2011681*	0.0760
Low agricultural potential	-0.1367245*	0.0500
Farm income	0.0000015*	0.0870
Age of head	0.0010751***	0.0000
Education of head	-0.0006022^{NS}	0.4790
Without technical guidance	0.0008311^{NS}	0.4270
Seed costs	-0.0000037^{NS}	0.3910
Intercept	3.160977***	0.0000

Notes: 1) The Likelihood ratio statistics for the model is 1,677.69 with $P<0.00001$. 2) P-Value^{HC} denotes heteroscedasticity consistent P values. 3) * implies significance at 10% and *** implies significance at 1%. 4) ^{NS} refers to no significant difference.

Table 5 – Impacts of climate scenarios on conditional land value (with and without transgenic seed production)

Variable	Treated	Control	ΔTT	P-value
Land value (current period)	56,134.57	42,134.19	14,000.37	0.001
A1B Scenario				
Land value (2010-2039)	63,303.41	41,570.25	21,733.15	0.000
Land value (2040-2069)	56,184.08	42,045.39	14,138.68	0.000
Land value (2070-2099)	55,121.21	40,635.91	14,485.29	0.000
A2 Scenario				
Land value (2010-2039)	56,607.35	43,864.05	12,743.29	0.006
Land value (2040-2069)	56,348.82	43,068.50	13,280.32	0.000
Land value (2070-2099)	56,531.78	40,736.71	15,795.07	0.001

Notes: 1) “Treated” refers to producers that use transgenic seeds, and “Control” refers to producers that do not use them. 2) Land values are represented in R$ 1000. 3) ΔTT was estimated by kernel matching. 4) P-values based on the standard error were calculated by bootstrap.