Acta Scientiarum
http://www.uem.br/acta
ISSN printed: 1679-9275
ISSN on-line: 1807-8621
Doi: 10.4025/actasciagron.v36i1.15375

Effects of climate change on irrigation adoption in Brazil

Dênis Antônio da Cunha[1*], Alexandre Bragança Coelho[1], José Gustavo Féres[2] and Marcelo José Braga[1]

*[1]Programa de Pós-graduação em Economia Aplicada, Departamento de Economia Rural, Universidade Federal de Viçosa, Av. Peter Henry Rolfs, s/n, 36570-000, Viçosa, Minas Gerais, Brazil. [2]Instituto de Pesquisa Econômica Aplicada, Rio de Janeiro, Rio de Janeiro, Brazil. *Author for correspondence. E-mail: denis.cunha@ufv.br*

ABSTRACT. The aim of this paper is to analyse the effects of climate change on irrigation adoption in Brazil. Temperature and precipitation projections for the 2010-2099 periods were employed under a number of different climate scenarios according the 4th Assessment Report of Intergovernmental Panel on Climate Change (IPCC). The results show that irrigation adoption will be affected by climate change. Given current conditions, irrigation has generally been adopted in Brazil to cope with reduced precipitation and temperature variations. The estimated irrigation probabilities in the future scenarios were quite different across Brazilian regions. The main explanation for this pattern is the distinct climatic conditions and production structures. Considering future climate change, over the next 30 years (2010 to 2039), the irrigation probability is expected to increase in all Brazilian regions. However, this trend is reversed in the long run.

Keywords: climatic variability, adaptation, irrigated farming.

Efeitos das mudanças climáticas sobre a adoção de irrigação no Brasil

RESUMO. O principal objetivo deste estudo foi analisar os efeitos das mudanças climáticas sobre a utilização de irrigação no Brasil. Foram utilizadas projeções de temperatura e precipitação para o período de 2010 a 2099, sob diferentes cenários climáticos, conforme o 4º relatório do Painel Intergovernamental de Mudanças Climáticas. Os resultados confirmaram que a decisão de irrigar será afetada pelas mudanças climáticas. Dadas as condições atuais, a irrigação tem sido adotada no Brasil mais como resposta à redução da precipitação do que às variações de temperatura. As probabilidades de irrigação estimadas para os cenários futuros foram bastante diferentes entre as regiões brasileiras. A principal explicação para esse padrão são as distintas condições climáticas e estruturas de produção. Considerando as mudanças climáticas, há expectativa de aumento na probabilidade de irrigação para os próximos 30 anos (2010 a 2039) em todas as regiões brasileiras. No entanto, esta tendência é invertida no longo prazo.

Palavras-chave: variabilidade climática, adaptação, agricultura irrigada.

Introduction

Global climate change and its consequences have been widely discussed by the scientific community, mainly from the 1990s on. Such changes, the magnitude of which is not fully known, are manifested in different ways, especially global warming. Based on the information available, studies have indicated effects on the current period and constructed projections for future scenarios. The uncertainty surrounding the magnitude of regional and sectorial impacts will persist in the foreseeable future and additional research is necessary.

The agricultural sector is one of the most vulnerable to climate change because it depends heavily on temperature and rainfall (DESCHÊNES; GREENSTONE, 2007). Climate influences plant growth and development, as well as several components of the agricultural chain, such as land preparation for sowing, planting dates, and the harvest, transport and storage of crops. Climatic conditions can also affect the relationship between plants and pathogens, leading to social and economic losses. In addition, adverse weather phenomena that are difficult to predict in the medium and long term, such as frost, drought, hail or excessive rainfall, can increase the risks associated with agriculture.

According to Seo and Mendelsohn (2008b), to effectively measure the impacts of climate change on agriculture, one must take adaptation strategies into account. The analysis cannot simply estimate how a particular culture will be affected, but should recognise that profit-maximising producers will change their production decisions according to distinct climate scenarios. Studies that assume that producers will continue planting the same varieties without changing their production techniques certainly overestimate losses.

Planning for climate adaptation necessarily requires a comparison of potential decisions, taking into account the advantages and limitations of each technique and the uncertainties associated with climate change (PIDGEON; FISCHHOFF, 2011). The main adaptation strategies in the agricultural sector include crop diversification and switching, changes in planting and harvesting seasons, adoption of irrigation practices, use of soil conservation techniques, shading and genetic breeding. According to Magrin et al. (2007) and Seo (2011), irrigation is a major adaptation measure implemented by farmers in Latin America and elsewhere in response to climate change. By adopting irrigation practices, farmers reduce the potential risks associated with insufficient rainfall.

According to the 2006 agricultural census (IBGE, 2006), irrigated agriculture in Brazil occupies approximately 4.4 million hectares, corresponding to 6% of total cultivated land. Most irrigated areas are located in the South and Southeast regions. Notwithstanding the small share in terms of total cropland, irrigated areas have been increasing rapidly[1]. This rapid expansion continues: according to Christofidis (2006), there are approximately 30 million hectares of soil suitable for the sustainable development of irrigated agriculture in Brazil[2]. Most of the potential irrigated land is located in the North and Mid-West regions, the main axis of the Brazilian agricultural frontier. Moreover, there are abundant water resources in Brazil (the country holds approximately 12% of the planet's fresh water reserves). According to Margulis and Dubeux (2010), we must also consider that while some estimates indicate reduced surface water in Brazil due to climate change, the volume of groundwater in the main watershed tends to increase or at least remain constant, without compromising the possibility of adopting this adaptive strategy.

In this context, the main objective of this paper is to analyse the effects of climate change on irrigation adoption in Brazilian counties, considering this technique as an adaptive strategy. Simulations were performed to verify changes in the decision to irrigate under future climate change scenarios. We also studied regional effects and the main factors associated with irrigation adoption.

This analysis is important because there has been an increase in interest, among rainfed farmers mainly after the production losses that occurred in 2004 and 2005, in irrigation systems. However, the lack of capital that has characterised the sector in recent years has inhibited the adoption of irrigation. Thus, this study aims to assist the design of specific credit policies for the implementation of such systems. In addition, we wish to extend the literature about the effects of climate change on irrigation adoption, which is still very limited in Brazil.

Material and methods

A multi-output production model based on Negri et al. (2005) was used to explore the complex influences of climate on agricultural production decisions. This model permits both output and input substitution and a discrete choice of inputs, e.g., farmers can adapt to new climate conditions by changing the varieties produced or the production techniques. In this paper, the emphasis is on the adoption of irrigation, which is modelled explicitly as an adaptive strategy.

The model assumes that the choice between adopting irrigation or practicing dryland agriculture is made by producers to maximise their profits. Thus, the probability that such a form of farming is chosen depends on its profitability. This decision can be represented by

$$\max \ \prod(P_q, P_x, \varpi, N, E) = \max_{X,T}\{P_q{}'Q - P_x{}'X - \varpi T \ : \ Q \in Q(X, E, N, T)\} \qquad (1)$$

where:

Q is a vector of agricultural products and X is a vector of variable inputs;

P_q and P_x refer, respectively, to vectors of the exogenous prices of products and inputs;

T is a scalar that represents the discrete irrigation choice ($T = 1$ if there is irrigation);

ϖ is the annual cost of irrigation and E is a vector of exogenous variables, including soil and climatic characteristics (such as soil types, temperature and rainfall), demographic factors, socioeconomic, and structural factors that affect the irrigation decision;

N is the amount of land used for agricultural production, which is regarded as a fixed input;

lastly, $Q(X, E, N, T)$ is the restricted set of production possibilities imposed by production technology, land restrictions (N), exogenous variables (E) and the discrete irrigation choice (T).

---

[1] Irrigated areas increased 1.2 million hectares between the census years of 1996 and 2006, which in percentage terms corresponds to a 42% increase in irrigated area.

[2] The term 'sustainable' indicates that the estimate has taken into consideration the existence of suitable soils, the availability of water resources that do not have the risk of conflict with other water utilisation priorities and compliance with environmental legislation.

The decision to produce using irrigation, as opposed to dryland production, is assumed to be discrete: the irrigation system is either installed or not. As T^I and T^S refer to the production technology of irrigated and dryland production, respectively, the associated indirect profit functions may be written as

$$\begin{aligned}\Pi_{1i}(P_q, P_x, \varpi, N, E) &= \max_X \{P_q'Q - P_x'X - \varpi T^I : Q \in Q(X, E, N, T^I)\} \\ \Pi_{2i}(P_q, P_x, N, E) &= \max_X \{P_q'Q - P_x'X \ : Q \in Q(X, E, N, T^S)\}\end{aligned} \quad (2)$$

A profit-maximising producer *i* will install irrigation infrastructure $\Pi_{1i}(P_q, P_x, \varpi, N, E) > \Pi_{2i}(P_q, P_x, N, E)$ This decision making process is such that only optimal choices are observed. Hence the choice is not an exogenous variable, but an optimisation action influenced by the environment in which the producer is situated. In other words, the decision to irrigate depends on water availability, soil characteristics, the variety planted, socioeconomic and climatic conditions.

Adding random error terms, to represent unobserved variables that influence profits under both rainfed and irrigated regimes, the profit functions given by (2) may be expressed in stochastic terms. The farm now faces a probabilistic choice and adopts irrigation when

$$\Pi^I(P_q, P_x, \varpi, N, E) + \varepsilon_I > \Pi^S(P_q, P_x, N, E) + \varepsilon_S \quad (3)$$

where ε_I and ε_S denote additive, random and independent errors.

Defining p^I as the probability of installing irrigation capacity, we have:

$$\begin{aligned}p^I(T = T^I \mid P_q, P_x, \varpi, N, E) &= \Pr[\Pi^I(P_q, P_x, \varpi, N, E) \\ &- \Pi^S(P_q, P_x, N, E) > \varepsilon_S - \varepsilon_I]\end{aligned} \quad (4)$$

Any standard probability model can be used to estimate p^I, for example, $p^I(T = T^I \mid P_q, P_x, \varpi, N, E) = F\{h(W_i)\}$. In this paper, a Probit model was selected, where $F(\cdot)$ is the normal cumulative distribution and $h(W_i)$ is a function of covariates with linear and higher order terms.

Description of data set

To compose the W_i vector, three categories of variables were used: socioeconomic, agronomic and climatic (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 that the same geographic area is being compared in different time periods. Because MCAs represent county-level observations, to simplify the exposition we will refer to them as 'counties'[3].

Table 1. Variables description.

Variables	Description
Summer temperature	Summer average temperature (°C).
Summer precipitation	Summer total precipitation (mm).
Winter temperature	Winter average temperature (°C).
Winter precipitation	Winter total precipitation (mm).
Temperature variability	Second moment of temperature distribution.
Precipitation variability	Second moment of precipitation distribution.
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.
Erosion potential	Proportion of land area in the county with high erosion potential.
Land owner	Number of farms in which the farmer is the land owner.
Internet access	Number of farms with access to the Internet.
Farm's income	Value of income earned by the farms (1,000 R$).
Age of head	Number of farms runned by someone whose age group is 25 to 45 years old.
Education of head	Number of farms which is managed by someone graduated in a university.
Without technical guidance	Number of farms that had not received any technical guidance.

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

Information about observed temperature and precipitation were 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 precipitation (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 a single month from each season and, at the same time, maintains a measure of the trends in intra-annual

---

[3] The use of farmer-level data for each variable would be ideal. However, the IBGE provides these data without identifying geographic coordinates (latitude and longitude) to preserve the privacy of farmers who completed Agricultural Census questionnaires. Therefore, it is not possible to assign values of climate variables to each producer. To overcome this difficulty, we used MCA.

variation. To construct the variables, all climate data were converted into arcGIS shapefiles using their XY coordinates, integrating these grid-points with the MCA boundaries layer, and the average temperature and precipitation were calculated for each MCA. Unlike previous analyses of the Brazilian case, which included only the first moments of the temperature and precipitation distributions, in this study climate variability was considered by including the second moments of these distributions.

It is important to highlight that the decision to only consider summer and winter temperature and rainfall, instead of all four seasons, was based on studies by Seo and Mendelsohn (2008a) and Seo (2010, 2011). According to the authors, such a specification is more appropriate to studies regarding South America, as this region does not present four well-defined seasons, as is the case in the USA, for example[4].

For the projected climate values, average data generated by 10 General Circulation Models (GCMs) were used[5]. The emission scenarios, A1B and A2, are based on the 4th Assessment Report of the IPCC (2007). Emissions scenarios for radiatively important substances result from socioeconomic and technological development pathways. The A1B scenario describes a future where there will be a balance across all energy sources (fossil intensive and non-fossil). This balance is defined as not relying too heavily on a particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies. The A2 scenario describes a very heterogeneous world. The underlying theme is self-reliance and the preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented, and per capita economic growth and technological change are more fragmented and slow than in other scenarios (IPCC, 2007).

For each model, climate data for four time slices were provided: 1961-1990 (named ‘current’), 2010-2039 (‘2020’), 2040-2069 (‘2050’) and 2070-2099 (‘2070’). Table 2 summarises the climate scenarios of the three models for the years 2020, 2050, and 2080.

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^{-1})				
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^{-1})				
A1B	56	63 (+11.1%)	63 (+11.1%)	63 (+11.1%)
A2	56	64 (+12.5%)	62 (+9.7%)	63 (+11.1%)

Time slices were used rather than single year projections to avoid the possibility of selecting an outlier projection-year. Timeslices 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.

Results and discussion

We begin by examining the irrigated area in Brazil. Figure 1 shows the spatial distribution of irrigated land in Brazil. The state of Rio Grande do Sul presents the largest irrigated area in the country, with 794,000 hectares, representing approximately 22% of the total, primarily due the production of rice in flooding systems. The states of São Paulo and Minas Gerais are also highlighted and have 747,000 and 453,000 hectares of irrigated land, respectively (approximately 17 and 10% of the total, respectively). In the Northeast region, the state of Bahia has 287,000 hectares of irrigated land (6.5% of the total), mainly due the fruit production in the northernmost area of the state. The North region has less irrigated area compared to other regions in Brazil, generally due to the smaller proportion of agricultural land and the prevalence of extensive livestock farming.

The spatial distribution pattern of irrigated land observed in Figure 1 can be related, among other factors, to the climate characteristics of the regions. According to Silva et al. (2010), the geographical regions can be described as follows:

North: high temperatures throughout the year and a well-defined rainfall pattern (experiences a dry season from June to November and a wet season from December to May). The warm and humid climate virtually eliminates the need for irrigation.

Northeast: characterised by high temperatures and an uneven rainfall pattern, with an annual average ranging from less than 250 to 750 mm. The climate conditions are extremely favourable to

---

[4] However, several specifications, including other seasons, were tested. The estimated models, with variables for summer, autumn, winter, and spring, generally present few statistically significant coefficients, confirming their inadequacy for the Brazilian case.

[5] The models used were: 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.

irrigated agriculture, especially in fruit cultivation, horticulture and grain production. Recently, this region has seen increased adoption of irrigation systems, such as sprinkler and drip, especially in fruit production.

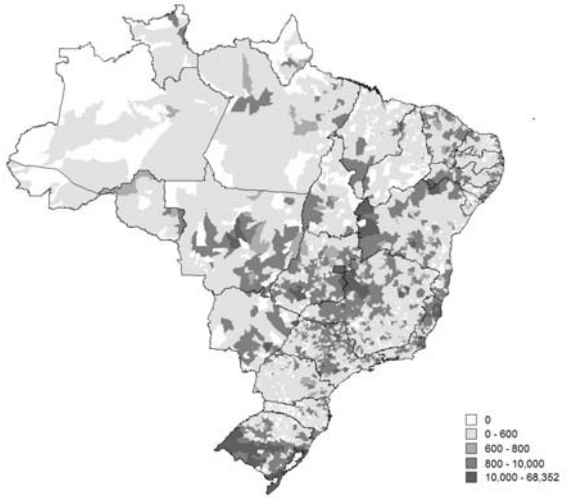

Figure 1. Irrigated area (ha) in Brazil according to Agricultural Census (IBGE, 2006).

Southeast: presents high temperatures in summer and mild ones in winter. Moreover, there is a wet season during summer while the winter is moderately dry. Farmers usually adopt irrigation only in a complementary way, especially during winter.

South: characterised by warm and wet summers and cold and dry winters. There is no regularity or uniformity in the rainfall and climate patterns. Regarding irrigation, this region has large flooded areas, especially in rice production in rotation with pastures. In years with particularly dry winters, irrigation may be an additional guarantee for production.

Central-West: this region is warm and wet during the summer and dry during the winter. The rainfall distribution pattern in the far west of the region can reach up to 2,500 mm year^{-1}, reaching 1,000 mm year^{-1} in the east of the region, requiring both supplemental and continuous irrigation during the six-month dry season.

Regarding the main crops produced in the Brazilian agricultural sector, the cultivation of rice and other grains, as well as sugar cane, are the major irrigation users, with 1,241.716 and 1,044.936 hectares, respectively, corresponding to 28 and 23% of the total irrigated area in the country. The production of soybean, fruits, horticulture, ornamental plants and coffee are also notable for their use of irrigation; altogether, they account for approximately 26% of irrigated land in Brazil.

After this brief description of irrigated areas in Brazil, we present descriptive statistics for the variables used in this study. The values for two types of agricultural production are shown in Table 3. There were no significant differences in mean temperature. Difference between rainfed and irrigated production can be observed mainly in precipitation variables. Irrigated production received lower rainfall volume; this difference was more significant during winter. Therefore, when precipitation is abundant, farmers tend to practice rainfed agriculture, but as the conditions becomes drier, there is a gradual transition to irrigated systems. Similar results are found by Seo (2011), who examined irrigation in Latin America. It is also important to emphasise that irrigators and dryland farmers were exposed to high precipitation variability and low temperature variation.

Differences can also be observed in agronomic and socioeconomic variables. Dryland producers had less access to water and were located in counties with poor soil quality. The average number of farms that did not receive technical guidance was lowest among irrigators; these farms also had greater access to the Internet and higher levels of education. In general, producers with these characteristics are expected to be knowledgeable about irrigation technology and therefore are more likely to adopt the technique.

Table 3. Descriptive statistics on agricultural production in Brazil.

Variables	Irrigators		Rainfed	
	Mean	Std	Mean	Std
Summer temperature	24.43	1.97	24.67	2.01
Summer precipitation	168.86	74.10	171.46	74.64
Winter temperature	20.02	3.65	20.63	4.31
Winter precipitation	52.67	51.31	59.46	52.15
Temperature variability	3.74	2.71	3.75	3.28
Precipitation variability	5,437.18	3,398.00	5,529.35	4,137.05
Water resources	969.14	2,478.62	958.06	1,949.93
High agricultural potential	0.11	0.27	0.09	0.24
Low agricultural potential	0.56	0.43	0.57	0.41
Erosion potential	0.43	0.36	0.38	0.35
Land owner	1,160.67	2,475.59	1,189.63	2,078.59
Internet access	25.64	66.02	12.2	21.90
Farm’s income	41,641.30	134,372.00	20,597.36	38,461.33
Age of head	527.93	1,195.65	585.52	1,119.25
Education of head	47.69	83.35	29.10	43.68
Without technical guidance	42,999.50	219,918.60	71,510.35	254.928,80
Number of counties	3,123		808	

Note: Land values are represented in R$ 1,000.

Following the proposed methodology, the first part of the analysis consisted of estimating a Probit model (Table 4). The dependent variable took the value 1 (one) if there was irrigated land in a given county, 0 (zero) otherwise. The explanatory variables included were those described in Table 1. The model was highly significant according to the Likelihood Ratio statistic. The parameters are mostly significant at the 5% level, and all climate coefficients are significantly different from zero.

The estimated probit model indicates that agronomic, socioeconomic, and climate conditions influence the use of irrigation in Brazil. To test the robustness of the signs and significances of the parameters shown in Table 4, alternative specifications were tested, including only climatic variables or only agronomic and socioeconomic conditions. In all of these estimations, the variables' signs were the same and the estimated parameters were statistically significant. This result indicates, as in Mendelsohn and Seo (2007), Kurukulasuriya et al. (2011) and Seo (2011), that irrigation adoption is sensitive to both temperature and precipitation, which validates it as an adaptive strategy.

Table 4. Probit estimatives.

Variables	Estimatives	P-Value^{HC}
Summer temperature	-0.973374	0.076
Summer temperature squared	0.019682	0.059
Summer precipitation	-0.003958	0.000
Winter temperature	0.496995	0.034
Winter temperature squared	-0.014755	0.001
Winter precipitation	-0.003417	0.000
Temperature variability	-0.104093	0.025
Precipitation Variability	0.000053	0.000
Water resouses	0.000146	0.059
High agricultural potential	0.232210	0.035
Low agricultural potential	-0.008683	0.908
Erosion potential	0.262831	0.001
Land owner	-0.000079	0.192
Internet access	0.007533	0.000
Farm's income	0.000004	0.000
Age of head	0.000217	0.060
Education of head	0.004495	0.002
Without technical guidance	-0.000002	0.000
Intercept	9.333422	0.051

Notes: The Likelihood Ratio statistic for the model is 292.46 with P-value < 0.0000; P-Value^{HC} denotes heteroscedasticity consistent P values.

Regarding agronomic and socioeconomic conditions, the results confirm previous expectations. Access to water resources and the availability of land with high agricultural potential are equally important. The role of information also seems important. Farmers with internet access are more likely to irrigate. However, if the farmers do not take advantage of technical guidance, the irrigation probability decreases. The results for age and education indicate that a farmer's decisions are limited by technical expertise and management capacity. Finally, the higher the farmer's income, the higher the irrigation probability, as the installation of irrigation systems involves high costs.

Important conclusions can be made regarding the climate variables. An analysis of the linear and quadratic terms of summer temperature indicated a U-shaped relationship. In others words, if temperature rises, the irrigation probability decreases to a minimum level and then increases. This pattern can be attributed to summer characteristics; temperature increases are followed by increasing rainfall during summer in Brazil. In addition, water input volume in an agriculture system depends on species, cropland, soil type, sowing date and plant development stage. During the seeds' maturation and germination stages, as well as during initial seedling growth, the presence of excess water in the soil can be harmful to plants because this can lead to increased soil humidity and cause the growth of fungus and other pathogens (BERNARDO, 1997; NEGRI et al.; 2005).

Moreover, it is well known that irrigation is a widespread strategy designed to meet the water requirements of crops, and high temperatures can have different impacts, depending on soil humidity. Hence if the soil's available water content for plant growth is kept constant, irrigation requirements decrease even when temperature increases. However, if the environment becomes warmer and exceeds the optimum growth temperature, plant development is likely to be impaired. Thus, an increase in irrigation represents a strategy to mitigate the adverse effects of high temperatures.

For winter temperatures, the signs indicated an opposite pattern. In other words, increased temperature increases the probability of irrigation up to a maximum value that then decreases. This result is similar to Mendelsohn and Seo (2007) and Seo (2011). When irrigation decisions are made prior to the growing season based on expected weather conditions for the period, it is reasonable that higher irrigation is more likely when higher temperatures are expected. However, as stated by Mendelsohn and Seo (2007), for certain levels of temperature increases, the expected irrigation profitability becomes less significant because plants have heat tolerance limits. Thus, irrigation efficiency decreases and the gains may not compensate for the costs.

The explanation provided by Mendelsohn and Seo (2007) also applies to the sign of temperature variability. Initially, it was expected that increased temperature variance would lead to increased irrigation. However, the negative sign makes sense if increased variance represents an increased risk of substantial periods of high (or low) temperatures and if, for certain levels of increase (decrease) in temperature, irrigation does not have substantial adaptive power and is less profitable. This could indicate that irrigation in Brazil is adopted in response to water stress rather than a warmer climate.

The rainfall variables exhibited the expected signs. As rainfall increases, the probability of irrigation decreases. Irrigation is a response to water scarcity and is crucial for increased yields (COELHO et al., 2006). However, as noted by

Mendelsohn and Seo (2007), the marginal contribution of irrigation to the profitability of producers decreases as rainfall increases. This is reasonable, as producers do not need to make intensive use of irrigation techniques in areas where rainfall volumes are high. In the case of rainfall variance, the positive sign may indicate risk-averse producers, who tend to become irrigators when there is an increased risk of droughts.

After the Probit estimation, it was possible to evaluate irrigation probability under future climate scenarios. The objective of the simulation was to analyse how the irrigation decision will be affected by changes in temperature and precipitation. According to Rolim et al. (2012), due to climate change, we cannot continue to design irrigation systems and conduct irrigation management based solely on historical records from weather stations and assume that the statistical parameters of the meteorological data remain unchanged over time; it is necessary to consider the climate data relative to climate change scenarios. This analysis was performed using the temperature and precipitation values estimated in future scenarios proposed by the IPCC (2007).

Following Seo (2011), simulations were performed that changed climate conditions and kept socioeconomic and agronomic conditions unchanged. According to Seo (2011), it should be noted that many features other than climate will change in the future, e.g., technological factors, economic development, agricultural policy, international trade regimes, etc. However, the objective of this type of simulation is to separate the effects of climate from other changes in economic conditions.

Figure 2 shows the probability values for irrigation adoption estimated for the current period and for future climate change scenarios. The standard deviations indicate that all calculated values are statistically significant at the 1% level. Overall, it has been observed that, with respect to the current period, there was an increase in the probability of irrigation during the first simulation period (2010-2039). However, in the next simulation periods (2040-2069 and 2070-2099) the probability decreased substantially. Both scenarios presented similar rates, although the estimated probabilities were lower in A2. Regarding estimates for Brazil, the simulations indicated an increase of six percentage points in 2020. However, in the medium and long term (simulations for 2050 and 2080, respectively), there may be a decrease of eight to twenty-seven percentage points relative to the current period.

In regional terms, the South and Southeast exhibited the highest irrigation probability. Conversely, the North exhibited the lowest estimates. This allows us to infer that agriculture in the South and Southeast will likely be better prepared to cope with possible adverse effects of climate change than other regions (if irrigation is in fact an effective adaptive strategy). However, the North will be more exposed, which may affect the incomes of farmers in the region.

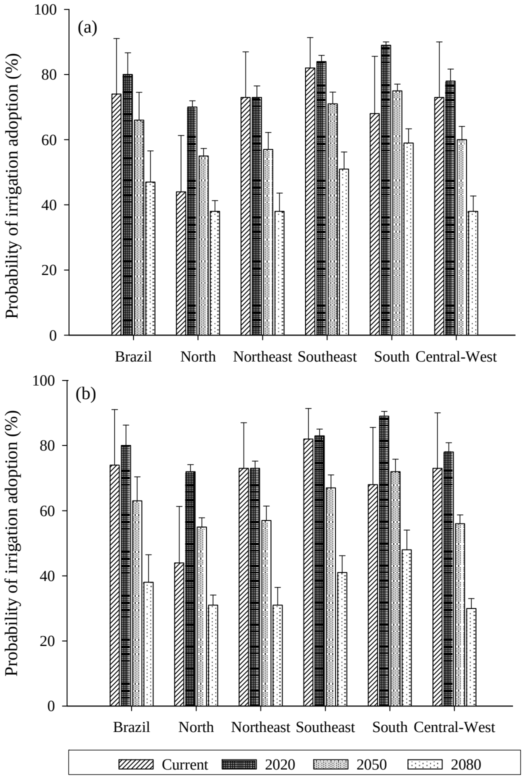

Figure 2. Probability of irrigation adoption (current and future simulations) estimated for Brazil and its regions, A1B (a) and A2 (b) scenarios.

The higher irrigation probability observed in the Southeast and South regions are supported by the results presented in Christofidis (2008) and by the analysis of the effects of climate change on Brazilian agriculture conducted by Embrapa (2008). This study indicates that in the southern region, the area of low risk to soybean production will likely be reduced because of more intense dry spells and water stress, which lead to an increased need for irrigation. The study of Embrapa (2008) also asserts that coffee production in some regions of Minas Gerais (in part of the Triângulo Mineiro, the northern and central regions of the state) and the cultivation of sugarcane in significant areas of the state, other than São Paulo and Mato Grosso, will only face low levels of risk if maintenance irrigation is employed (in certain locations, constant irrigation will be necessary).

Based on the trends in climate variables predicted in this study, other conclusions regarding the results presented in Figure 2 can be made. According to Cline (2007), irrigation becomes necessary as climate conditions become drier. Nevertheless, the need for increased irrigation is due to the difference between evapotranspiration and precipitation. Therefore, irrigation depends on the extent of temperature increase and precipitation rates. We believe that these decreases in irrigation probability are the result of the increase in precipitation during the medium and long terms (2040-2069 and 2070-2099), according to the chosen climate scenarios.

Moreover, plants have limited heat tolerance, which indicates that irrigation, given certain temperature levels, is no longer an efficient adaptive strategy. According to the climatic change estimates used in this study, temperatures are expected to increase by up to 3.44°C (scenario A2) in the summer and 3.9ºC (A2) in the winter. On the one hand, this is the most likely explanation for the decrease in the irrigation probabilities observed in the simulations. Moreover, it also explains the higher probabilities estimated in the South, once the lowest temperature increases are expected in that region. In this context, Wahid et al. (2007) argues that the adverse effects of heat stress can be mitigated by developing crop plants with improved thermotolerance using several genetic approaches. However, for this purpose it is imperative to obtain thorough understandings of the physiological responses of plants to high temperatures, their heat tolerance mechanisms and possible strategies for improving crop thermotolerance.

Although the irrigation probability will decrease (Figure 2), the investment in irrigation must continue to represent a substantial share of agricultural investment. Nevertheless, according to Faurès (2007), the pattern of investment will change substantially from those observed in previous decades. The author notes that new investment will be much more focused on enhancing the productivity of existing systems through upgrading infrastructure and reforming management processes. Irrigation will need to adapt to serve an increasingly productive agriculture.

Finally, it is necessary to note some limitations of this study. In this paper, we do not capture the full range of adaptation strategies that can be employed; in particular, when assuming fixed portions of land, it was not possible to analyse how the pattern of land use for (non) agricultural purposes will change. Because this is a partial equilibrium study, it does not study the implications of these results in terms of the effects on other sectors of the economy. Future studies should account for these issues.

Conclusion

Our results confirmed the expectation that irrigation is influenced by climate and should be modelled as an adaptive measure. Irrigation probabilities among Brazilian regions were quite different. The main explanations are the distinct climatic conditions and production structures. Given future climate change, there is an expected increase in the irrigation probability for the next 30 years in all regions. This trend is reversed in the long run. This result may be associated with the climate change predictions employed, e.g., increases in precipitation and temperature.

Brazil will experience a decreasing trend in irrigation probability, although this pattern is less significant in the South and Southeast. We showed that the more capitalised farmers are better able to invest in irrigation technologies, making them potentially less affected by the effects of climate change. Thus, one should encourage the expansion of credit policies to the implementation of irrigation technology, especially for less capitalised farmers.

Acknowledgements

Thanks are due to LACEEP (Latin American and Caribbean Environmental Program), FAPEMIG (Fundação de Amparo à Pesquisa do Estado de Minas Gerais) and NEMESIS (Núcleo de Estudos e Modelos Espaciais Sistêmicos) for their financial assistance.

References

BERNARDO, S. Impacto ambiental da irrigação no Brasil. In: SILVA, D. D.; PRUSKI, F. F. (Ed.). **Recursos hídricos e desenvolvimento sustentável da agricultura**. Brasília: MMA/SRH/ABEAS, 1997. p. 79-88.

CLINE, W. R. **Global warming and agriculture**: impact estimates by country. Washington, D.C.: Peterson Institute for International Economics, 2007.

COELHO, E.; COELHO FILHO, M.; SIMÕES, W.; COELHO, Y. Irrigação em citrus nas condições do nordeste do Brasil. **Laranja**, v. 27, n. 2, p. 297-320, 2006.

CHRISTOFIDIS, D. Água na produção de alimentos: o papel da academia e da indústria no alcance do desenvolvimento sustentável. **Revista de Ciências Exatas**, v. 12, n. 1, p. 37-46, 2006.

CHRISTOFIDIS, D. O futuro da irrigação e a gestão das águas. **Item**, n. 80, p. 40-47, 2008.

DESCHÊNES, O.; GREENSTONE, M. The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather. **American Economic Review**, v. 97, n. 1, p. 354-385, 2007.

EMBRAPA-Empresa Brasileira de Pesquisa Agropecuária. **Aquecimento global e a nova geografia da produção agrícola no Brasil**. 2008. Available from: <http://www.embrapa.br/publicacoes/tecnico/aquecimentoglobal.pdf>. Access on: July 9, 2009.

FAURÈS, J. M. Reinventing irrigation. In: MOLDEN, D. (Org.). **Water for food, water for life**: a comprehensive assessment of water management in agriculture. London: Earthscan, 2007. p. 353-394.

IBGE-Instituto Brasileiro de Geografia e Estatística. **Censo agropecuário 2006**: Brasil, grandes regiões e unidades da federação. Rio de Janeiro: IBGE, 2006.

IPCC-International Panel on Climate Change. Climate change 2007: synthesis report. Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change. In: PACHAURI, R. K.; REISINGER, A. (Ed.). **Fourth Assessment Report of the Intergovernmental Panel on Climate Change**. Geneva: IPCC, 2007. p. 1-103.

KURUKULASURIYA, P.; KALA, N.; MENDELSOHN, R. Adaptation and climate change impacts: a structural Ricardian model of irrigation and farm income in Africa. **Climate Change Economics**, v. 2, n. 2, p. 149-174, 2011.

MAGRIN, G.; GARCIA, C. G.; CHOQUE, D. C.; GIMENEZ, J. C.; MORENO, A. R.; NAGY, G. J.; CARLOS, N.; VILLAMIZAR, A. Latin America. In: PARRY, M. L.; CANZIANI, O. F.; PALUTIKOF, J. P.; VAN DER LINDEN, P. J.; HANSON, C. E. (Ed.). **Climate change 2007**: impacts, adaptation, and vulnerability – Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2007. p. 581-615.

MARGULIS, S.; DUBEUX, C. B. S. **Economia da mudança do clima no Brasil**: custos e oportunidades. São Paulo: IBEP Gráfica, 2010.

MENDELSOHN, R.; SEO, N. **Changing farm types and irrigation as an adaptation to climate change in Latin American agriculture**. World Bank Policy Research Working Paper 4161. Washington, D.C.: World Bank, 2007.

NEGRI, D. H.; GOLLEHON, N. R.; AILLERY, M. P. The effects of climatic variability on US irrigation adoption. **Climatic Change**, v. 69, n. 2-3, p. 299-323, 2005.

PIDGEON, N.; FISCHHOFF, B. The role of social and decision sciences in communicating uncertain climate risks. **Nature Climate Change**, v. 1, n. 1, p. 35-41, 2011.

ROLIM, J.; TEIXEIRA, J.; CATALÃO, J. Irrigation management of crops rotations in a changing climate. **Geophysical Research Abstracts**, v. 14, n. 1, p. 14427, 2012.

SEO, N. A microeconometric analysis of adapting portfolios to climate change: adoption of agricultural systems in Latin America. **Applied Economic Perspectives and Policy**, v. 32, n. 3, p. 489-514, 2010.

SEO, N. An analysis of public adaptation to climate change using agricultural water schemes in South America. **Ecological Economics**, v. 70, n. 4, p. 825-834, 2011.

SEO, N.; MENDELSOHN, R. A Ricardian analysis of the impact of climate change on South American farms. **Chilean Journal of Agricultural Research**, v. 68, n. 1, p. 69-79, 2008a.

SEO, N.; MENDELSOHN, R. An analysis of crop choice: adapting to climate change in South American farms. **Ecological Economics**, v. 67, n. 1, p. 109-116, 2008b.

SILVA, H. R.; CHRISTOFIDIS, D.; MAROUELLI, W. A. Situação da irrigação no Brasil. In: PRIETO, D.; RIVERA, R.; SILVA, H.; MAROUELLI, W.; CHRISTOFIDIS, D.; ULLOA, A.; VAN SCHOUWEN, G.; ESPADA, R.; BLANCO, M.; JARA, R.; GARCIA, C.; ROEL, A. (Ed.). **El riego en los países del Cono Sur**. Montevidéo: IICA, 2010. p. 51-64.

WAHID, A.; GELANI, S.; ASHRAF, S.; FOOLAD, M. R. Heat tolerance in plants: an overview. **Environmental and Experimental Botany**, v. 61, n. 3, p. 199-223, 2007.

Received on November 29, 2011.
Accepted on July 5, 2012.