

**GABRIEL ALVES DE SAMPAIO MORAIS**

**THREE ESSAYS ON IRRIGATED AGRICULTURE IN BRAZIL**

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Economia Aplicada, para obtenção do título de *Doctor Scientiae*.

Orientador: Marcelo José Braga

**VIÇOSA - MINAS GERAIS  
2019**

**Ficha catalográfica preparada pela Biblioteca Central da Universidade  
Federal de Viçosa - Câmpus Viçosa**

T

M827t  
2019           Morais, Gabriel Alves de Sampaio, 1986-  
                  Three essays on irrigated agriculture in Brazil / Gabriel  
                  Alves de Sampaio Moraes. – Viçosa, MG, 2019.  
                  114 f. : il. (algumas color.) ; 29 cm.

Texto em inglês.

Inclui apêndices.

Orientador: Marcelo José Braga.

Tese (doutorado) - Universidade Federal de Viçosa.

Referências bibliográficas: f. 87-99.

1. Irrigação. 2. Propriedade rural. 3. Renda agrícola.

I. Universidade Federal de Viçosa. Departamento de Economia Rural. Programa de Pós-Graduação em Economia Aplicada.

II. Título.

CDD 22. ed. 631.587


**GABRIEL ALVES DE SAMPAIO MORAIS**

**THREE ESSAYS ON IRRIGATED AGRICULTURE IN BRAZIL**

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Economia Aplicada, para obtenção do título de *Doctor Scientiae*.

APROVADA: 30 de outubro de 2019.

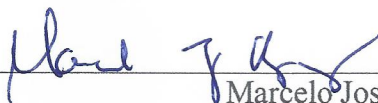
Assentimento:



---

Gabriel Alves de Sampaio Morais

Autor



---

Marcelo José Braga

Orientador

A minha avó, Vera Lúcia de Sampaio Morais, professora de excelência.  
A Lídia Lacerda Sampaio Sabiá (*in memoriam*) pelo amor incondicional.  
Aos meus pais e amigos de todas as horas.

## **ACKNOWLEDGMENTS**

God for my life, family and friends.

My parents for their love, encouragement and unconditional support.

My friends, chosen as family, companions of all hours.

The Federal University of Viçosa, for the opportunity and welcome.

Professor Dr. José Marcelo Braga, for the guidance, support and trust.

Dr. Lilyan E. Fulginiti and Dr. Richard K. Perrin for the guidance abroad.

Dr. Felipe de Figueiredo Silva for the excellent co-orientation.

Dr. Carlos Otávio de Freitas and Dr. Mateus Neves for their collaboration in the research.

Dr. Dênis Antonio da Cunha for his assistance in providing external databases.

My classmates in the 2015.2 PhD class for their companionship and support.

The committee of the thesis for availability and contributions.

IBGE and technical staff and collaborators for their research assistance.

CNPq, for granting the scholarship for this research.

CAPES, for the scholarship granted during doctorate sandwich program.

## RESUMO

MORAIS, Gabriel Alves de Sampaio, D.Sc., Universidade Federal de Viçosa, outubro de 2019. **Three essays on irrigated agriculture in Brazil.** Orientador: Marcelo José Braga.

A tecnologia de irrigação é uma importante ferramenta capaz de minimizar os efeitos adversos do clima, assegurar o montante produzido, elevar as taxas de produtividade agrícola e aumentar o emprego no meio rural, o que por sua vez gera renda e pode contribuir para a diminuição dos índices de insegurança alimentar no meio rural. Apesar dos múltiplos benefícios, a taxa de adoção de irrigação no Brasil ainda é muito baixa dada o potencial de incorporação de novas áreas, fazendo com que os efeitos dessa tecnologia sobre o processo produtivo sejam subestimados e pouco explorados. Nesse sentido, a presente tese buscou analisar o efeito da adoção da irrigação sobre aspectos importantes da agricultura irrigada brasileira, como a eficiência técnica entre irrigantes e produtores de sequeiro; o impacto da irrigação na oferta de grãos e demanda por fatores produtivos; e a receita bruta adicionada decorrente da adoção da tecnologia de irrigação. Para atingir tais objetivos, foram elaborados três capítulos: *Irrigation, technical efficiency and farm size in Brazil*; *Irrigation effects on grain sector in the Brazilian Southeast: A short-run analysis*; e *The value of irrigation adoption in the Brazilian agriculture*. No primeiro capítulo, analisou-se o efeito da adoção da tecnologia de irrigação sobre a eficiência técnica dos estabelecimentos agropecuários brasileiros. A abordagem utilizada combinou a estrutura de fronteira de produção estocástica, levando em conta o viés de seleção na adoção da irrigação (abordagem de Heckman) com a técnica de balanceamento por entropia. Os resultados mostraram que a irrigação contribuiu para o aumento da eficiência técnica dos irrigantes em 2,51 pontos percentuais em relação aos produtores de sequeiro, sendo este efeito maior para o grupo de grandes produtores. No segundo capítulo, analisou-se o efeito da irrigação sobre a oferta de grãos e demanda por fatores produtivos na região Sudeste do Brasil. Para tal, um sistema de equações foi estimado utilizando-se da abordagem da função de lucro quadrática restrita. Os resultados apontaram para um efeito positivo sobre a oferta de grãos e demanda por trabalho. Além disso, a irrigação contribuiu para um aumento de 2,1% (cerca de US\$ 83,45 milhões) na receita média gerada pelos produtos considerados. No terceiro e último capítulo, objetivou-se obter uma medida do valor da adoção de irrigação em termos de receita bruta adicionada quando a terra é irrigada, relativa àquela não irrigada, por meio da abordagem da função de produção. Os

resultados mostraram uma receita bruta adicional em decorrência do uso de irrigação em US\$1.492,15/ha, sendo o valor da irrigação para o Brasil estimado em US\$ 2,96 bilhões. Os resultados trazem informações úteis ao delineamento de políticas voltadas ao desenvolvimento da agricultura irrigada no Brasil, como por exemplo, a necessidade de políticas voltadas aos pequenos produtores em relação ao fornecimento de serviços de assistência técnica especializada e de crédito rural, bem como aquelas voltadas à propriedade no que diz respeito à dotação de recursos hídricos e eletrificação rural. Além disso, os resultados podem fornecer informações que podem auxiliar na formatação de políticas de cobrança de água usada na irrigação. Por fim, conclui-se que a tecnologia de irrigação tem um importante papel na eficiência técnica dos produtores, na expansão da oferta de produtos, na geração de emprego rural e na geração de receita bruta adicionada ao setor agrícola.

Palavras-chave: Irrigação. Eficiência Técnica. Tamanho de Estabelecimento. Oferta de grãos. Receita do produtor. Valor da irrigação.

## ABSTRACT

MORAIS, Gabriel Alves de Sampaio, D.Sc., Universidade Federal de Viçosa, October, 2019. **Three essays on irrigated agriculture in Brazil.** Adviser: Marcelo José Braga.

The Irrigation technology is an important tool capable of mitigating the adverse effects of climate change, ensuring the yields, raising agricultural productivity rates and increasing employment in rural areas, which generates income and raises food security. Despite its multiple benefits, irrigation adoption in Brazil is still low given the potential for incorporation of new arable land, making the effects of this technology on the production process underestimated and underexplored. The present thesis seeks to analyze the effect of irrigation adoption on important aspects of the Brazilian irrigated agriculture, such as the technical efficiency between irrigators and rain-fed producers; the effect of irrigation on grain supply and demand for productive factors; and added gross revenue from the adoption of irrigation technology. To achieve those goals, three chapters are developed: *Irrigation, technical efficiency and farm size in Brazil*; *Irrigation effects on grain sector in the Brazilian Southeast: A short-run analysis*; and *The value of irrigation adoption in the Brazilian agriculture*. The first chapter analyzes the effect of irrigation technology adoption on the technical efficiency of Brazilian agricultural establishments. The methodological approach combines the stochastic production frontier structure, taking into account the selection bias (Heckman's approach), with the entropy balancing technique. The results show that irrigation adoption contributes to increasing the technical efficiency of irrigators by 2.51 percentage points compared to rain-fed farmers, on average. The greatest effect is observed for the group of large farmers. In the second chapter, we analyze the effect of irrigation on the supply of grains and the demand for productive factors in the Southeast region of Brazil. A system of equations is estimated using the restricted quadratic profit function approach. The results point toward a positive effect on the supply of grains and demand for labor. In addition, irrigation contributes to a 2.1% increase (US\$ 83.45 million) in the average revenue generated by the grains analyzed. The third and last chapter aims to obtain a measure of value of the irrigation adoption in terms of gross added revenue when land is irrigated, relative to a non-irrigated land, using the production function approach. The results show an additional gross revenue due to irrigation of US\$ 1,492.15/ha, on average, and the estimated value of irrigation for Brazilian agriculture is US\$ 2.96 billion. The overall results provide useful information to

design public policies that aim to develop irrigated agriculture in Brazil, such as the need for policies toward small producers regarding the provision of specialized technical assistance and rural credit services, as well as those related to water resources and rural electrification within the farm. In addition, the results may provide useful information that can assist water charging policies used in irrigation. Finally, I conclude that irrigation technology plays an important role in the technical efficiency of producers, in expanding the outputs supplies, in generating rural employment and gross revenue added to the agricultural sector.

**Keywords:** Irrigation. Technical efficiency. Farm size. Grain supply. Revenue. Irrigation value.

## SUMMARY

1	Introduction.....	11
1.1	Problem and its importance.....	12
1.2	Objectives.....	14
1.2.1	General Objectives.....	14
1.2.2	Specific Objectives.....	14

### CHAPTER 1

#### IRRIGATION, TECHNICAL EFFICIENCY AND FARM SIZE IN BRAZIL.....15

1	Introduction.....	15
2	Technical Efficiency and Irrigation.....	17
3	Empiric Model.....	19
3.1	Entropy Balancing.....	19
3.2	Sample Selection Model.....	21
3.2.1	Selection Equation.....	21
3.2.2	Stochastic Frontier Approach (SFA).....	22
4	Empirical Application and Data Source.....	23
5	Results.....	28
5.1	Descriptive Analysis and Entropy Balancing.....	28
5.2	Production Elasticities.....	30
5.3	Technical Efficiency Scores.....	34
6	Conclusions.....	37

### CHAPTER 2

#### IRRIGATION EFFECTS ON GRAIN SECTOR IN THE BRAZILIAN SOUTHEAST: A SHORT-RUN ANALYSIS.....39

1	Introduction.....	39
2	Background.....	42
3	Theoretical Framework.....	45
4	Empirical Application.....	47
4.1	Data Source.....	49
5	Results.....	53
5.1	Effect of irrigation on revenue and policy implication.....	58

6	Conclusions.....	60
---	------------------	----

### CHAPTER 3

	THE USE VALUE OF IRRIGATION ADOPTION FOR BRAZILIAN AGRICULTURE...	62
1	Introduction.....	62
2	Assessing the value of irrigation water.....	65
3	Theoretical Framework.....	66
4	Empirical Model.....	67
4.1	Data Source.....	69
5	Results.....	70
5.1	Elasticities and the Value of Irrigation Adoption.....	75
5.2	Post estimation Analysis.....	81
6	Conclusions.....	82
	FINAL REMARKS.....	84
	REFERENCES.....	87
	Appendix.....	100

## 1 Introduction

Irrigation projects in Brazil were implemented first in the South region to make rice growing feasible, and it was extended to coffee plantations in Southeast Region. Thereafter, a large number of public irrigation projects were implemented from the 1970s in the semi-arid region, which has benefited from technological advances.

According to the Ministry of National Integration - MI (2008), water resources management in Brazil had three phases: (i) until 1940, when water capacity exceeded demand and public actions focused on flood control, stream regulation, energy production and water capture for public supply; (ii) between 1940 and 1970, when the accelerated development of industrial and agricultural activities, combined with urban and housing expansion, implied the first conflicts between water supply and demand; and (iii) from 1970, when water is perceived as a scarce natural resource and in many cases unfit for human and industrial consumption.

Alves and Vieira Filho (p.259, 2019) highlight that the growth of irrigation in Brazil was driven by the development of irrigated districts through government actions, followed for private initiatives in a cooperative manner; and finally by individualized private initiatives. The economic viability of projects depends on maturity, development of supply chains, incorporation of new technologies, efficient selection of agents and private entrepreneurship.

According to the World Bank (2004), investments during the 70's, 80's and 90's were estimated to have used public funds in excess of US\$ 2 billion for irrigation projects to develop 200,000 hectares in the Brazilian semiarid, an investment average of US\$ 10,000/hectare.

Nowadays, Brazil is a major worldwide player in agriculture production. The country produced 6% of the world's agricultural and it is among the ten countries with the largest irrigated area in the world (Food and Agriculture Organization – FAO, 2017), which appears in a group of countries with irrigated areas between 4 and 7 million hectares (FAO, 2017). Nevertheless, irrigated areas in Brazil are still considered small compared to the total agricultural area and to the territorial extension (CUADRA *et al.*, 2019).

The great variability of precipitation in the Brazilian regions led farmers to adopt irrigation to mitigate the adverse effects of climate and help farmers to ensure the production. The Brazilian agricultural sector is one of the main economic activities in the generation of employment and income, being able to raise the standard of living of the population regarding poverty reduction and food security. Thus, irrigation adoption can be used as a tool to reduce dependency on variable rainfall and water availability (TUBIELLO, 2005); decreasing the

uncertainty surrounding crop yields and securing income and employment in rural areas (MARRA *et al.*, 2003). Moreover, irrigation systems are an important technology through which agricultural productivity rates can be increased (DRIDI; KHANNA, 2005).

### **1.1 Problem and its importance**

Despite of all benefits related to irrigation technology adoption in agriculture, there is a low percentage of farmers that use irrigation in Brazil, around 6.3% in 2006 (IBGE, 2009). The low adoption of irrigation technology might be due to the irrigation costs; absence of water resources; difficulties faced in the credit market; and levels and frequency of precipitation (CRISTÓFIDIS, 2013). To alleviate water scarcity, irrigation systems are becoming more efficient (SCHAIBLE and AILLERY, 2012), maximizing water productivity rather than land productivity (SEPASKHAN *et al.*, 2006), while irrigation systems adoption can generate higher yields and allow the production of valuable crops, and reduce production costs (STUBBS, 2016).

Brazilians regions have observed an increase in droughts and water shortages in the past few years which affect agricultural production and rural income, while irrigation is expected to increase in the next 30 years for all regions (CUNHA *et al.*, 2015). The adoption of irrigation can help counter these negative factors by leading to higher crop yields by sustaining adequate soil moisture in the growing period (LOBELL *et al.*, 2009); achieving higher rates of agricultural productivity (MKANTHAMA *et al.*, 2018); and allowing the impacts of seasonal and inter-annual hydrological variability on agriculture to be smoothed out (TURRAL *et al.*, 2010).

Several studies for developed and developing countries have been analyzed how irrigation adoption can help farmers to move towards the best technology practice, in other words, to increase the yields holding the amount of inputs used in the production. This movement toward the best practice is known as technical efficiency improvement, which is often used to design programs for performance improvements (O'DONNELL *et al.*, 2008). The findings in Babatunde *et al.* (2017), Opata *et al.* (2018), and Mkanthama *et al.* (2018) have shown that irrigators are more efficient than rain-fed farmers. On the other hand, Melesse and Ahmed (2015), Tiruneh *et al.* (2017) and Makombe *et al.* (2017) found an opposite relation of the previous studies. This outcome can be explained by the fact that after the adoption of new technologies, adopters may need more time to learn how to use the technology efficiently. Hence, there is no consensus whether irrigation technology can help farmers become more

efficient or not. Moreover, to our best knowledge, technical efficiency between irrigators and rain-fed farmers was not accessed for Brazilian agriculture; we only found few studies accessing technical efficiency for small irrigated areas, where all the farmers have been used irrigation. Then, the objective of this research is to fill in this gap in the literature.

One of the main limitations of the approach adopted to estimate technical efficiency in the cited studies is not to consider the endogenous characteristics of irrigation adoption, since the adoption is an individual choice of the farmer, which can be affected by the farm and producer characteristics, for instance, the farmer managerial capacity. Thus, the true effect of irrigation adoption on farmer's performance may be biased. (BRAVO-URETA *et al.*, 2012; VILLANO *et al.*, 2015). In this context, one of the contributions of this research is to mitigate some limitations evidenced in the literature through an empirical strategy that considers the effects of endogenous sample selection. Our analysis also extends to identify the effect of irrigation on the technical efficiency between irrigators and rain-fed heterogeneous farmers differentiated by farm size due to complexity of irrigation systems management, providing useful information on which size is most affected by irrigation technology adoption in terms of efficiency.

The benefits of irrigation to ensure the production and make the output supply stable are recognized. However, there are still difficulties in assessing its importance in the current quantity produced, its role in the revenue generation, and food and nutritional security as well (ANA, 2016). Agricultural Census and Livestock in 2006 reported that Southeast region presents the highest fraction of irrigated land in Brazil, surpassing the South region in irrigation expansion. This result is mainly due to the growth in the use of center pivots in the last two decades. In general, the main irrigated crops are grains (coffee, corn, beans, soybeans, etc.), besides the traditional crops (sugarcane and oranges). Moreover, the Southeast region is characterized by the developed stage of mechanization in agriculture, and dominated by technically advanced commercial farmers (FAO, 2015).

Thus, we aim to estimate the farm marginal effect of irrigated land expansion in the grain sector in the Southeastern region due its importance to reveals how much of grain supply can be achieved given an increase in one irrigated hectare, and also the capacity of irrigation to increase input demand. Notwithstanding, the approach used allows to evaluating the irrigation effect on farmers' revenue, which measures the opportunity cost of this technology, and policy actions can be designed to those crops most valuable. Our analysis also accounts for short term weather and farm size, since these factors might impose production losses.

The contribution of the yield increase due to irrigation expansion has resulted in varying levels of depletion of water sources, since 70% of freshwater in the country have been used in irrigated agriculture (ANA, 2018), and much of the water used in irrigation are not traded among economic agents (FERRARINI *et al.*, 2016). As argued by Nikouei *et al.* (2013), under this arrangement, water resources face overexploitation, while Mesa-Jurado *et al.* (2010; 2012) highlighted that rational management of water requires the knowledge of the value of the resource. In this context, it is important for policy purposes to identify the overall value of the irrigation adoption in Brazilian agriculture.

To evaluate the value of irrigation for Brazilian agriculture, we seek to estimate the total gross value added by irrigation based on production value and irrigated hectares through production function approach. The extra production value due to irrigation allows us to evaluate and obtain estimates of the additional revenue flow attributable to irrigation, giving a sense of how much is the use value of irrigation adoption in the Brazilian agriculture, providing support to water price policy in the case of charging for water used in irrigation.

## **1.2 Objectives**

### **1.2.1 General Objective**

Analyze the effect of irrigation on Brazilian agriculture

### **1.2.2 Specifics Objectives**

- a) Verify if irrigation technology adoption can make farmers more technically efficient;
- b) Analyze the relationship between average technical efficiency and farm size;
- c) Evaluate how irrigation affects the supply of grains and demand for productive factors in the Brazilian southeastern region;
- d) Determine the return of irrigation in terms of contribution in the generation of revenue in the grain sector in the Brazilian southeastern region;
- e) Evaluate the yield response when a hectare is converted into irrigated;
- f) Measure the extra gross production value attributable to irrigation per hectare;
- g) Obtain the overall value of irrigation for Brazilian agriculture.

This thesis is structured in three chapters. The first chapter is in line with the specific objectives "a" and "b". The second chapter meets the specifics objectives "c" and "d"; and the third chapter attend to specifics objectives "e", "f" and "g".

## CHAPTER 1

### IRRIGATION, TECHNICAL EFFICIENCY AND FARM SIZE IN BRAZIL

#### 1. Introduction

The great variability of precipitation in the Brazilian regions led farmers to adopt irrigation to mitigate the adverse effects of climate change. In relation to the implementation of irrigation systems, there is the development of Brazilian agricultural sector, which is one of the main economic activities in the generation of employment and income, being able to raise the standard of living of the population regarding poverty reduction and food security.

Irrigation systems development is an important technology through which agricultural productivity rates can be increased (Dridi; Khanna, 2005); it also has potential to minimize the risks caused by climate change, which is associated with one of the main causes of agricultural production vulnerability (Kurukulasuriya *et al.*, 2006). Irrigation adoption can be used as a tool to reduce dependency on variable rainfall and water availability (Tubiello, 2005); decreasing the uncertainty surrounding crop yields and securing income and employment in rural areas (Marra *et al.*, 2003).

Cunha *et al.* (2014) analyzed the irrigation adoption as an adaptive strategy under climate change scenarios in Brazil. They concluded that irrigation adoption is affected by climate change, and is used as a response to the precipitation reduction. Although adoption is not uniform across Brazilian regions, irrigation technology adoption is expected to increase in the next 30 years for all regions. Since agricultural sector is said to be the sector most affected by climate change (Rosenzweig *et al.*, 2014), irrigation adoption is used as an adaptive strategy (Finger *et al.*, 2011; Van Passel *et al.*, 2017).

Irrigation systems are increasingly becoming more efficient (Evans; Sadler, 2008; Schaible; Aillery, 2012). Testing the ability of irrigation systems to alleviate water scarcity is an important research agenda that can provide useful information to policymakers (Koundouri *et al.*, 2006). As argued by Njuki and Bravo-Ureta (2016), the greatest interest lies on the arid and semi-arid regions, where non-uniform precipitation constrains the natural development of crops. In addition, the competition for existing freshwater supplies requires maximizing water productivity in crop production (Pereira *et al.*, 2003; Sepaskhan *et al.*, 2006).

Irrigation technology allows the farmer achieve higher yields maintaining the amount of other inputs constant, that is, the capacity to move farmers toward the best practice, known as potential production. This movement toward the efficient frontier is termed as technical efficient improvement. Technical efficiency estimates are often used to design programs for performance improvement, which involve changes in the management (e.g., education and training programs) and structure of the firm, as the operating environment (O'Donnell *et al.*, 2008).

Although all benefits related to irrigation technology adoption in agriculture, there is a low percentage of farmers that use irrigation in Brazil, around 6.3% (IBGE, 2009), which generates an uncertainty regarding the effects of this practice on the farmers' productive performance. The uncertainty lies on the effects of irrigation on technical efficiency among irrigators and rain-fed farmers for different farms sizes, which might respond differently to irrigation adoption as adaptive strategy to climatic variability and regard to irrigation efficiency and effectiveness (Vanschoenwinkel; Van Passel, 2018), being small farmers and poorer populations most affected (Vanderlugt, 2011). Moreover, as farm size increases, the feasibility, implementation, operations and management of irrigation systems may become increasingly complex; this may compromise farmers' performance. However, this is a hypothesis that must be tested. The farm size has been discussed in the literature because of its influence on production, efficiency and productivity (Rada, Helfand and Magalhães, 2019).

Despite the fact that most of irrigation projects come from private initiatives, irrigation adoption has received governmental attention regarding the development of projects and provision of credit to rural producers (ANA, 2009). The goal is to adapt to climate variation and increase returns of production and profitability. Technical efficiency difference between irrigators and rain-fed farmers could justify an increase in investments and in support by governmental policies to encourage the adoption of irrigation technology, generating economic development of rural Brazil, especially in areas of climatic and socioeconomic vulnerability.

Bravo-Ureta *et al.* (2012) argue that one of the main limitations of the approach adopted to estimate technical efficiency is not to consider the endogenous characteristics of some variables, such as irrigation adoption, since the adoption is an individual choice of the farmer, which can be affected by observable factors (e.g. farm and producer characteristics, such as income, schooling, experience, etc.) and unobservable factors (e.g. farmer managerial capacity). Villano *et al.* (2015) point out that by disregarding these characteristics, the results

may be biased, which limits the analysis of the true effect of irrigation adoption on farmer's performance.

Given the lack of studies on agricultural technical efficiency comparing irrigation adopters and non-adopters in Brazil, the objective of this research is to fill in this gap in the literature and identify the effect of irrigation on the technical efficiency of the irrigators and rain-fed heterogeneous farmers differentiated by farm size due to complexity of irrigation systems management. In this context, one of the contributions of this research is to mitigate some limitations evidenced in the literature through an empirical strategy that combines the stochastic frontier approach and a method that considers the effects of endogenous sample selection. Thus, this study aims to answer three questions: *Are irrigators more efficient than rain-fed farmers in Brazil? What is the relationship between technical efficiency and farm size for both groups? And for which farm size irrigation adoption generates greater difference in technical efficiency between irrigators and rain-fed farmers?*

Our findings indicate that irrigation technology adoption increase farmers' technical efficiency, which irrigators are 2.51 percentage points more efficient than non-adopters, on average. We found an inverted U-shaped relationship between technical efficiency and farm size for both groups, where *small* farms are more efficient. However, irrigation adoption has a greater effect for *medium* and *large* farms in terms of technical efficiency.

This chapter is organized in five sections besides this introduction. In the following section we present a brief literature on technical efficiency and irrigation. The empirical model is presented in Section 3; Empirical application and data source are presented in Section 4. Results are shown in Section 5, and finally, in Section 6 we expose our final conclusions about the research.

## **2. Technical Efficiency and Irrigation**

Technical efficiency differences between irrigators and rain-fed farmers were assessed in several studies. Anang *et al.* (2017) compared technical efficiency of smallholder irrigated and rain-fed rice farms in Northern Ghana. On average, the irrigators were 9.2 percentage points (p.p.) more efficient than rain-fed farmers. The authors reinforce the need for investment in irrigation infrastructure as a mechanism to reach poverty reduction and food security.

Babatunde *et al.* (2017) examined the determinants of yield gap and technical efficiency between rain-fed and irrigated rice production in Nigeria. The result showed that irrigated rice

producers were around 11 p.p. more technically efficient than rain-fed farmers. Opata *et al.* (2018) also found that irrigators were 38 p.p. more technically efficient than rain-fed farmers in rice production in Nigeria. Mkanthama *et al.* (2018) found a great difference in technical efficiency in rice production in Tanzania, where technical efficiency was 96% for irrigators compared to 39% for rain-fed farmers. Low technical efficiency for rain-fed producers was also found by Makombe *et al.* (2007), where rain-fed farmers' technical efficiency was 6% and for irrigators around 24%.

On the other hand, there are studies that pointed out opposite findings, where rain-fed farmers are more technically efficient than irrigator producers. Gebrehaweria *et al.* (2012) estimated technical efficiency of irrigated and rain-fed smallholder agriculture in Ethiopia. They found that rain-fed were 82% technically efficient, while irrigators were 45%. They also found that access to credit and number of skilled household members reduces the technical inefficiency of irrigated agriculture.

Melesse and Ahmed (2015) compared the technical efficiency between irrigators and rain-fed farmers in potato production in Eastern Ethiopia. Technical efficiency score for rain-fed farmers was 75% and for irrigators 50%, while Tiruneh *et al.* (2017) found an average technical efficiency (TE) of 81% and 68%, respectively. Factors related to schooling, soil condition and seed size affected TE, while the age of the household head positively affected the TE of irrigators, indicating that experience through age matters in production.

Also for Ethiopia, Makombe *et al.* (2017) estimated and compared the levels of production and technical efficiency of different small-scale farmers. The average technical efficiency for the modern irrigated system was 71% and for rain-fed 78%. Vrachioli, Stefanou and Tzouvelekas (2018) found similar findings to Tiruneh *et al.* (2017), but for farmers that had adopted sprinkler irrigation using data covering 56 small-scale greenhouse farms from the island of Crete, Greece. Average technical efficiency to farmers who adopted sprinklers is lower than the group of non-adopters.

These findings highlight that there is no consensus whether irrigation adoption can make farmers more efficient compared to non-adopters or not. This outcome can be explained by the fact that after the adoption of new technologies, adopters may need more time to learn how to use the technology efficiently. For Brazilian agriculture, to the best of our knowledge,

no research measured and compared technical efficiency between irrigators and rain-fed farmers; we only found studies for small specific irrigated areas<sup>1</sup>.

### 3. Empiric Model

Two methodological steps are used to identify the effect of irrigation on farmers' technical efficiency. Due to the possibility of selection bias in irrigation adoption from pre-treatment observable characteristics, the technical efficiency scores comparison between irrigators and rain-fed farmers becomes impracticable.

The decision to irrigate is a farmer optimization problem influenced by their personal characteristics, economic conditions, and climatic factors, among others (Cunha *et al.*, 2015; Vanschoenwinkel; Van Passel, 2018; Watto; Mugeru, 2019). Thus, comparison between irrigators and rain-fed producers would result in an overestimation of the technical efficiency due to the self-selection bias (Vrachioli, Stefanou and Tzouvelekas, 2018).

*Entropy Balancing* method is appropriate to find a group as similar as possible to the group of irrigators to eliminate the bias caused by such observable characteristics. Hence, the strategy consists of estimating the production function using the *Stochastic Frontier Approach (SFA)* for each group considered through the two-stage approach developed by Heckman (1979). The combination of the two approaches allows us to obtain comparable technical efficiency scores between the groups and within the groups (according to the farm size), and also free from biases from observable and unobservable characteristics (Sipiläinen; Lansink, 2005; Freitas, 2017).

Finally, the production stochastic frontier approach developed by Battese and Coelli (1995) allows us to model an equation to explain the factors that influence technical efficiency (or its variability) of the farmers. A similar approach was used by Jiang and Sharp (2015), among others.

#### 3.1. Entropy Balancing

Hainmueller (2012) developed a multivariate method that allows us to weight a data set such that variables distributions in the reweighted observations satisfy a set of special

---

<sup>1</sup> For more information see Barros *et al.* (2004); Mariano and Pinheiro (2009); Sousa, Justo and Campos (2013); and Silva *et al.* (2017).

conditions of moments, so that there is an exact equilibrium on the first, second, and larger moments of the distributions of independent variables in both treatment and control groups. In summary, this method allows the researcher to specify a desirable level of equilibrium for the covariates, using a set of conditions associated with the moments of the distribution.

To demonstrate the weighting procedure proposed by Hainmuller (2012), consider a sample with  $n_1$  observations belonging to the treatment group and  $n_0$  control units, which were randomly selected from a population of size  $N_1$  and  $N_0$ , respectively ( $n_1 \leq N_1$  e  $n_0 \leq N_0$ ). Let  $D_i \in \{1,0\}$  be a binary treatment variable, where it assume the value equal to 1 if unit  $i$  belongs to the treatment group, and 0 otherwise. Let  $X$  be a matrix containing the observations of  $J$  pre-treatment exogenous variables;  $X_{ij}$  corresponds to the value of the  $j$ -th covariate of unit  $i$ , such that  $X_i = [X_{i1}, X_{i2}, \dots, X_{iJ}]$  refers to the characteristic vector of unit  $i$  and  $X_j$  refers to the column vector with  $j$ -th covariates.

The entropy balancing generalizes the propensity score weighting approach by estimating the weights directly from a set of equilibrium constraints that exploit the researcher's knowledge about the sample moments. Consider  $w_i$  the weight of the entropy balancing chosen for each control unit, which were found by the following reweighting scheme that minimizes the entropy metric distance:

$$\min_{w_i} H(w) = \sum_{\{i|D=0\}} w_i \log(w_i/q_i) \quad (1)$$

subject to the equilibrium and the normalization constraints

$$\sum_{\{i|D=0\}} w_i c_{ri}(X_i) = m_r \quad r \in 1, \dots, R \quad (2)$$

$$\sum_{\{i|D=0\}} w_i = 1 \quad (3)$$

$$w_i \geq 0 \text{ for all } i, \text{ such that } D = 0 \quad (4)$$

Where  $q_i = 1/n_0$  is a basis weight and  $c_{ri}(X_i) = m_r$  describes a set of  $R$  imposed constraints on the covariates moments in the reweighted control group. Initially, the covariates are chosen and included in the re-weighting procedure. For each covariate, a set of balancing constraints (Equation 2) is specified to match the covariate distributions moments between treatment groups and re-weighted controls. The moment constraints can be the mean (first moment), the variance (second moment), and the asymmetry (third moment). A typical balancing restriction is formulated such that  $m_r$  contains the moment of a specific covariant

$X_j$  for the treatment group. The momentum function for the control group is specified as:  $c_{ri}(X_{ij}) = X_{ij}^r$  or  $c_{ri}(X_{ij}) = (X_{ij} - \mu_j)^r$  with mean  $\mu_j$ .

Thus, to a set of units, entropy balancing looks for weights  $W = [w_i, \dots, w_{n_0}]'$  which it minimizes Equation 1, where is the entropy distance between  $W$  and the weight base vector  $Q = [q_i, \dots, q_{n_0}]'$ , subject the balance constraints in Equation 2, normalization constraint (Equation 3), and non-negativity constraint (Equation 4).

The moment restriction applied here refers to the imposition of the first moment. Thus, for all explanatory variables (chosen based on their influence on the irrigation adoption), the method calculates the means in the treatment group and seeks for a set of entropy weights such that the weighted means of the control group are similar. Such weights are used in the next steps to obtain unbiased estimates of selection bias caused by observables factor.

### 3.2. Sample Selection Model

The existence of sample selection bias due to the fact that there are factors influencing the irrigators and rain-fed producers' technical efficiency that are different from those influencing the probability to adopt irrigation should be verified. The methodological procedure proposed by Heckman (1979) allows us to verify the possible selection bias mentioned. The method consists in two stages, which a binary choice model is estimated in the first stage with the purpose of explaining, through the selection equation, the probability of farmers to adopt irrigation.

In the second stage, the production stochastic frontier for each group (irrigators and rain-fed farmers) is estimated. Thus, the Inverse of Mill's Ratio (obtained in the first step) is incorporated as a covariate with the purpose of correcting the sample selection bias. We also use the weighting scheme obtained in the Entropy Balancing to estimate the production function. The existence of the selection bias is confirmed when the Inverse of Mill's Ratio is statistically significant (GREENE, 2011).

#### 3.2.1. Selection Equation

The selection equation proposed by Heckman (1979) is estimated using a *Probit* model, where the likelihood of a farmer to adopt irrigation is explained. Let  $d_i^*$  be a binary variable

that represents the (unobservable) selection criterion as a function of a vector of exogenous variables  $z_i$ . The Probit model can be defined as:

$$d_i = \alpha' z_i + \varepsilon_i \quad (5)$$

where  $\alpha$  is the vector of parameters to be estimated and  $\varepsilon_i$  is the error term distributed as  $N(0, \sigma_w^2)$ . The latent variable  $d_i^*$  is observed and receives the value 1 when  $\alpha' z_i + \varepsilon_i > 0$ , and zero otherwise:

$$d_i^* = 1[\alpha' z_i + \varepsilon_i > 0], \quad \varepsilon_i \sim N(0,1) \quad (6)$$

According to Heckman (1979), the Inverse of Mill's ratio is described as follow:

$$\lambda_i = \frac{\phi(C_i)}{1 - \Phi(C_i)} = \frac{\phi(C)}{\Phi(-C_i)} \quad (7)$$

where  $\phi$  and  $\Phi$  are, respectively, the density and distribution function for a standard normal variable,  $C$ . The Inverse of Mill's Ratio is given by  $\lambda_i$ , which is monotone decreasing function of the probability that an observation is selected into the sample,  $\Phi(-C_i) (= 1 - \Phi(C_i))$ .

### 3.2.2. Stochastic Frontier Approach (SFA)

After weighting the sample using the Entropy Balancing and taking into account the sample selectivity bias due to the irrigation adoption decision, the production function and technical efficiency scores is estimated by the Stochastic Frontier Approach (SFA).

The SFA has been widely used in studies of crop efficiency and productivity due to random factors involved in production that cannot be neglected (Battese, 1992; Coelli, 1995; Bravo-Ureta et al., 2007), as well as factors which influence the production technical efficiency.

We follow Battese and Coelli (1995) approach to specify the stochastic frontier that simultaneously models the technical inefficiency, which can be specified as:

$$Y_i = f(X_i \beta) e^{(v_i - u_i)} \quad (8)$$

where  $Y_i$  represents the production value of the  $i$ -th farm ( $i = 1, \dots, N$ );  $X_i$  is a vector ( $1 \times k$ ) of inputs and other explanatory variables associated with the production of the  $i$ -th farm;  $\beta$  is a vector ( $k \times 1$ ) of unknown parameters to be estimated;  $v_i$  represents the random error term

that captures shocks that are out of producer control (climate, pests and diseases, measurement errors, etc.), which is assumed to be independent and identically distributed (iid)  $N(0, \sigma_v^2)$  and;  $u_i$  are non-negative random variables associated to technical inefficiency of production, i.e., it is the part that constitutes a downward deviation with respect to the production frontier (best practice), which are assumed to be independently distributed, where it is obtained by truncation (at zero) of a normal distribution with mean  $z_i\delta$  and variance  $\sigma^2$ , such that  $N(z_i\delta, \sigma_u^2)$ .

Thus, the equation (8) specifies the stochastic frontier production function in terms of original production values. Following the specification of Battese and Coelli (1995), the term that explains the technical inefficiency of production,  $u_i$ , can be represented by:

$$u_i = z_i\delta + w_i \quad (9)$$

where  $z_i$  is a vector ( $1 \times m$ ) of explanatory variables associated with the technical inefficiency of the  $i$ -th productive unit<sup>2</sup>;  $\delta$  is a vector ( $m \times 1$ ) of unknown coefficients and;  $w_i$  are random errors defined by the truncation<sup>3</sup> of a normal distribution with mean zero and variance  $\sigma^2$ . We assume a half-normal distribution of the error term  $u_i$ . This equation can be modeled by specifying that inefficiency component is heterocedastic, which the variance expressed as a function of the covariates defined in  $z_i$ .

Once the stochastic production frontier is estimated, the technical efficiency scores are obtained following Battese and Coelli (1988) specification, which this efficiency measure is based on the conditional expectation of  $u_i$ , given the random error. The separation of the frontier deviations into their random components and inefficiency can be defined as the ratio between the observed and the potential output:

$$ET_{ij} = \frac{Y_{ij}}{Y_{ij}^*} = \frac{Y_{ij}}{f(X_{ij})} = \frac{\exp(X_{ij}\beta + v_{ij}) E[\exp(-u_{ij})|e]}{\exp(X_{ij}\beta + v_{ij})} = E[\exp(-u_{ij})|e] \quad (10)$$

where the value of  $ET_{ij}$  will be in the range [0; 1], where zero represents complete inefficiency and 1, full efficiency.

#### 4. Empirical Application and Data Source

<sup>2</sup> This unilateral term may follow the half-normal, truncated normal, exponential and gamma distribution.

<sup>3</sup> The truncation point of  $w_i$  is  $(-z_i\delta)$ , that is,  $w_i \geq -z_i\delta$

As discussed before, we use Entropy Balancing Method to obtain the weights for the control groups. Thus, we estimate the selection equation using a *Probit* as described in Equation (6). The variables specified in the following are described later.

$$\begin{aligned}
d_i^* = & \alpha_0 + \alpha_1 \text{gender} + \alpha_2 \text{age} + \alpha_3 \text{age}^2 + \alpha_4 \text{schooling} + \alpha_5 \text{experience} + \alpha_6 \text{tv} \\
& + \alpha_7 \text{phone} + \alpha_8 \text{internet} + \alpha_9 \text{energy} + \alpha_{10} \text{farm.status} \\
& + \alpha_{11} \text{urban} + \alpha_{12} \text{qualif} + \alpha_{13} \text{ag.family} + \alpha_{14} \text{priv.exten} \\
& + \alpha_{15} \text{gov.exten} + \alpha_{16} \text{coop} + \alpha_{17} \text{financ} + \alpha_{18} \text{ag.pract} \\
& + \alpha_{19} \text{chem} + \alpha_{20} \text{fert} + \alpha_{21} \text{soilph} + \alpha_{22} \text{water} + \alpha_{23} \text{vl.land} \\
& + \alpha_{24} \text{summer.prec} + \alpha_{25} \text{winter.prec} + \alpha_{26} \text{summer.temp} \\
& + \alpha_{27} \text{winter.temp} + \alpha_{28} \text{winter.temp.sd} \\
& + \alpha_{29} \text{summer.temp.sd} + \alpha_{30} \text{winter.prec.sd} \\
& + \alpha_{31} \text{summer.prec.sd} + \varepsilon_i
\end{aligned} \tag{11}$$

Battese and Coelli (1995) argue that is necessary to define the functional form of the production function. Several functional forms have been used in economic production analyzes, such as the Translog and Cobb-Douglas specifications. The last one presents constant returns to scale, unit elasticity of substitution and its coefficients directly represent the output elasticity of inputs (Tegegne, Tadesse and Zemedu (2014). The Translog specification is more flexible while is more likely to be susceptible to multicollinearity (Thiam *et al.*, 2001). We had estimated those two functional forms. Although the Likelihood Ratio Test (LR Test) had indicated a Translog specification as the best functional form of the production function, we have observed that, mostly, the coefficients are not statistically significant, and the percentage of monotonic violations seems too high, which is inconsistent with economic properties. Thus, we have chosen the Cobb-Douglas as a result of its simplicity.

We estimate a Cobb-Douglas production function weighted by the vectors of weights obtained by Entropy Balancing and the Inverse of Mill's Ratio (*Mills*) from Heckman's procedure (Equation 7). We also use several controls to estimate the production function, as dummies for each Brazilian Federative Unit (State); climatic variables and its interactions with Brazilian macro-regions dummies; and dummies of farm size. Following Battese and Coelli (1995), the Cobb-Douglas can be expressed as:

$$\ln Y_i = \beta_0 + \sum_{k=1}^N \beta_k \ln X_{ki} + \sum_{n=1}^N \beta_n \ln C_{ni} + \sum_{n=1}^N \sum_{r=1}^5 \beta_{nr} \ln C_{ni} R_r + \rho \text{Mills} + \sum_{h=1}^{26} \text{FU}_h + \sum_{g=1}^4 G_g + v_i - u_i \tag{12}$$

where  $Y_i$  represents the gross value of the production of farm  $i$ ;  $X_{ki}$  is a vector of inputs  $k$  used in production, which are: land, labor, capital, and purchased inputs (expenses);  $C_n$  represents

the climatic variables;  $R_r$  represents the dummies for the five Brazilian regions;  $FU_h$  represents dummies for Federative Units (States); and  $G_g$  represents dummies for the four farm size considered. Such dummies were included to capture fixed effects and to control spatial autocorrelation. Furthermore, the standard errors were clustered by at the municipality level. The climatic variables are considered as non-market inputs, that is, they are not found in the market, and therefore, according to Hughes *et al.* (2011), the production function can be termed as "*climate adjusted production frontier*". Finally, the selection bias hypothesis is verified by evaluating the statistical significance of parameter  $\rho$ . The error term  $v_i$  is due to random factor and  $u_i$  is due to inefficiency.

The production technical inefficiency term  $u_i$  (Equation 9) specified by Battese and Coelli (1995) is modeled by a set of covariates already recurrent in the literature with the purpose to explain inefficiency variability, being specified as follows:

$$u_i = \delta_0 + \delta_1 \textit{schooling} + \delta_2 \textit{experience} + \delta_3 \textit{rural.extension} + \delta_4 \textit{financing} + w_i \quad (13)$$

where *schooling* refers to the manager's education level and it is divided into 7 categories (higher education as base category); *experience* refers to manager's experience into four categories (over 10 years of experience as base category); *rural.extension* is a dummy variable that receives value 1 if the producer accessed any type of technical assistance; *financing* is a dummy variable that receives value 1 if the producer received any type of financing; and  $w_i$  is the random error term which it is assumed to be a half normal distribution. In the case of rural extensions services and financing, the results imply a correlation on technical efficiency scores since those services are a farmers' decision and may be endogenous.

The dataset used in the present research comes from the 2006 Agricultural and Livestock Census at farm level, which only can be accessed in the Brazilian Institute of Geography and Statistics (IBGE) headquarter in Rio de Janeiro, Brazil. The dataset contains information for more than 5 millions farms observations.

To prepare the dataset for this research, we had performed some treatment, such as the exclusion of farmers that did not report area (255,019 observations); farms settled in the urban area (192,350 observations); and farms classified as special sectors - favelas, barracks, lodgings, boats, indigenous villages, nursing homes, etc. (117,530 observations). We also excluded farms belonging to rural settlements (139,496 observations) to avoid possible variables measurement errors.

In addition, we only have included those farms owned by an individual producer, i.e., we excluded those farmers which were considered condominium, consortium or partnership, cooperative, public limited company or by quotas of limited liability, public utility institutions, government (Federal, state or municipal) or other condition (190,911 observations). Likewise, farms which producer type is "not identified" (20,440 observations) were excluded. After the exclusion and transformations, 915,746 observations were deleted (17.7% of the original sample), and the final sample is composed by 4,259,865 farms.

The dataset were also organized into four classes according to the farm size (very small, small, medium and large). The sizes were classified by IBGE according to the fiscal module classes<sup>4</sup>. Furthermore, the database generation was performed by the SAS<sup>®</sup> software, and the methodological procedures were performed using the STATA<sup>®</sup> software.

The treatment variable, that is, the indicative of the use of irrigation, is a dichotomous variable and represents the answer to the following question: "Did you use irrigation in the farm?". After the database treatments, 6.22% of the farmers declared to have used irrigation technology within the farm.

In addition to economic variables, we also use socioeconomics, institutions, agronomics and climatic characteristics in both entropy balancing and selection equation. All these variables were provided by 2006 Agricultural and Livestock Census, except those related to climate. Variables used in the sample selection (Equation 11) are described as follow: *Gender* is a dummy variable equals 1 if the farm's manager is male and 0 otherwise; *age* is the manager's age; *schooling* is a categorical variable related to the farm manager's education level: do not read and write, literate, incomplete elementary school, complete elementary school, agricultural technician, high school and higher education (base); *experience* is a categorical variable that represents the years in which the manager is in the farm header activity: up to one year, between 1 and 5 years, between 5 and 10 years, over 10 years (base). We also have included information on some resources as *tv* (television), *phone*, *internet* and *energy*, which are dummies variables that receive value equal 1 if the farmer has the resource, and 0 otherwise.

Other characteristics as farm ownership, whether the farmer lives in urban area or not, the presence of skilled labor in the farm workforce and familiar farm classification may influence irrigation technology adoption. We explore the farm ownership (*farm.status*) by including a

---

<sup>4</sup> Fiscal module classification is defined as the minimum area required for rural properties to be considered economic viable, ranging in area from 5 to 110 hectares. Based on the fiscal module, the farms can be classified into: very small (less than 1 fiscal module); small (between 1 and 4 fiscal module); medium (between 4 and 15 fiscal module); and large (more than 15 fiscal module). (Landau et al., 2012).

categorical variable: Owner (base), tenant, partner and occupant. *Urban* is a dummy set with value 1 if the farm's manager lives in an urban zone and zero otherwise; *qualif* is a dummy that capture the presence of skilled labor with value equal 1, and 0 otherwise; and *ag.family* is a dummy related to familiar farm classification<sup>5</sup> which is equal 1, and 0 otherwise.

We consider that the access to services and financing play an important role on the likelihood of irrigation adoption. In this sense, we capture access to services by including dummies set with values equal 1 if the farmer had received private extension services (*priv.exten*), governmental extension services (*gov.exten*), and if they were co-ops membership (*coops*). *Financ* is a dummy that represents the access to any type of financial resource (rural credit).

We also have added variables to capture agronomic characteristic and natural resources endowment on the likelihood of irrigation adoption: *Ag.pract* is a dummy equals 1 that indicates if the farmer uses any agricultural practice<sup>6</sup>, and 0 otherwise; *chem*, *fert* and *soilph* are dummies that inform whether the farmer used chemicals, fertilizers and/or have corrected the soil pH or not, respectively. These dummies received values 1 in an affirmative case, and zero otherwise. To capture natural resources endowment we set a dummy equal 1 if the farm has any water resource<sup>7</sup> (*water*), and zero otherwise. Furthermore, we also included the value of the land (*vl.land*) in US\$ of 2006.

The climatic variables are cumulative precipitation (in millimeters) segregated by summer (*summer.prec*) and winter (*winter.prec*); and both summer and winter temperature (*summer.temp* and *winter.temp*) in Celsius degree for the period of 2003-2006, which were averaged by municipality<sup>8</sup>. We also have included both temperature and precipitation standard deviations by season as a proxy to intra-annual climatic anomaly. The climatic dataset was obtained from the Climate Research Unit – CRU/University of East Anglia<sup>9</sup>. As our analysis in this research uses a cross-sectional dataset in the production function, we assume that climatic dataset of three years before (2003-2005) of the production process and for the current year (2006) is sufficient enough to help farmers to decide to use irrigation or not.

---

<sup>5</sup> Classified according to Law 11.326 of 07/24/2006.

<sup>6</sup> Refers to practices such as: planting in a level curve; terraces; crop rotation; use of crops for pasture recovery; fallow or rest of the soil; burned; and protection of slopes

<sup>7</sup> Refers to resources such as: rivers or streams; natural lakes or dams; and wells/cisterns.

<sup>8</sup> To use climatic variables at the farm level, it would be necessary to obtain the longitude and latitude of the farm, which violates the confidentiality of the dataset provided by IBGE. In this sense, the assumption adopted in this research is that the climatic variables at the municipal level fit a good approximation for those that would be observed within the farm.

<sup>9</sup> We are grateful to Laís Rosa de Oliveira from “Natural and Environmental Resource Economics Research Group – PPGEA/UFV/Brazil” for work on the dataset.

We use in the production function the gross value of production in 2006 (GVP) as a proxy to the output (dependent variable). As inputs, we use land, labor, expenses and capital. *Land* is the sum of the farm area designed to crops and pastures (in hectares); *Labor* is the sum of both familiar and hired labor; *Expenses* are the sum of purchased inputs (US\$ of 2006) as energy, soil correctives, fertilizers, agrochemicals, animal medicines, transportation, packages, seeds and seedlings, and feed/salt; and *Capital* is the sum of buildings, land and vehicles (US\$ of 2006).

## 5. Results

### 5.1. Descriptive Analysis and Entropy Balancing

The descriptive statistics of the variables used are displayed in Table 1.1, which also shows the result of the Entropy Balancing. In general, farmers that use irrigation have higher levels of schooling, reaching 4.5% on higher education when compared to rain-fed farmers, 2.5%. Irrigators also have a higher share of electricity and workforce with skilled labor. Regarding the age, experience and farm ownership, there are no disparities on averages between the groups.

Although the large proportion of irrigators having water resources in the farm, around 87%, we also observe a large proportion of farmers that have water resources into the farm and do not use irrigation technology (74.2%). This result may be related to the lack of knowledge on how to use irrigation, or the low proportion of rain-fed farmers that received rural extension (mainly governmental extension) and accessed financial resources when compared to irrigators (Table 1.1). However, we should consider that irrigation is not needed when farmers are facing some regularity in precipitation levels.

Significant differences in the proportion of irrigators that used agricultural practices (e.g. crop rotation), agrochemicals, fertilizers and soil pH correctives are observed, which imply that those farmers had used irrigation technology jointly to some soil management seeking to ensure crops' yield. Thus, the value of the land (asset) of the irrigators is greater than rain-fed farmers due the technology embodiment (Schoengold and Ziberman, 2007).

The great difference between the groups is observed in the gross value of production obtained in 2006 by the irrigators' farmers, which is almost three times when compared to rain-fed producers. This result shows the importance of irrigation in national agricultural production in terms of value produced and, therefore, productivity gains from irrigation, which demonstrates the advantages of this technology. The value of land, buildings and

vehicles (*proxy* for capital), expenses in purchased inputs and labor have a higher average for irrigators when compared to the rain-fed. On the other hand, there are no significant differences in the amount of land employed in crops and pastures, which reinforce productivity gains due to irrigation.

**Table 1.1 – Mean of the variables used in the Entropy Balancing, Selection Equation and Stochastic Production Frontier**

Variables	Non Balanced Sample		Balanced Sample	
	Rain-Fed (Control)	Irrigators	Rain-Fed (Control)	Irrigators
<i>Gender</i>	0.876	0.912 <sup>***</sup>	0.912	0.912 <sup>ns</sup>
<i>Age</i>	50.36	49.32 <sup>***</sup>	49.32	49.32 <sup>ns</sup>
<i>Read and write</i>	0.096	0.084 <sup>***</sup>	0.084	0.084 <sup>ns</sup>
<i>Do not read and write</i>	0.252	0.151 <sup>***</sup>	0.151	0.151 <sup>ns</sup>
<i>Literate</i>	0.054	0.038 <sup>***</sup>	0.038	0.038 <sup>ns</sup>
<i>Incomplete elementary</i>	0.424	0.458 <sup>***</sup>	0.458	0.458 <sup>ns</sup>
<i>Complete Elementary</i>	0.081	0.112 <sup>***</sup>	0.112	0.112 <sup>ns</sup>
<i>Agric. Technician</i>	0.012	0.022 <sup>***</sup>	0.022	0.022 <sup>ns</sup>
<i>High School</i>	0.057	0.090 <sup>***</sup>	0.09	0.090 <sup>ns</sup>
<i>Higher Education</i>	0.025	0.045 <sup>***</sup>	-	-
<i>Exp_1</i>	0.026	0.019 <sup>***</sup>	-	-
<i>Exp_1to5</i>	0.166	0.162 <sup>***</sup>	0.162	0.162 <sup>ns</sup>
<i>Exp_5to10</i>	0.169	0.165 <sup>***</sup>	0.165	0.165 <sup>ns</sup>
<i>Exp_10</i>	0.639	0.654 <sup>***</sup>	0.654	0.654 <sup>ns</sup>
<i>Private Extension</i>	0.123	0.185 <sup>***</sup>	0.185	0.185 <sup>ns</sup>
<i>Governmental Extension</i>	0.084	0.170 <sup>***</sup>	0.170	0.170 <sup>ns</sup>
<i>Co-op Membership</i>	0.409	0.443 <sup>***</sup>	0.443	0.443 <sup>ns</sup>
<i>Television</i>	0.198	0.240 <sup>***</sup>	0.240	0.240 <sup>ns</sup>
<i>Telephone</i>	0.230	0.401 <sup>***</sup>	0.401	0.401 <sup>ns</sup>
<i>Internet</i>	0.011	0.030 <sup>***</sup>	0.030	0.030 <sup>ns</sup>
<i>Energy</i>	0.684	0.876 <sup>***</sup>	0.876	0.876 <sup>ns</sup>
<i>Financing</i>	0.181	0.230 <sup>***</sup>	0.230	0.230 <sup>ns</sup>
<i>Qualification</i>	0.037	0.075 <sup>***</sup>	0.075	0.075 <sup>ns</sup>
<i>Urban</i>	0.133	0.146 <sup>***</sup>	0.146	0.146 <sup>ns</sup>
<i>Agr. Practice</i>	0.581	0.699 <sup>***</sup>	0.699	0.699 <sup>ns</sup>
<i>Water Resource</i>	0.742	0.868 <sup>***</sup>	0.868	0.868 <sup>ns</sup>
<i>Agrochemicals</i>	0.259	0.573 <sup>***</sup>	0.573	0.573 <sup>ns</sup>
<i>Soil pH</i>	0.068	0.237 <sup>***</sup>	0.237	0.237 <sup>ns</sup>
<i>Fertilizers</i>	0.314	0.745 <sup>***</sup>	0.745	0.745 <sup>ns</sup>
<i>Value of Land</i>	71,784.18	91,683.00 <sup>***</sup>	91683.00	91683.00 <sup>ns</sup>
<i>Agr. Family</i>	0.852	0.779 <sup>***</sup>	0.778	0.778 <sup>ns</sup>
<i>Owner</i>	0.838	0.852 <sup>***</sup>	0.852	0.852 <sup>ns</sup>
<i>Tenant</i>	0.046	0.534 <sup>***</sup>	-	-
<i>Partner</i>	0.028	0.278 <sup>***</sup>	0.278	0.278 <sup>ns</sup>
<i>Occupant</i>	0.087	0.665 <sup>***</sup>	0.665	0.665 <sup>ns</sup>
<i>Summer precipitation</i>	161.01	162.69 <sup>***</sup>	162.69	162.69 <sup>ns</sup>

<i>Winter precipitation</i>	53.07	43.02***	43.02	43.02 <sup>NS</sup>
<i>Summer temperature</i>	25.7	25.43***	25.43	25.43 <sup>NS</sup>
<i>Winter temperature</i>	21.87	21.38***	21.38	21.38 <sup>NS</sup>
<i>Summer Prec. S. Dev.</i>	81.23	82.96***	82.96	82.96 <sup>NS</sup>
<i>Winter Prec. S. Dev.</i>	30.37	25.14***	25.14	25.14 <sup>NS</sup>
<i>Summer Temp. S. Dev.</i>	0.718	0.812***	0.812	0.812 <sup>NS</sup>
<i>Winter Temp. S. Dev.</i>	0.790	0.797***	0.797	0.797 <sup>NS</sup>
<i>GVP</i>	10,900.92	31,225.24	-	-
<i>Labor</i>	2.65	3.55	-	-
<i>Land</i>	42.21	42.6	-	-
<i>Capital</i>	86,426.93	125,403.53	-	-
<i>Purchased Inputs</i>	3,629.29	8,721.85	-	-
<b>N° Obs.</b>	3,994,641	265,224	3,994,641	265,224

**Note:** \*\*\*: Means are statistically different from the control group (rain-fed) at 1%; NS: Means are statistically the same as in the control group at 1%.

**Source:** Research results

The result of the Entropy Balancing, which is based on the mean of the covariates (first moment of the sample), can be observed in the column "Balanced sample" in Table 1.1. Before the Entropy Balancing the means of the variables between irrigators and rain-fed farmers were statistically different. After the Entropy Balancing, we did not find any statistically significant difference between the groups. This balance is confirmed by the non-significance of the null hypothesis of the test of equality of means (Table 1.1). It implies that, for each treatment group there is a similar control, differing only for irrigation adoption.

## 5.2. Production Elasticities

We estimated the stochastic production frontier for the total sample and for both irrigators and rain-fed farmers. The parameters of the Cobb-Douglas function were obtained by the Maximum Likelihood. Therefore, the coefficients estimated represent the production elasticities, except for climatic variables<sup>10</sup>. Results are shown in Table 1.2.

Wald statistic indicates a good fit of the model, rejecting the null hypothesis of joint insignificance of the variables for the three estimated models at 1%. The hypothesis of the sample selection bias in the irrigation adoption was statistically confirmed by the significance of the estimated coefficients for the Inverse of Mill's Ratio for both irrigators and rain-fed farmers, which imply that there are unobservable factors that influence the decision to irrigate.

<sup>10</sup> For a better visualization, we omitted the parameters of climatic variables and its interactions with dummies of Brazilian regions; and parameters of the Federative Units (states). We have calculated climatic semi-elasticity ( $\partial \ln y / \partial x$ ) rather than elasticities, which means a percentage increase/decrease in production value due an increase/decrease in one degree Celsius (for temperature) and one millimeter (for precipitation). Results are shown in Table A1 in the Appendix.

In summary, we found that water resources endowment in the farm are capable of increasing the likelihood of irrigation adoption, since the decision to irrigate is straightforward related to the availability of this resource within the farm. Also, the use of agrochemicals, soil pH correction and soil fertilization contributed positively to the probability of irrigation technology adoption. Nonetheless, these inputs were the ones that most influenced the probability of adopting irrigation, including the electricity endowment into the farm<sup>11</sup>.

**Table 1.2 – Estimation of Stochastic Production Frontier for the total sample, irrigators and rain-fed farmers, 2006.**

<i>Ly(GVP)</i>	<b>Total Sample (Pooled)</b>	<b>Irrigators</b>	<b>Rain-Fed</b>
<i>lx1 (Land)</i>	0.215*** (0.00999)	0.221*** (0.0154)	0.278*** (0.00694)
<i>lx2 (Labor)</i>	0.284*** (0.00738)	0.264*** (0.0111)	0.268*** (0.00657)
<i>lx3 (Purchased Inputs)</i>	0.385*** (0.00639)	0.335*** (0.00899)	0.333*** (0.00530)
<i>lx4 (Capital)</i>	0.0575*** (0.0115)	0.0291* (0.0171)	0.0722*** (0.00472)
<i>Very Small</i>	-0.589*** (0.04364)	-0.727*** (0.05718)	-0.504*** (0.04201)
<i>Small</i>	-0.522*** (0.03398)	-0.658*** (0.04392)	-0.437*** (0.03736)
<i>Medium</i>	-0.352*** (0.02499)	-0.464*** (0.03356)	-0.296*** (0.02982)
<i>Mills Irrigators</i>	-	2.548*** (0.2016)	-
<i>Mills Rain-Fed</i>	-	-	1.149*** (0.0605)
<i>Constant</i>	3.915 (7.6080)	16.29 (12.1063)	-8.469 (8.6966)
<b><i>Inefficiency (Usigma)</i></b>			
<i>Read and write</i>	-0.625*** (0.0281)	-0.543*** (0.0483)	-0.742*** (0.0261)
<i>Do not read and write</i>	-0.609*** (0.0281)	-0.516*** (0.0487)	-0.785*** (0.0250)
<i>Literate</i>	-0.313*** (0.0409)	-0.218*** (0.0740)	-0.442*** (0.0340)
<i>Incomplete Elementary</i>	-0.681*** (0.0232)	-0.638*** (0.0407)	-0.746*** (0.0224)
<i>Complete Elementary</i>	-0.522*** (0.0236)	-0.514*** (0.0413)	-0.529*** (0.0242)
<i>Agricultural Technician</i>	-0.155*** (0.0297)	-0.200*** (0.0490)	-0.124*** (0.0345)

<sup>11</sup>Marginal effects for selection equation (Probit) are shown in Table A2 in the Appendix.

<i>High School</i>	-0.327*** (0.0213)	-0.328*** (0.0379)	-0.317*** (0.0230)
<i>exp_1</i>	1.008*** (0.0249)	1.046*** (0.0433)	0.990*** (0.0238)
<i>exp_1to5</i>	0.453*** (0.0149)	0.456*** (0.0267)	0.460*** (0.0141)
<i>exp_5to10</i>	0.238*** (0.0146)	0.242*** (0.0285)	0.237*** (0.0124)
<i>Technical Assistance</i>	-0.261*** (0.0222)	-0.170*** (0.0417)	-0.282*** (0.0167)
<i>Financing</i>	-0.591*** (0.0153)	-0.557*** (0.0253)	-0.639*** (0.0152)
<i>Constant</i>	2.606*** (0.0245)	2.419*** (0.0422)	2.753*** (0.0237)
<i>Vsigma</i>	0.00500 (0.0250)	0.0680** (0.0347)	-0.148*** (0.0192)
<i>E(Sigma_u)</i>	2.775	2.5696	2.8501
<i>Sigma_v</i>	1.0025*** (0.0125)	1.0346*** (0.0179)	0.9284*** (0.0088)
<i>Lambda (λ)</i>	0.734	0.713	0.754
<i>Log-Likelihood</i>	-8.613e+06	-530808	-8.055e+06
<i>Wald Test</i>	42683.85	22400.31	64020.64
<i>Chi2</i>	42684***	22400***	64021***
<i>N° Obs.</i>	4,259,865	265,224	3,994,641

**Source:** Research results. **Note:** \*\*\* p-value<0.01, \*\* p-value<0.05, \* p-value<0.1

The estimated model for the Brazilian agriculture (pooled) indicates that *purchased inputs* and *labor* are the inputs that most contribute to the formation of the gross value of production (GVP) in 2006, indicating that an increase in 10% in the amount used of these factors would lead to an increase, on average, of 3.85% and 2.84% in GVP, respectively. Similar results were found in Freitas (2017) and Rada *et al.* (2019). On the other hand, *land* and *capital* were the factors that contributed less to the GVP, since an increase in 10% in these inputs would lead to an increase, on average, in 2.15% and 0.57% in GVP, respectively.

Regarding the production elasticities related to irrigators and rain-fed farmers, there were significant differences in the contribution of each input to the GVP formation. For the irrigators, we observed the same pattern found for the *pooled* model, since the *purchased inputs* and *labor* were the inputs that most contributed, on average, to GVP formation.

On the other hand, *purchased inputs* and *land* are the factors that most contributed to an increase of GVP for rain-fed farmers. This result can be explained in part by the lack of knowledge of the irrigation benefits and productive techniques, or constrains in the credit market, which make the adoption of new technology more difficult. Thus, the only alternative for these farmers increase their production is through increments in the expenses and in the

workforce. However, Ullah and Perret (2014) points out that labor-intensive farming system can be a source of employment for rural populations.

The variance of the model was re-parameterized according to Battese and Coelli (1995), such that  $\sigma_s^2 = \sigma_u^2 + \sigma_v^2$  and  $\lambda = \sigma_u^2/\sigma_s^2$ . The value of  $\lambda$  is between zero and the unity. If  $\lambda$  is close to zero, it implies that deviations from production frontier are entirely due to random noise, while a value around the unity indicates that most of the deviations are due to inefficiency. Thus, for the *pooled* model, we can infer that 73.4% of the deviations to the efficient frontier come from technical inefficiency sources; for irrigators, 71.3%, and for rain-fed farmers is 75.4%. This result may be an indicator that irrigators are more efficient than rain-fed farmers. This result also indicates that the Stochastic Production Frontier approach is suitable, since  $\lambda$  were equal to zero, the production function could be estimated by Ordinary Least Squares (OLS).

Table 1.2 also shows the result for inefficiency equation. We modeled this equation which the error term (inefficiency) variance is a function of a covariates vector. If a variable tends to decrease the inefficiency variance, it implies that the observations are close to the efficiency average level. For all models, we can infer that farmers' schooling levels in the lower bound decrease the variance when compared to farmers that have higher education (base). On the other hand, low levels of experience are associated with an increase in the inefficiency variance when compared to those who have more than 10 years of farm's management. This result implies that higher education is not enough to increase efficiency, but it can be observed once the farmer has a high level of experience. Tiruneh *et al.* (2017) found that experience through age matters in production.

Genius *et al.* (2014) suggest that the high levels of experience linked to a technology transmission channel, such as technical assistance services and social network, may be more important in new technologies adoption in irrigation than education levels. Although this study did not consider technical efficiency, they argued that technical assistance and social learning through experience could help them in this task. In addition, Speelman *et al.* (2008) found that education did not significantly affect technical efficiency, while Watto and Mugeru (2019) argued that in relation to education effects on technical efficiency, researchers should consider the relevance of the farmer's education to his farming business.

We also found that any type of access to technical assistance and financing (credit) influences farmers to reach the efficiency average level since this factors decrease inefficiency variance. The findings of Karagiannis *et al.* (2003), Haji (2007), Freitas (2017)

and Watto and Mugeru (2019) also confirm the positive effect of financial resources and extension services in improving farmer's technical efficiency.

Notwithstanding, our result can be evaluated through descriptive statistics in Table 1.1, which only 2.5% of rain-fed and 4.5% of irrigators has higher education level, while 67.6% (rain-fed) and 60.9% (irrigators) do not read and write or did not complete elementary school. On the other hand, 63.8% (rain-fed) and 65.3% (irrigators) have more than 10 years of experience in farm management. Moreover, 12.3% and 8.4% of rain-fed farmers had access to private and governmental technical assistance, respectively. Better result can be observed to irrigators, where 18.5% and 17% of them had access to private and public assistance respectively, which corroborate with Foster and Rosenzweig (1995; 2010) and Genius *et al.* (2014) on the role of social learning, learning-by-doing and extension services (mainly governmental assistance) in irrigation technology adoption and efficiency improvements.

### 5.3. Technical Efficiency Scores

The unbiased technical efficiency scores (TE) were obtained for all models estimated and classified by farm size. Table 1.3 shows the result. We found that average technical efficiency of the irrigators is 29.65%, whereas for those who are rain-fed is 27.14%, which imply that irrigators are technically more efficient than rain-fed farmers at 2.51 percentage points (p.p.). These results imply that irrigation technology adoption is capable to move farms to the best practice, that is, the potential production. However, there is a lot of room for both irrigators and rain-fed farmers to increase production maintaining the same amount of inputs.

**Table 1.3 – Mean of technical efficiency scores by farm size, 2006.**

Balanced Sample	Mean	Very Small	Small	Medium	Large
<i>Total Sample (Pooled)</i>	<b>0.2730</b> (0.1974) [4,259,865]	<b>0.2439</b> (0.1865) [3,283,910]	<b>0.2629</b> (0.1776) [694,116]	<b>0.2528</b> (0.1825) [208,881]	<b>0.2408</b> (0.1862) [72,959]
<i>Irrigators</i>	<b>0.2965</b> (0.1702) [265,224]	<b>0.2909</b> (0.1744) [196,078]	<b>0.3155</b> (0.1540) [47,999]	<b>0.3063</b> (0.1609) [15,337]	<b>0.3019</b> (0.1655) [5,810]
<i>Rain-Fed</i>	<b>0.2714</b> (0.1990) [3994642]	<b>0.2721</b> (0.2014) [3087832]	<b>0.2740</b> (0.1891) [646,117]	<b>0.2602</b> (0.1935) [193,544]	<b>0.2474</b> (0.1976) [67,149]

**Note:** Standard deviations in ( ); Number of observations in [ ]

**Source:** Research results.

The values of the standard deviations for both irrigators and rain-fed (0.1702 and 0.1990, respectively) suggest that, in relation to the mean, there is a great dispersion of the data, i.e., a great heterogeneity in terms of technical efficiency, which leads to a low average of TE. To confirm this result, TE distributions are shown in Figure A1 in the Appendix for both groups.

We found for all models estimated that technical efficiency (TE) scores by farm size, on average, increase from the group of *very small* to *small* farmers. Then, the average TE scores decrease as farm size increase. Therefore, *small* farmers are the most technically efficient, which imply they are those that transform productive factors into gross production value more efficiently, which corroborates to Schutz (1965), who argued that small farmers are poor but efficient.

A test of equality of means (t-test) between both groups irrigators and rain-fed farmers and within each group taking into account the farm size was performed to verify if the technical efficiency mean scores were different from each other or were statistically the same. Table 1.4 shows the result. We can note that all the means of technical efficiency between and within the groups were statistically different. Between irrigators and rain-fed, the difference is 0.02509 and t-test is equal to -63.3885, which imply the rejection of the null hypothesis of equality of means.

**Table 1.4 – Test of equality of means (t-test) of the technical efficiency scores, 2006**

	Total Sample		Irrigators		Rain-Fed	
	Diff.	t-test	Diff.	t-test	Diff.	t-test
<i>Very Small x Small</i>	-0.0190 <sup>***</sup> (0.0002)	-77.7469	-0.0245 <sup>***</sup> (0.0008)	-28.2470	-0.0019 <sup>***</sup> (0.0002)	-7.1581
<i>Very Small x Medium</i>	-0.0088 <sup>***</sup> (0.0004)	-21.1575	-0.0154 <sup>***</sup> (0.0014)	-10.5884	0.0118 <sup>***</sup> (0.0004)	25.1434
<i>Very Small x Large</i>	0.0030 <sup>***</sup> (0.0006)	4.3718	-0.0109 <sup>***</sup> (0.0023)	-4.7174	0.0246 <sup>***</sup> (0.0007)	31.4414
<i>Small x Medium</i>	0.0101 <sup>***</sup> (0.0004)	22.6568	0.0091 <sup>***</sup> (0.0014)	6.3279	0.0137 <sup>***</sup> (0.0004)	27.9911
<i>Small x Large</i>	0.0220 <sup>***</sup> (0.0006)	31.7548	0.0136 <sup>***</sup> (0.0021)	6.3062	0.0266 <sup>***</sup> (0.0007)	34.5956
<i>Medium x Large</i>	0.0119 <sup>***</sup> (0.0007)	15.1403	0.0044 <sup>*</sup> (0.0024)	1.7862	0.0128 <sup>***</sup> (0.0008)	14.7484

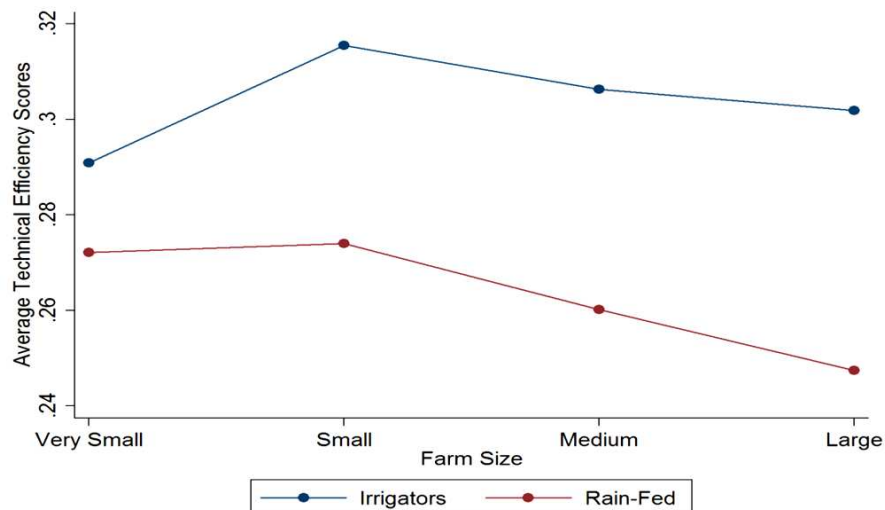
**Note:** \*\*\* p-value<0.01, \*\* p-value<0.05, \* p-value<0.1; Standard Error in ( ); Diff means the difference of technical efficiency average.

**Source:** Research results.

We display the behavior of technical efficiency and farm size in Figure 1.1. The greatest difference in terms of average TE between irrigators and rain-fed is for the *large* farmers, following by the group of *mediums*, where the formers are 5.45 p.p. more efficient than the non-adopters, and the latter are 4.61 p.p. more efficient, which imply that, although *small* farmers are, on average, more efficient than the others groups, the irrigation technology adoption has a stronger effect on TE for the *large* farmers.

The smallest difference in TE due to irrigation adoption was found for the *very small* farms, around 1.88 percentage points. This last result can be partly explained by the lack of knowledge on how to operate the technology, difficulties faced on credit market and/or the lack of extension services. Helfand and Levine (2004) pointed out that *large* farmers can have preferential access to institutions and services that can help reduce technical inefficiency such as rural electricity, technical assistance, and market access. Also, the *large* farmers are more intensive in technologies and inputs that increase productivity, for instance, irrigation technology.

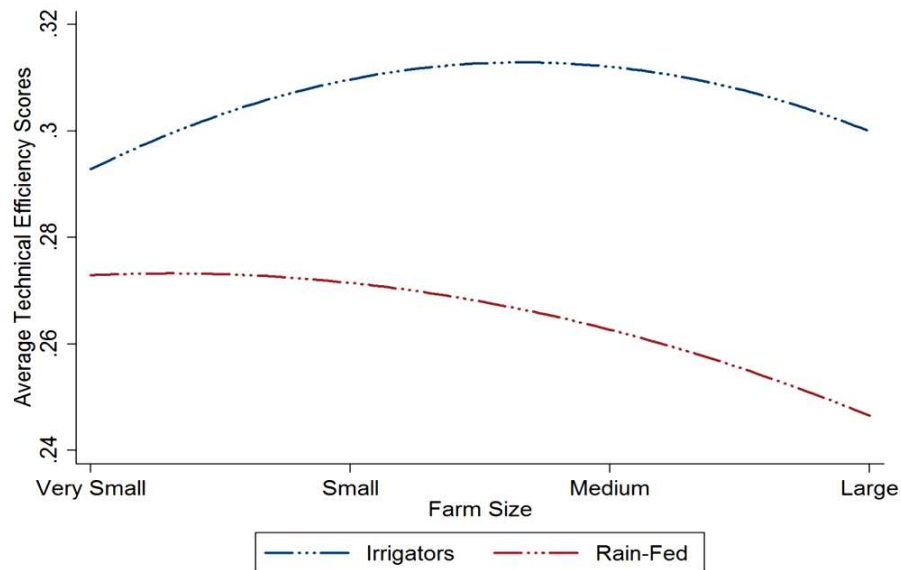
**Figure 1.1 – Average technical efficiency scores by irrigation adoption and farm size, 2006.**



Source: Research results

Figure 1.2 shows the behavior between technical efficiency scores and farm size as a smoothed shape of this relationship (quadratic prediction). We found a U-inverted relationship between farm size and technical efficiency. Similar behavior between technical efficiency (or technical efficiency change) and farm size were found in Helfand and Levine (2004), Freitas (2017) and Rada *et al.* (2019). They also found the highest efficiency levels for small farms.

**Figure 1.2 – Smoothed shape of average technical efficiency scores by farm size.**



Source: Research results

## 6. Conclusions

Irrigated agriculture in Brazil is an effective tool to alleviate poverty and improve income distribution, generating employment at lower costs than those in other sectors of the economy, which increase food supply at lower prices than those produced in non-irrigated areas and significant increase in productivity of land and labor factors.

In this sense, the present research aimed to identify the effect of irrigation technology adoption on the productive performance of farmers, in terms of technical efficiency. The analysis also extended to different farm sizes. Dataset at farm level of 2006 Agricultural and Livestock Census were accessed in the Restricted Access Room (SAR) of the Brazilian Institute of Geography and Statistics - IBGE.

Regarding the technical efficiency, both irrigators and rain-fed had a low level of technical efficiency, where irrigators are more efficient than rain-fed farmers in 2.51 percentage points. The analysis by farm size showed that, in both groups, the small farmers are more efficient than the remaining sizes. However, the greatest difference observed in efficiency scores between irrigators and non-adopters was for medium and large farms, which imply that irrigation technology has a significant effect on the efficiency gain for those groups.

The outline of public policies to encourage irrigation adoption can be led, initially, to the effective provision of rural extension services, the increase in skilled workforce in the farm, formulation of projects that promote rural electrification and water resources within the farm, since these factors contributed to the increase of irrigation technology adoption. Nevertheless, electricity and water resources are, in general, prerequisites for the implementation of irrigation systems. The role of public policies also relies on rural technical assistance provision and credit market access due to the importance of these factors to increase efficiency.

Irrigation revealed itself capable of making farmers more efficient, which shows the effectiveness of the technology. However, greater investments in public policy on irrigated agriculture are suggested with special attention to very small producers, 77% of the total, which irrigation adoption had less impact on technical efficiency, which is correlated to farmers' managerial skills. To achieve improvements in rural development, the management of governmental credit and investment programs is also essential in those tasks.

## CHAPTER 2

### IRRIGATION EFFECTS ON GRAIN SECTOR IN THE BRAZILIAN SOUTHEAST: A SHORT-RUN ANALYSIS

#### 1. Introduction

The irrigation projects in Brazil were developed first in the South region. The use of irrigation systems was driven by private agents to make rice growing feasible, and was extended to coffee plantations in the State of São Paulo in the Southeast Region (Ministry of National Integration-MI, 2008). The irrigated areas in Brazil are still considered small compared to the total agricultural area; to the territorial extension; and to the set of favorable physical-climatic factors, including water availability (Cuadra *et al.*, 2019).

On the other hand, annual increases in the irrigated areas have remained high in recent years, indicating that this potential has been used in areas significantly larger each year, mainly in the Southeast region with grains, sugar-cane and orange production (ANA, 2016; 2017). The region has presented successive and expressive increments on irrigated land since 1970, which also has greater diversification of irrigation methods among the Brazilian regions<sup>12</sup>.

São Paulo and Minas Gerais States account for 34.0% of the total irrigated land in Brazil and 87.9% of the Brazilian southeastern, driving the region to respond nowadays to the largest irrigated area, 39.0% of the total (ANA, 2018). The percentage of farmers that adopted irrigation technology in Brazil was around 6.3% in 2006 while the Southeast region presented an adoption rate of around 11.8% in the same year (IBGE, 2006).

It should be pointed out that the low adherence to irrigation technology might be due to the irrigation costs; absence of water resources within the farm; difficulties faced in the credit market by the farmers, mainly small farmers; and levels and frequency of precipitation (Cristófidis, 2013). To alleviate water scarcity, irrigation systems are becoming more efficient (Schaible; Aillery, 2012), maximizing water productivity rather than land productivity (Sepaskhan *et al.*, 2006), while irrigation systems adoption generate higher yields, allowing the production of valuable crops and reducing production costs as well (Stubbs, 2016).

---

<sup>12</sup> The main irrigation methods used in Brazil are: flooding, furrows, traditional sprinkler, sprinkler by central-pivot; micro-sprinkler and dripping (localized); and others (bucket, hand watering, etc.). Those methods will be discussed in the next section.

The Agência Nacional de Águas – ANA (Brazilian Water Agency, in English) highlights that although all the benefits related to irrigation are recognized, there are still difficulties in assessing its importance in the current quantity produced and its role in the food and nutritional security of the Brazilian society due to the unavailability of data or the impossibility of data disaggregation in relation to the agriculture.

The literature about the effects of irrigation on the productive structure of farmers is not so vast. This gap leads to an inconclusive result in relation to the real effect of irrigation, mainly on the supplies of grains, demands for productive factors, and the return in terms of extra revenue achieved by irrigation (Okada *et al.*, 2018). Nonetheless, the knowledge on how irrigation technology and adaptive capacity to climatic variability among farm sizes is a relevant research goal because structural changes in the distribution of farm sizes have implications for rural economies, consumers in both export and local markets, and for new producers entering the industry (Vanschoenwinkel; Van Passel, 2018).

Climatic variations are expected to adversely affect food production in some important regions of the world, generating possibly significant losses, most likely affecting small farmers and poorer populations (Vanderlugt, 2011). Although the growth of irrigated agriculture generally results in water use overexploitation, several benefits are recognized, such as the increase in the productivity, the reduction of unit costs, the mitigation of climatic risks, the optimization of inputs and equipment, and mainly in the increase of food supply, making its stable in the short and long run. (Cuadra *et al.*, 2019).

The Southeast Region has presented increasingly irrigated areas expansion, mainly with central-pivots in the last two decades (ANA, 2016); and is characterized by the developed stage of mechanization in agriculture, being this region dominated by technically advanced commercial farmers (FAO, 2015). Moreover, irrigation practices in the winter season allow the farmers to crop twice rather than once a year, which may reflect why the fraction of irrigated land in the Southeast is higher than other regions, and why most of the crop plantations are those more valuables. The region also has the proximity of the main commodities exporting ports in Brazil, Port of Santos and Port of Paranaguá, which leads the region to be in advantage in terms of rural development and agricultural market structure. These interesting aspects caused the Southeast Region to be chosen as our object of analysis in this research. Furthermore, to the best of our knowledge, there is no research evaluating the grain sector and/or the effect of irrigation on grain production in southeastern Brazil, while grains production represents 55% of the total agricultural production in the region.

Thus, we seek in this chapter to answer the following questions: *How much of grain supply can be achieved through irrigation technology? What is the role of the farm heterogeneity in terms of size in the response to irrigation expansion? And how much of each grain revenue and in total grain revenue is due to irrigation in southeastern Brazil?* To answer those questions, we propose to estimate the irrigation effect on grains supplies, input demands and farmers' revenue using more than 308 thousand farm observations from 2006 Agricultural and Livestock Census.

We aim to estimate the farm marginal effect of irrigated land expansion due to its importance to reveals how much grain supply can be achieved through irrigation technology and the capacity to increase input demand, allowing measuring the irrigation effects on the farmers' revenue. The marginal effect of irrigation is estimated on coffee, rice, soybeans, corn, and beans supplies as well as labor and fuel demand in the short-run, which are obtained using derivative properties from a restricted quadratic normalized profit function. Our estimates also take into account different farm sizes to evaluate how the farm heterogeneity responds differently to irrigation and short-run weather effects since these factors might impose production losses (Pereda, 2012).

Our analysis contributes to the literature by providing estimates on how much revenue of each output is due to irrigation and also the change in total revenue of the grain sector. Added revenue due to irrigation measures the opportunity cost of irrigation while comparisons for different commodities allow us to rank commodities according to their revenue efficiency relative to irrigation use (Moolman *et al.*, 2006). Thus, policies' actions can be driven to those crops mostly valuable in terms of added revenue achieved through irrigation technology and/or based on the revenue participation of each crop within the total amount of revenue generated for the entire sector.

We found that irrigation expansion affects positively all grains supplies and labor demand, which the supplies and labor demand of the very small and small farmers are those most affected by irrigation in the short run. The change in the grain sector revenue due to irrigation is 2.10% (around US\$ 83.45 million), where changes in the revenue of coffee, corn, and beans represent 97% of the total added revenue. We also found that output supplies and input demands respond differently to heterogeneous farm sizes facing irrigation expansion and short-term weather effects.

This chapter is organized in five sections besides this introduction. The following section we present a background of irrigated land and grain production in the Southeast region. The

theoretical framework and empirical model are described in Sections 3 and 4, respectively. Our results are shown in section 5; and our final conclusions are exposed in Section 6.

## **2. Background**

Throughout the 20th century, a set of institutions focusing on issues of climate, water availability and sanitation were created, being fundamental to the development of irrigation in Brazil. The second phase of government actions in the irrigation expansion came in the late 1960s, while the 1970s is recognized as the starting point for irrigated perimeter projects across the country (Bursztyn, 2008).

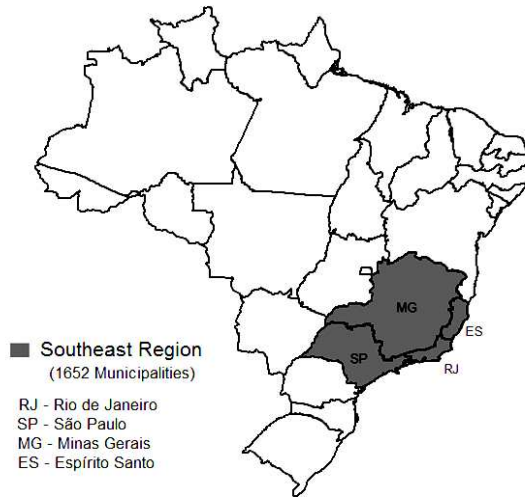
In 2002/2003, the Ministério da Agricultura, Pecuária e Abastecimento – MAPA (Ministry of Agriculture, Livestock and Food Supply, in English) created the Irrigated Agriculture Support Program (Proirriga) seeking to finance the implementation, renovation or conversion of irrigation systems, including infrastructure of buildings, which was managed by the Banco Nacional de Desenvolvimento Econômico e Social – BNDES (National Bank for Economic and Social Development, in English). The program was joined to the Rural Property Storage Program (Proazem), resulting in the Incentive Program for Irrigation and Production in Protected Environment (Moderinfra) (EMBRAPA, 2010). Moderinfra is in force until the present and is the main channel to finance credit to the producers to develop and expand irrigated agriculture. Moreover, the More Irrigation Program was launched in 2012 with the purpose to invest in the regional economy, generate employment and income, and ensure production (BRASIL, 2013).

Christofidis (2008; 2013) points out some goals of those policies, such as expansion of irrigated areas and increasing productivity on an environmentally sustainable basis; reduce the climatic risks; promote local and regional development; increasing the competitiveness of agribusiness for generation of employment and income; supplying outputs for domestic market and generating surplus exports; training of human resources; and generation and transfer of technologies related to irrigation.

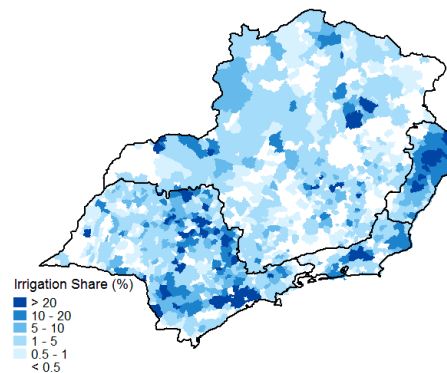
As Brazilian agriculture in general, irrigated agriculture in the Southeast Region is dynamic and diversified, which more than 70 different crops are associated with different irrigation methods. Figures 2.1a and 2.1b show the Southeast Region and the fraction of irrigated land, respectively. Despite irrigation technology adoption in the Southeast region achieves 12%, we can observe some municipalities facing high irrigation share, for instance, in Espírito Santo and São Paulo. The percentage of irrigated land in relation to the total land

used in agriculture easily surpasses 20% in some municipalities, which implies that those places are mostly based on irrigated production. Figure 2.2 displays the amount of irrigated land in thousands of hectares by irrigation method and for each Federative Unit of the Southeast region in 2006.

**Figure 2.1a – Southeast Region**



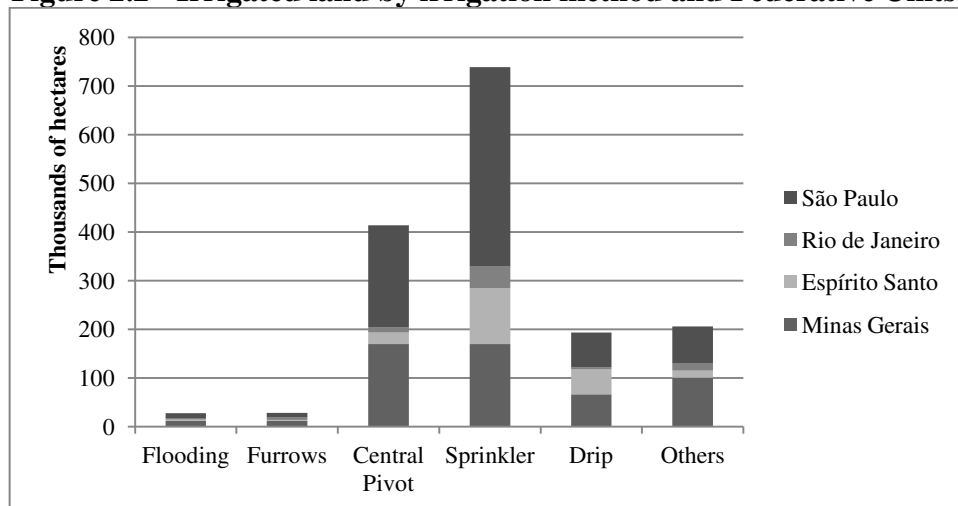
**Figure 2.1b – Irrigated Land (%)**



**Source:** Author’s elaboration based on 2006 Agricultural and Livestock Census.

In spite of diversity, it is possible to extract some large scale patterns between irrigation methods and crops, such as the strong correlation between flooding and rice; dripping and coffee; conventional sprinkler and sugarcane; and central pivots in the grain production, especially, beans, corn and soybeans (ANA, 2018).

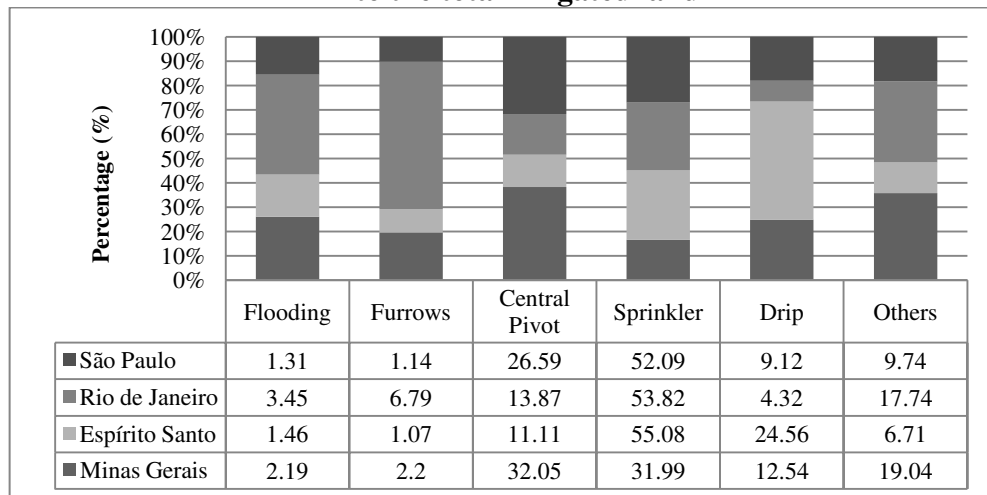
**Figure 2.2 - Irrigated land by irrigation method and Federative Units.**



**Source:** Research Results based on 2006 Agricultural and Livestock Census

Figure 2.3 displays the percentage of irrigated land by irrigation method in relation to the total irrigated land in the Southeast Region. We can observe large areas irrigated by sprinkler and central-pivot. These two methods represent more than 78% of irrigated land in São Paulo and 64% in Minas Gerais. Drip irrigation can be found in Espírito Santo and Minas Gerais mostly to irrigate coffee and corn, which represents 24.5% of irrigated land to the former and 12.5% to the latter. Rio de Janeiro has 53% of irrigated land by sprinklers mostly to produce corn, beans, and fruit plantations.

**Figure 2.3 - percentage of irrigated land by irrigation method in relation to the total irrigated land**



**Source:** Research Results

In some rural areas in southeastern region affected by water scarcity in specific periods of the year, some crops and harvests are only feasible with the supplementary application of water, although production can be carried out with smaller risks in the rainy summer season (ANA, 2017). Figures A2 in the Appendix displays the distribution of the production across the Southeast region aggregated at the municipality level for the set of grains analyzed in this research: coffee, rice, soybeans, corn, and beans. Despite of a larger production observed in the region for those outputs, which represent more than 50% of total production, the percentage of farmers that adopted irrigation technology to produce each output is still low: 14.07% for rice; 7.63% for soybeans; 6.35% for beans; 4.66% for corn; and 3.3% for coffee. Thus, the low percentage of irrigation adoption might imply that most of the amount produced in the Southeast region comes from medium and large farms with a high irrigation rate since the region is mostly mechanized and capital intensive.

### 3. Theoretical Framework

The duality between the production function and the profit function was first investigated in Gorman (1968) and McFadden (1978). The profit function is the mathematical representation of the solution of the economic agent's optimization problems, which is defined as profit maximization (Lau, 1976).

Chambers (1988) argues that profit maximization with fixed product implies the same configuration of inputs when implemented by the cost minimization problem. Thus, if the duality between the profit function and the cost function exists, a conjugate relationship between the profit function and the production function can be developed (Chambers, 1988). The profit function approach allows us to retrieve relevant information on the production process, such as output supply relations, demand for productive factors, and own and cross elasticities (Diewert and Morrison, 1989).

Thus, we propose to identify the effect of irrigation on grain production and productive factors using derivative properties of a restricted profit function. It represents that some inputs, such as irrigated land, can be fixed (or quasi-fixed), since the possibility of changing the quantities of these inputs are constrained in the short run.

Carey and Zilberman (2002) argue that farmers face difficulties when choosing and/or changing production input-output, such as irrigation technology. Therefore, choices related to this technology are long-term decisions and considered as fixed (or quasi-fixed) in the short term. According to Huffman and Evenson (1989), the fixed factors are not under the control of farmers, or are only partially under their control, or when under control demand some time and cost of adjustment.

In the case of irrigation, the preparation of land to be irrigated and the irrigation system implementation demands a certain period of time, being therefore not feasible in the short term. The existence of these inputs delimits the production possibilities set, leading the problem of profit maximization to a restricted problem.

Lau (1976) and Huffman e Evenson (1989) argue that taking into account a production decision for many outputs and inputs (multi input-output), the farmers make choices on  $n + m + 1$  products  $y_i$ , which they supply  $n + 1$  outputs, such as  $y_i > 0$ ,  $i = 0, \dots, n$  and require  $m$  variables inputs, such as  $y_i < 0$ ,  $i = n + 1, \dots, n + m$ . The quasi-fixed factors vector can be represented by  $z_k$ , where  $z_k \geq 0$ ,  $k = 1, \dots, K$ .

Since the profit function is normalized, the output at which its price is used to normalize

the function can be defined by  $y_0$ , i.e., a numeraire output. Thus,  $p_0$  is a numeraire price, which can be set equal the unit, such as  $p_i = p_i/p_0$ ,  $i = 1, \dots, n + m$ , where  $p_i$  is the numeraire price of  $y_i$ ,  $i = 1, \dots, n + m$ , and  $p_i > 0$ . This procedure impose homogeneity of degree one in prices  $\mathbf{p}$ . The profit function can be represented by  $\pi = f(\mathbf{p}, \mathbf{z})$ , where  $\pi$  is the normalized restrict profit ( $\pi = \pi'/p_0$ ),  $\mathbf{p}$  is a vector of  $n + m$  normalized prices and  $\mathbf{z}$  is a vector of  $K$  quasi-fixed inputs.

The first derivative of the restricted profit function with respect to each output price can be performed using envelope theorem to obtain the correspondent output supply:

$$\frac{\partial \pi}{\partial p_i} = y_i^*(\mathbf{p}, \mathbf{z}) > 0, \quad i = 1, \dots, m \quad (1)$$

The input demand is obtained taking the first derivative of the restrict profit function in respect to each input price:

$$\frac{\partial \pi}{\partial p_i} = y_i^*(\mathbf{p}, \mathbf{z}) < 0, \quad i = 1, \dots, n \quad (2)$$

The numeraire output supply or input demand equations also can be represented by Equation (1) or (2) and obtained using homogeneity properties, which depend of the price (of the input or output) chosen to normalize the restrict profit function. Also from Equation (1)-(2) we can use the second derivative of restricted profit function in respect to price to obtain output/input own and cross elasticities:

$$\frac{\partial^2 \pi}{\partial p_i^2} \frac{p_i}{\partial \pi / \partial p_i} = \frac{\partial y_i^*}{\partial p_i} \frac{p_i}{y_i^*} \quad i = 0, 1, \dots, n + m \quad (3)$$

where the elasticity predicted by Equation (3) is positive if  $y_i^*$  is an output and negative if  $y_i^*$  is an input. The former result is due to own price elasticity for output supply and the latter is due to own price elasticity for input demands.

To estimate the effect of quasi-fixed input on output supply or a variable input, i.e., input demand, we can obtain the output and input elasticity in respect to the quasi-fixed input:

$$\frac{\partial^2 \pi}{\partial p_i \partial z_k} \frac{z_k}{\partial \pi / \partial p_i} = \frac{\partial y_i^*}{\partial z_k} \frac{z_k}{y_i^*} = \lambda_{z_k}^{y_i} \leq 0 \quad (4)$$

where  $\partial\pi/\partial p_i = y_i^*$ . The theory does not impose any sign on  $\lambda_{z_k}^{y_i}$ , in which a positive sign implies a percentage increase on output supply or input demand due to a percentage increase in the quasi-fixed input, and a percentage decrease otherwise. If  $\lambda_{z_k}^{y_i}$  is equal to zero, there are no effects of the quasi-fixed input on output supply or input demand. To measure the irrigation effect on the revenue of each farm output, we multiply the marginal effect of each farm by the output price and the total irrigated land in the farm. Thus, if we sum the effect over farmers as a whole we obtain the effect of the irrigation on the revenue of each output for the southeastern region:

$$\delta_{i,z_1} = p_i * \frac{\partial y_i^*}{\partial z_k} * \sum_{j=1}^J z_{1,j} \quad (5)$$

where  $j = 1, \dots, J$  represents each farmer producing the output  $i$ ;  $p_i$  is the output price;  $\partial y_i^*/\partial z_k$  is the marginal effect of irrigation on output supply; and  $z_{1,j}$  is the irrigated land in hectares. Thus, we can divide each  $\delta_{i,z_1}$  by the total revenue of each output observed in the market to obtain a relative measure, i.e., the proportion of added revenue of each output due to irrigation in relation to total revenue of that output:

$$\psi_i = \frac{\delta_{i,z_1}}{p_i * Y_i} \quad (6)$$

where  $Y_i = \sum_{j=1}^J y_{ij}$  represents the quantity produced over all farmers. To obtain a relative measure for the grain sector, we obtain the total revenue gain due to irrigation summed over outputs and farmers and divide by the total revenue observed in the grain sector in the Southeast region.

#### 4. Empirical Application

To obtain a system of supply – for coffee, rice, soybean, corn and beans – and demand equations – for labor and fuel; and then to evaluate the effect of quasi-fixed inputs on production, Diewert et al. (1989) suggest that a flexible functional form is preferable, which have been employed in several studies, such as the translogarithmic function in McKay *et al.* (1983), the normalized quadratic function in Shumway *et al.* (1988), Huffman and Evenson (1989), and Schuring *et al.* (2011), and the generalized Leontief function in Lopez (1984). According to Huffman and Evenson (1989), the normalized quadratic function is preferable

due to linear homogeneity in the output and input prices. Lau (1976) and Lopez (1985) argue that the normalized quadratic function has additional implications on production technology, such as weak separability between inputs and outputs, and quasi-homotheticity. In this sense, we assume that our restricted profit function can be represented by a quadratic functional form to obtain the output supply and input demand using derivative properties. Since Equation (1) and (2) are linear on normalized input prices and quasi-fixed inputs, we can obtain:

$$\frac{\partial \pi}{\partial p_i} = y_i^* = \alpha_i + \sum_{j=1}^{n+m} \beta_{ij} p_j + \sum_{k=1}^5 \gamma_{ik} z_k + \sum_{s=1}^4 \phi_{is} f s_s + \sum_{k=1}^5 \sum_{s=1}^4 \varphi_{iks} z_k f s_s + \sum_{f=1}^4 f u_i + \varepsilon_{yi} \quad (7)$$

where  $i = 1, \dots, n + m$  represent outputs/inputs;  $p_j$  are the respective output/input prices;  $z_k$  are quasi-fixed inputs;  $f s_s$  represent dummies of farm size (three out of four);  $f u_i$  represent dummies of Federative Units in southeastern region (three out of four);  $\varepsilon_{yi}$  represent random shocks for each equation; and  $\alpha_i$ ,  $\beta_{ij}$ ,  $\gamma_{ik}$ ,  $\phi_{is}$  and  $\varphi_{iks}$  are parameters to be estimated. Symmetry property is imposed across equations ( $\beta_{ij} = \beta_{ji}$ ) since five outputs supplies and two input demands are considered in this research. The formers are equations for coffee, rice, soybeans, corn and beans; and the latter are labor and fuel;  $y_i^*$  is positive if represents an output supply and negative for input demand. The quasi-fixed inputs ( $z_k$ ) are capital, rain-fed cropland, irrigated land, temperature, precipitation and farm size.

From Equation (2) and parameters estimated in Equation (7), the output supply and input demand own and cross elasticities can be recovered by Equation (8); and cross elasticities in relation to the numeraire output can be recovered by Equation (9):

$$\eta_{y_i p_j} = \frac{\partial y_i^*}{\partial p_i} \frac{p_i}{y_i^*} = \beta_{ij} \frac{p_i}{y_i^*} \quad (8)$$

$$\eta_{y_i p_0} = \frac{\partial y_i^*}{\partial p_0} \frac{p_0}{y_i^*} = -\frac{1}{y_i^*} \sum_{j=1}^{n+m} \beta_{ij} p_j \quad (9)$$

We expect that own price elasticities in Equation (8) are positive for output supplies and negative for input demand. In relation to the cross elasticities, the outputs are *complementary* if  $\eta_{y_i p_j} > 0$  and *substitutes* if  $\eta_{y_i p_j} < 0$ . The same relation holds between input price and

output supply. On the other hand, the inputs are *complementary* if  $\eta_{y_i p_j} < 0$  and *substitutes* if  $\eta_{y_i p_j} > 0$ .

The quasi-fixed input effects ( $\lambda_{z_k}^{y_i}$ ) on output supply and input demand are obtained using Equation (4) and parameters estimated in Equation (7):

$$\lambda_{z_k}^{y_i} = \frac{\partial y_i^*}{\partial z_k} \frac{z_k}{y_i^*} = \left( \gamma_{ik} + \sum_{s=1}^4 \varphi_{iks} f_{S_s} \right) * \frac{z_k}{y_i} \quad (10)$$

where  $z_k$  are the quasi-fixed factors; and the effects of  $z_k$  by farm size can be evaluated jointly by the parameters  $\gamma_{ik}$  and  $\varphi_{iks}$ . The effect of irrigation ( $z_1$ ) on each output revenue and total revenue, i.e., the grain sector revenue for Brazilian Southeast region, we use Equations (5)-(6) and the parameters estimated in Equation (7) to obtain

$$\delta_{i,z_1} = \bar{p}_i * \left( \gamma_{ik} + \sum_{s=1}^4 \varphi_{iks} f_{S_s} \right) * \sum_{j=1}^J z_{1,j} \quad (11)$$

where  $\bar{p}_i$  is the average output price;  $\sum_{j=1}^J z_{1,j}$  is the irrigated land in hectares summed over producers; and  $\delta_{i,z_1}$  is the added revenue of each output due to irrigation. The relative measure is obtained by the ratio  $\delta_{i,z_1} / (p_i * Y_i)$ , where  $Y_i = \sum_{j=1}^J y_{ij}$  represents the quantity produced over all farmers. Agricultural sector revenue gain due to irrigation in Southeast region is obtained by summing up all revenue gains ( $\delta_{i,z_1}$ ) and dividing by the total revenue observed in the production of those outputs in the region.

The jointly estimation of output supplies and input demand described in Equation (7) generate a system of equations, which the error term of one of the equations may be contemporaneously correlated with the error term of the others, leading to a Seemingly Unrelated Regression (SUR) estimation (Zellner, 1962).

#### 4.1. Data Source

In this research we have used a dataset at the farm level from 2006 Agricultural and Livestock Census for Brazilian Southeast region, which only can be accessed at the Brazilian Institute of Geographic and Statistics headquarter in Rio de Janeiro. We have selected only

farmers that had produced at least one of the following outputs: coffee, rice, soybeans, corn and beans. Thus, the final dataset contains more than 308 thousands farms observations. The grains were chosen based on the proportion of farmers that use irrigation to produce them<sup>13</sup> and also based in their relevance on total value of production in Southeast region, which together, represent around 55% of total production value for the region.

We have included information on the following quasi-fixed inputs: capital, rain-fed cropland, irrigated land, temperature, precipitation and farm size. *Capital* is the sum of the value of buildings, land (asset) and vehicles; *Rain-fed cropland* represents the land used in crops minus the irrigated cropland; *Irrigated land* is the total of irrigated land (in hectares) used in the production; *Temperature* is the municipality average temperature in degree Celsius for 2006; *Precipitation* is the municipality<sup>14</sup> cumulative average precipitation in millimeters for 2006; and *Farm size* is represented by *dummies* for four different size based on the fiscal module approach<sup>15</sup>. Climatic Dataset was obtained from the Climate Research Unit – CRU/University of East Anglia<sup>16</sup>.

It is important to highlight that the short-term weather conditions used in this research represent events during the growing and the harvesting seasons, which are not observed by the farmers when choosing the output-input mix that optimizes their outcomes. As our analysis is a restricted problem, that is, evaluated in the short-run, the climate for the year of the production process can determine failures in the outcome (Pereda, 2012). Our interest lies in how the farmers respond to the unexpected climatic conditions.

Vanschoenwinkel and Van Passel (2018) suggest that farmers are very heterogeneous and different farm types (such as farm size and crop choice) might respond differently to irrigation practices and weather effects. To test their argument, besides the inclusion of *dummies* for

---

<sup>13</sup> 2006 Agricultural and Livestock Census did not report the amount of irrigated land used in each output produced, while the survey does report only information on the proportion of farmers that use irrigation to produce each output; and the amount produced when the farmer use irrigation technology.

<sup>14</sup> To use climatic variables at the farm level, it would be necessary to obtain the longitude and latitude of the farm, which violates the confidentiality of the dataset provided by IBGE. In this sense, the assumption adopted in this research is that the climatic variables at the municipal level fit a good approximation for those that would be observed within the farm.

<sup>15</sup> Fiscal module classification is defined as the minimum area required for rural properties to be considered economic viable (Landau *et al.*, 2012), ranging in area from 5 to 110 hectares. Based on the fiscal module, the farms can be classified into: very small (less than 1 fiscal module); small (between 1 and 4 fiscal module); medium (between 4 and 15 fiscal module); and large (more than 15 fiscal module).

<sup>16</sup> We are grateful to Laís Rosa de Oliveira from “Natural and Environmental Resource Economics Research Group – PPGEA/UFV/Brazil” for work on the dataset.

four farms sizes, we have interacted them to the quasi-fixed input vector. Therefore, we are able to evaluate the effect of the quasi-fixed input on output supply and input demand by size.

In relation to the construction of output prices, some procedures were required. The sales prices reported by the survey are a simple average for the crop season in 2006 rather than different inter-annual sales prices. Furthermore, there is a lack related to price information for those farmers that did not sell or produce the outputs in that crop season. Therefore, we obtained the average price at the municipality level and replaced the missing prices by these average prices. This procedure assumes that producers have observed the output price in the market but chose not producing them, which also implies that farmers have full information about all the five output prices in the market.

The *Labor* and *Fuel* are the two variables inputs considered in this research. Labor price was calculated by the ratio of total wages expenses and the quantity summed of hired and familiar labor. Following the same procedure, fuel price was calculated by the ratio of fuel expenses and their quantities used in the farm, which included ethanol, charcoal, gas, gasoline, grease, lubricant, diesel, kerosene, and others. Labor input price was inputted through the procedure described before to those farmers that did not report wages expenses in the crop season. As all farmers reported that had positive expenses of fuel, then its price was used to normalize the restricted profit function.

Table 2.1 displays descriptive statistics of the variables used in the model (before price normalization) for the Southeast region and by farm size. We can note that soybean and corn prices increase when the farm size increases, which may be correlated to product differentiation through increases in added value by incorporating innovation into the production process. As workforce wages also increase when farm size increases, it may be due to skilled workers employed in the large farms. On the other hand, the prices of the remaining outputs decreases as the farm size increases, which can be explained by scale efficiency in production.

**Table 2.1 – Descriptive statistics of the raw variables in Southeast Region and by farm size, 2006.**

	Southeast		Very Small		Small		Medium		Large	
<i>Quantities</i> <sup>1</sup>	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>
<i>Coffee (y1)</i>	4364.66	27877	1871.71	7319	6568.24	21849	19349.65	66812	43044.03	162691
<i>Rice (y2)</i>	442.44	46973	226.46	8107	370.00	7603	904.61	14945	11616.93	405643
<i>Soybean (y3)</i>	6533.85	134305	145.23	6365	2811.08	36569	29829.57	134724	317674.70	1088637
<i>Corn (y4)</i>	19231.29	746317	6080.77	163350	30826.28	1608548	69240.09	366861	355292.70	1038656
<i>Bean (y5)</i>	887.31	25604	252.02	5992	777.80	19519	3425.63	28977	26827.73	195439
<i>Labor (x1)</i>	3.21	10	2.66	9	3.58	9	6.38	13	14.22	32
<i>Fuel (x2)</i>	893.16	24143	222.71	1660	1424.01	52661	4267.86	11534	15211.45	37872
<i>Prices</i> <sup>2</sup>										
<i>Coffee (p1)</i>	0.6187	10.7172	0.6191	11.9889	0.6379	5.9291	0.5906	6.9079	0.4242	3.8177
<i>Rice (p2)</i>	0.0192	0.1889	0.0199	0.1911	0.0182	0.1820	0.0157	0.1773	0.0160	0.2156
<i>Soybean (p3)</i>	0.0034	0.0734	0.0009	0.0416	0.0054	0.0845	0.0180	0.1701	0.0469	0.2501
<i>Corn (p4)</i>	0.1268	0.3556	0.1286	0.3484	0.1194	0.3501	0.1280	0.4239	0.1319	0.4737
<i>Bean (p5)</i>	0.1495	0.5865	0.1621	0.6054	0.1225	0.5373	0.1006	0.4981	0.0751	0.4337
<i>Labor (p10)</i>	427.32	17981	154.39	1894.92	774.41	30230.12	1909.90	42712.03	3755.71	48477.12
<i>Fuel (p11)</i>	2.1931	6.9646	2.3707	7.4964	1.7543	5.3814	1.6224	4.4859	1.5029	3.5760
<i>Fixed Factors</i>										
<i>Capital (US\$) (z1)</i>	115281.95	1545120	31174.21	735999.7	148618.23	375036.4	538055.81	2409514	2423763.72	9744627
<i>Precipitation (mm) (z2)</i>	124.34	19.7896	122.62	20.5504	128.68	16.8236	129.94	16.4139	129.20	16.1518
<i>Rain-Fed Land (ha) (z3)</i>	32.30	144.5868	7.24	7.5104	42.49	28.1876	158.92	103.1319	713.25	988.0588
<i>Irrigated Land (ha) (z4)</i>	1.16	26.8919	0.19	1.0387	1.03	5.6480	5.35	25.6071	38.68	225.2660
<i>Temperature (°C) (z5)</i>	22.10	1.5306	22.09	1.5377	22.07	1.4981	22.25	1.5217	22.62	1.5385
<b>N° Observations</b>	308601		225186		61292		18125		4000	

**Note:** 1) Quantities of output are defined in kilograms; labor is defined in number of workers (hired and family); Fuel are defined in liters; 2) Prices are defined in US\$ of 2006; ha = hectares; SD = standard deviation. **Source:** Research results.

## 5. Results

The own and cross elasticities of the output supplies and input demands are shown in Table 2.2, in which rows represent the response in quantities due to changes in prices (columns). The result for the system of equations estimated is presented in Table A3 in the Appendix. Evaluated at the average of the observations and for those farmers that at least produce one of the selected grains, the supplies are monotonic, but this is not true at each data point. The percentages of monotonicity violations are 4.8%, 5.86%, 2.9%, 8.95% and 4.11% for coffee, rice, soybean, corn, and beans, respectively. None of the elasticities have presented monotonicity violations for the labor.

**Table 2.2 – Average grain supply and input demand own and cross elasticities, Brazilian Southeast, 2006.**

	Elasticity with respect to the price of						
	<i>Coffee</i>	<i>Rice</i>	<i>Soybeans</i>	<i>Corn</i>	<i>Beans</i>	<i>Labor</i>	<i>Fuel</i>
<i>Coffee</i>	0.172 <sup>***</sup> (0.0091)	-0.0001 <sup>NS</sup> (0.0001)	-0.0001 <sup>***</sup> (0.00003)	-0.034 <sup>***</sup> (0.0033)	-0.001 <sup>**</sup> (0.0007)	0.015 <sup>***</sup> (0.0013)	-0.136 <sup>***</sup> (0.0101)
<i>Rice</i>	-0.015 <sup>NS</sup> (0.0195)	0.562 <sup>***</sup> (0.1366)	-0.009 <sup>***</sup> (0.0018)	0.003 <sup>NS</sup> (0.0514)	-0.027 <sup>NS</sup> (0.0427)	-0.007 <sup>NS</sup> (0.008)	-0.513 <sup>**</sup> (0.1462)
<i>Soybeans</i>	-0.001 <sup>***</sup> (0.0004)	-0.001 <sup>***</sup> (0.0002)	0.388 <sup>***</sup> (0.0143)	-0.003 <sup>*</sup> (0.0016)	3.00E-06 <sup>NS</sup> (0.0002)	0.033 <sup>***</sup> (0.0013)	-0.382 <sup>***</sup> (0.0144)
<i>Corn</i>	-0.043 <sup>***</sup> (0.0041)	0.0001 <sup>NS</sup> (0.0016)	-0.0005 <sup>*</sup> (0.0002)	0.052 <sup>NS</sup> (0.128)	-0.024 <sup>***</sup> (0.0066)	-0.001 <sup>NS</sup> (0.0012)	0.015 <sup>NS</sup> (0.1288)
<i>Beans</i>	-0.030 <sup>**</sup> (0.0136)	-0.006 <sup>NS</sup> (0.0096)	5.71E-06 <sup>NS</sup> (0.0004)	-0.137 <sup>***</sup> (0.0383)	0.281 <sup>***</sup> (0.0563)	0.034 <sup>***</sup> (0.0052)	-0.106 <sup>*</sup> (0.0558)
<i>Labor</i>	-0.016 <sup>***</sup> (0.0014)	0.0001 <sup>NS</sup> (0.0001)	-0.001 <sup>***</sup> (0.00004)	0.002 <sup>NS</sup> (0.0014)	-0.003 <sup>***</sup> (0.00048)	-0.001 <sup>***</sup> (0.0005)	0.020 <sup>*</sup> (1.6789)

**Note:** Parameters are significant at \*\*\*: 1%; \*\*: 5%; and \*: 10%; NS: Non-Significant; Standard errors in ( ). The elasticities of fuel (numeraire) were obtained by the coefficients of numeraire demand equation. **Source:** Research results.

We found a correct theoretical signal for the own elasticities of the output supplies and input demand, which are statistically significant, except for corn. Also, we found that output supplies are inelastic for all the grains selected. The largest price-effects compared to other outputs are for rice and soybeans, since an increase in 10% on its price would lead to an increase of 5.62% and 3.88% on its supply, respectively. Castro and Teixeira (2012) found rice supply elasticity by 3.2% and Wijetunga (2016) around 6.5%. Ball (1988) found output supply elasticity around 8.3% for aggregate grains in the United States. The most inelastic

supply is for coffee since an increase in 10% on its price would lead to an increase in its supply of 1.72%, which is consistent since coffee is the most valuable grain in the region.

Our results suggest that soybeans and corn are substitutes, and coffee is a substitute for soybeans and corn production. Pereda (2012) also found a similar relation between coffee, soybeans, and corn. Figueredo and Texeira (2002) also found that soybean is complementary to bean, but substitute for corn production. On the other hand, a complementary relation between soybeans and corn were found in Neves *et al.* (2016) and Freitas (2018), which diverges of our findings. This last result implies that crop rotation between soybeans and corn is not usual in the Southeast region.

The own price-effect for labor demand is consistent and suggests that it is inelastic in response to changes in the labor wages. Similar findings were found by Freitas (2018). The author argues that labor measurement that also includes familiar labor rather than only hired labor, an inelastic relation is expected because familiar workers are less volatile to changes in their wages. In general, labor price has a positive effect on output supplies while fuel price has an inverse effect. The adverse effect in fuel prices on output supply was expected since the Southeast region is capital intensive. Finally, we found that labor and fuel are substitutes in the production.

We have estimated the effect of irrigation, rain-fed land and weather in terms of semi-elasticity on each grain supply and labor demand, which represents a short-run effect. The results are reported in Table 2.3.

We found that increases in the irrigated land would lead to an increase in all the supplies. The highest effect of the irrigation is for beans and rice supply, in which an increase in one irrigated hectare would increase, on average, 0.91% and 0.43% its supply, respectively. The lowest effect of irrigation is for soybeans production; this result is consistent since this crop is drought resistant and a small productivity gain between irrigated and rain-fed production is observed in Brazilian agriculture for soybeans (EMBRAPA, 2013).

The effect of irrigation is not statistically significant to corn production, while the effect of rain-fed land expansion is significant and shows a positive effect, in which an increase in one hectare of non-irrigated land would lead to an increase of 0.47% on its supply.

Finally, irrigated and rain-fed land expansion would increase labor demand, where the irrigation effect is greater than non-irrigated land, which implies that irrigation is a tool of employment generation in the short run.

**Table 2.3 – Output and input semi-elasticity with respect to selected fixed factor, Southeast, 2006.**

	<b>Coffee</b>	<b>Rice</b>	<b>Soybean</b>	<b>Corn</b>	<b>Bean</b>	<b>Labor</b>
<b><i>Irrigation</i></b>	0.1896*** (0.0346)	0.4349** (0.1781)	0.0062* (0.0032)	0.3941 <sup>NS</sup> (0.5480)	0.9144*** (0.2261)	0.0287*** (0.0053)
<b><i>Rain-Fed</i></b>	0.0552*** (0.0046)	0.0243 <sup>NS</sup> (0.0617)	0.0054 <sup>NS</sup> (0.0013)	0.4737* (0.2625)	0.0295 <sup>NS</sup> (0.0251)	0.0059** (0.0009)
<b><i>Temperature</i></b>	-0.1076* (0.0418)	0.3716 <sup>NS</sup> (0.5368)	0.2062 <sup>NS</sup> (0.0222)	-1.044 <sup>NS</sup> (1.8622)	-0.5859 <sup>NS</sup> (0.2119)	-0.0293 <sup>NS</sup> (0.0081)
<b><i>Precipitation</i></b>	0.0577*** (0.0033)	0.0547 <sup>NS</sup> (0.0426)	0.0094 <sup>NS</sup> (0.0019)	0.1136 <sup>NS</sup> (0.1399)	-0.0416 <sup>NS</sup> (0.0166)	-0.001*** (0.0006)

**Note:** Parameters are significant at \*\*\*: 1%; \*\*: 5%; and \*:10%; NS: Non-Significant; Standard errors in ( ). **Source:** Research results.

Pereda (2012) argues that climate may affect agricultural production in two ways: in the long-run, where is evaluated by the historical observed climate, which might impact land use configuration; and in the short-run, where the weather conditions play an important role of determining crops, livestock failures and productivity losses once the farmers had decided what and how much to produce, which would imply that their production could deviate from an optimal production.

We assume in this research that weather effects on output supplies and input demand represents a short-run effect since our climatic variables are average temperature and cumulative precipitation of 2006, i.e., weather events during growing and harvesting seasons, which are not observed by farmers when they choose the output-input mix that optimizes their outcomes (Pereda, 2012). As shown in Table 2.3, a negative effect on coffee supply was found due to increases in temperature; and a positive effect due to increases in precipitation.

We did not find statistically significant weather effects on the remaining grains, which may be correlated with Vanderlugt's (2011) argument that farm heterogeneity could respond differently to climate variations. Thus, to test the argument that farm heterogeneity might affect different responses on irrigation expansion (Vanschoenwinkel; Van Passel, 2018) and weather effects (Vanderlugt, 2011) we have estimated the semi-elasticity for output supply and input demand in respect to irrigated land by farm size. The results are shown in Table 2.4.

As expected, we found a positive effect of irrigation on the supply for all selected grains; similar findings were found by Binswanger *et al.* (1987). It is important to highlight that up to a certain point, more irrigation implies more yield, but the increase in yield resulting from a

marginal increase in irrigation decreases as more water applied in the crops increases (Frija *et al.*, 2014).

**Table 2.4 – Average irrigation effect (semi-elasticities) on output supply and input demand, Brazilian Southeast Region, 2006.**

	Coffee	Rice	Soybean	Corn	Bean	Labor
<i>Very Small</i>	0.259*** (0.0542)	0.5107** (0.2305)	0.0054 <sup>NS</sup> (0.0402)	0.4949 <sup>NS</sup> (0.7910)	1.100*** (0.3083)	0.0376*** (0.0073)
<i>Small</i>	0.0949*** (0.0042)	0.2942*** (0.0542)	0.0078 <sup>NS</sup> (0.0055)	0.2949* (0.1620)	0.4958*** (0.0260)	0.0129*** (0.0019)
<i>Medium</i>	0.0382*** (0.0009)	0.0717*** (0.0155)	0.0102*** (0.0003)	0.0502*** (0.0047)	0.4387*** (0.0090)	0.0068*** (0.0004)
<i>Large</i>	0.0005*** (0.00006)	0.1279*** (0.0006)	0.0006*** (0.00005)	0.0024*** (0.0002)	0.0252*** (0.0003)	0.0009*** (0.00006)

**Note:** Parameters are significant at \*\*\*: 1%; \*\*: 5%; and \*:10%; NS: Non-Significant; Standard errors in parentheses. **Source:** Research results.

In general, we found a negative and linear relationship between the response of supplies due to irrigation and farm size, which implies that the very small and small groups present the highest average response when compared to the others sizes. This result may be in part explained taking into account the results found in Chapter 1, where the *very small* and *small* farms in Brazilian agriculture are, in general, more capable to transform inputs in outputs more efficient than *medium* and *large* farms; they usually are facing scarce resources, which reinforce the role of farm heterogeneity on technology adoption.

The findings in Table 2.4 also allow us to make some inferences: as predicted by Vanschoenwinkel and Van Passel (2018), different farm sizes present different responses in respect to irrigation: the very small and small groups seem to be more capable to achieve yields in terms of produced quantities due to irrigation. Although we are not controlling the scale of production, credit market access, rural extension services adoption, among other factors related to farmers' personal characteristics, like schooling, experience, management skills, and technical efficiency, it might be correlated to those aspects.

The semi-elasticities of grains supplies with respect to short-run weather effects by farm size are displayed in Table 2.5. In general, we found a negative effect of temperature increases on supplies, except for soybeans production. Pereda (2012) found that an increase in 1° Celsius would increase soybeans supply by 0.44%, on average. Our result shows an

increase in soybeans supply of 0.43% for medium and 0.33% for large farmers due to an increase in 1° Celsius, on average, which is consistent with Pereda's findings. It is important to highlight that the most suitable temperature to growing soybeans would be around 30° Celsius (EMBRAPA, 2013), while temperatures above this threshold are very harmful (Schlenker and Roberts, 2009). Similar findings in Pereda (2012) were found in coffee production, where increases in temperature would decrease its supply.

**Table 2.5 – Semi-elasticities, average weather effects in grain supply and input demand by farm size, Southeast, 2006.**

	Coffee	Rice	Soybeans	Corn	Beans	Labor
<b>Temperature</b>						
<i>Very Small</i>	0.0606* (0.0379)	0.5019 <sup>NS</sup> (0.4919)	-0.0163 <sup>NS</sup> (0.0294)	-1.609 <sup>NS</sup> (2.4911)	-0.2672 <sup>NS</sup> (0.2012)	-0.0047 <sup>NS</sup> (0.0076)
<i>Small</i>	-0.6003*** (0.0629)	-0.1183 <sup>NS</sup> (0.7628)	0.0666** (0.0287)	0.6696** (0.2857)	-1.4973*** (0.2503)	-0.0687*** (0.0093)
<i>Medium</i>	-0.5208*** (0.0191)	-0.0264 <sup>NS</sup> (0.3675)	0.4381*** (0.0198)	-0.3258** (0.1574)	-2.7286*** (0.2774)	-0.1502*** (0.0097)
<i>Large</i>	-0.4382*** (0.0080)	3.555*** (0.3195)	0.3329*** (0.0053)	-0.0319 <sup>NS</sup> (0.0358)	-3.4315*** (0.1506)	-0.2641*** (0.0105)
<b>Precipitation</b>						
<i>Very Small</i>	0.0456*** (0.0028)	0.0588* (0.0367)	-0.0019 <sup>NS</sup> (0.0021)	0.1201 <sup>NS</sup> (0.1857)	-0.0183 <sup>NS</sup> (0.015)	-0.0019*** (0.0005)
<i>Small</i>	0.0948*** (0.0056)	0.0387 <sup>NS</sup> (0.0686)	-0.0005 <sup>NS</sup> (0.0025)	0.1245*** (0.0257)	-0.0833*** (0.0225)	-0.002** (0.0008)
<i>Medium</i>	0.0865*** (0.0017)	0.0506 <sup>NS</sup> (0.0336)	0.0225*** (0.0018)	0.0272* (0.0144)	-0.2707*** (0.0253)	0.0094*** (0.0008)
<i>Large</i>	0.0494*** (0.0007)	0.0933*** (0.0300)	0.0196*** (0.0005)	0.0192*** (0.0033)	-0.4282*** (0.0141)	0.0175*** (0.0009)

**Note:** Parameters are significant at \*\*\*: 1%; \*\*: 5%; and \*:10%; NS: Non-Significant; Standard errors in ( ). **Source:** Research results.

Furthermore, interesting results are found for beans production, in which both precipitation and temperature increase would have a negative effect on its supply. We found that grains supplies and input demand, in general, would be most affected due to changes in temperature rather than changes in precipitation for all farm sizes analyzed. Moreover, the production of the beans would be most affected by temperature compared to other grains.

Finally, the size that would be most affected by weather effects would depend on the crops growing type.

We also estimated the effect of the rain-fed land on output supplies and input demand in terms of semi-elasticity. Our results suggest that rice supply would be affected negatively by rain-fed land expansion. As rice is mainly produced under the flooding irrigation method (Wijetunga, 2016), decreases in rice supply in response to increases in non-irrigated land were expected. All the other grains supplies were positively affected by an increase in non-irrigated land; however, the effect of irrigation expansion is greater than non-irrigated land expansion, which corroborates that irrigation technology is capable to increase and ensure the yields. The results are displayed in Table A4 in the Appendix.

### *5.1. Effects of irrigation on revenue and policy implication*

To evaluate the irrigation effect on the grain market we used the parameters estimated in the system of equations, the average output price, the total output produced, and the total irrigated land to estimate the market revenue change per output and for the entire sector as well. Results are displayed in Table 2.6 and show the observed total revenue, the total added revenue, the change in revenue due to irrigation, and the participation of each grain analyzed in the total revenue due to irrigation in the southeastern region.

We can observe that beans and rice revenue would have an increase of 6.81% and 5.31% due to irrigation. Corn's revenue also presents a great response due to irrigation, around 4.45%. This result implies that these commodities generate more added values due to irrigation adoption. Pereda (2012) found that irrigation in Brazil could increase corn profit share by 3.94% and 4% for coffee. The smallest revenue effect due to irrigation is for soybeans, around 0.17%. Soybeans' growing presents some advantages in non-irrigated land due to improvements in seed technology driven by the Empresa Brasileira de Pesquisa Agropecuária – Embrapa (Brazilian Agricultural Research Corporation, in English) among the last four decades. Thus, this crop drought resistant (EMBRAPA, 2013), implying that soybeans production is less efficient in generate revenue relative to irrigation use.

Our findings suggest an increase of 2.1% (US\$ 83.45 million) on outputs revenue due to irrigation in the Brazilian Southeast region, in which coffee's revenue represents 43.65% of this value, followed by corn (43.57%) and beans (9.77%).

**Table 2.6 – Average effect of irrigation on the change in the revenue in Southeast region and selected grains, Brazil, 2006.**

	<b>Southeast</b>	<b>Coffee</b>	<b>Rice</b>	<b>Soybean</b>	<b>Corn</b>	<b>Bean</b>
<i>Total Revenue (US\$)<sup>1</sup></i>	3,965.25	2,553.24	33.03	442.35	816.90	119.70
<i>Added Revenue (US\$)<sup>1</sup></i>	83.45	36.43	1.75	0.75	36.36	8.15
<i>Irrigation Effect on Revenue (%)</i>	<b>2.1</b>	<b>1.42</b>	<b>5.31</b>	<b>0.17</b>	<b>4.45</b>	<b>6.81</b>
<i>Participation on Added Revenue (%)</i>	-	<b>43.65</b>	<b>2.10</b>	<b>0.90</b>	<b>43.57</b>	<b>9.77</b>

**Note:** 1 = Values in US\$ millions. Exchange Rate: 2.15 (dec, 2006). **Source:** Research Results

It is important to highlight that those changes in revenue due to irrigation is based on irrigated land, average output price, total output supplied and parameters estimated rather than quantities and price of water used in irrigation. Dinh *et al.* (2018) showed using similar methodology that an arbitrary increase by 30% in the irrigation water price would lead a decrease in the water demand, implying a decrease in the output supply and then in the revenue of dairy (-0.9%), rice (-5.9%), and grains (-0.5%), while horticulture was the least responsive to changes in water prices. However, in the case of water dataset availability, we must make the assumption that each farmer pays for the irrigation water, which may be not appropriate for Southeast region agriculture. Despite the lack of information related to water use, our results showed that irrigation plays an important role in the grain supply stability and in the revenue increases.

Although revenue effects due to irrigation are stronger to beans and rice production, our results suggest that policies could be driven to expand irrigated production of coffee and corn since these crops represent 87.2% of the total added revenue due to irrigation, being these outputs more valuable compared to the others.

As we found a positive effect of irrigation on grain supply and also on the revenue of the grain sector in the Southeast region, it is important that government policies target the expansion of irrigation focusing on those products most valued. Moreover, those policies should also focus on farmers grouped as very small and small size, since they represent more than 92% of the total farmers in the Southeast region.

The policies at the micro-level could be designed in order to provide rural credit and technical assistance for those farmers producing coffee and soybeans in order to improve the capacity of the irrigation in their revenue' increase; and at the macro-level by reducing the taxation of coffee, corn and beans in the customs in order to increase exports, since those

grains represent more the 95% of added value in terms of revenue in grain production in the Southeast region.

Finally, as irrigation seems to be able to increase labor demand in the short-run, we can conclude that irrigation is an efficient tool in the employment generation and income in rural areas, which implicitly might alleviate poverty and achieve rural development. Policies toward workforce training to operate irrigation systems and the development of irrigation projects in order to absorber unemployed workers are welcome in rural areas, mainly in areas with socioeconomic vulnerability. Another target in the irrigation expansion is the understanding that irrigation technology is a mechanism of mitigation and adaptation to climate anomalies.

## 6. Conclusions

We aimed to evaluate in this chapter the role of irrigation on the Brazilian Southeast grain sector. We estimated a system of output supplies and input demands using the 2006 Agricultural and Livestock Census at the farm level. Output supplies refer to the main grain crops grown in the region: coffee, rice, soybeans, corn and beans; and input demands were estimated for labor and fuel. We used the derivative properties of a normalized restricted profit function to estimate own and cross-price effects on output supplies, short-run weather effects and changes in revenue due to irrigation. Our findings suggest a positive effect of irrigation on output supplies and labor demand in the short-run, and also capable to change revenue positively for each output and for the entire sector.

We also have tested the argument that farm heterogeneity might affect how farmers respond to irrigation expansion and weather. In general, we found a positive elasticity of supply for all outputs and input demand due to irrigation and a negative effect of temperature increases on output supplies, except for soybeans. The very small and small farms seem to be more capable to achieve yields in terms of produced quantities due to irrigation. Furthermore, we found that output supplies and input demands, in general, would be most affected due to changes in temperature rather than changes in precipitation for all farm sizes analyzed.

Our findings also suggest an increase of 2.1% on output revenue due to irrigation in the Brazilian Southeast region, in which coffee revenue represents 43.65% of this value; corn represents 43.57% and beans 9.8%. Beans and rice also faced increases in their revenue due to irrigation, by 6.81% and 5.31%, respectively. The well adapted to rain-fed agriculture, soybeans presented a change in revenue of 0.17%.

Although irrigation present great results when evaluated in an isolated way, this practice is generally implemented in the midst of other improvements in the "technological package" of the rural producer, that is, tends to be accompanied or preceded by improvements in other inputs, services, machinery, implements, climate knowledge and other facilities which together result in a number of benefits.

## CHAPTER 3

### THE VALUE OF IRRIGATION ADOPTION IN THE BRAZILIAN AGRICULTURE

#### 1. Introduction

Brazil is a major worldwide player in agriculture production. The country produced 6% of the world's agricultural in 2014 and it is among the ten countries with the largest irrigated area in the world; the leaders are China and India, followed by the United States, Pakistan, and Iran (Food and Agriculture Organization – FAO, 2017). Brazil appears in a group of countries with irrigated areas between 4 and 7 million hectares, which is closest to Thailand, Mexico, Indonesia, Turkey, Bangladesh, Vietnam, Uzbekistan, Italy and Spain (FAO, 2017).

Despite the leadership in irrigated areas, only a small share of the land used in agriculture in Brazil is irrigated, around 3%, while only 6.3% of the farmers adopt irrigation technology in the country, which is mainly farms with more than 500 hectares (Brazilian Institute of Geography and Statistics – IBGE, 2006). Brazil, whose irrigated land adds up to only 1% of the irrigated area in the world (Ministry of Environment – MDA, 2006), still has a lot of room to increase its use of irrigation which can largely improve the country's agricultural production.

Several regions in Brazil have observed an increase in droughts and water shortages in the past few years which affect agricultural production and rural income (Cunha *et al.*, 2015). The adoption of irrigation can help counter these negative factors by leading to higher crop yields by sustaining adequate soil moisture in the growing period (Lobell *et al.*, 2009); achieving higher rates of agricultural productivity (Mkanthama *et al.*, 2018); and allowing the impacts of seasonal and inter-annual hydrological variability on agriculture to be smoothed out (Turrall *et al.*, 2010).

The use of irrigation might also allow farmers to access domestic and international markets (Schaible; Aillery, 2012); increase farm income and rural employment (Marra *et al.*, 2003); enhance food security (Droogers, 2004); alleviate poverty (Lipton *et al.*, 2003; Hussain; Hanjra, 2004); and help mitigate the effects of climate change by maintaining agricultural productivity in scenarios with lower rainfall rates (Vanschoenwinkel; Van Passel, 2018),

mainly in regions with semi-arid climate and socio-economic vulnerability (Zougmore *et al.*, 2010; Njuki; Bravo-Ureta, 2016).

Agência Nacional de Águas (Brazilian Water Agency, in English) points out that around 70% of freshwater in the country is used in irrigated agriculture, while water is an increasingly scarce resource. Despite its scarcity, the demand for irrigation is expected to increase in all regions (Cunha *et al.*, 2015). However, the irrigation of agricultural crops affects the dynamics of water and soil properties such as salinity, being these effects slow to revert in the short-term (Suárez, 2013).

Water management for agriculture is becoming increasingly complex since its management requires several factors as technical knowledge, infrastructure, and factors related to social and economic issues (Rosenzweig *et al.*, 2004). Thus, irrigation water use must be supplied facing a context of diminishing availability, due environmental awareness, population growth, economic development and others factors (Iglesias; Garrote, 2015), which lead the adoption of more technically efficient irrigation systems to maintain water consumption with reduced applications as a drought response (Schuck *et al.*, 2005). The knowledge needed mostly has been provided by extension services, which help farmers to adapt and implement viable solutions, thus gaining more benefits from irrigation technology (Levidow *et al.*, 2014).

What are less clear in the role of irrigated agriculture is the contribution of the yield increase due to irrigation adoption (Ozdogan, 2011) as well as yield response to different water management practices, and thus current on-farm water-efficiency levels (Levidow *et al.*, 2014). The value of water used in production is another complex task due the difficulty to quantify its value because different agents conceptualize and describe their values differently, i.e., the private sector tends to use finance concepts, while governmental sector often employ economics and civil society concepts (e.g. environmental issues; property rights-based or social-goods concepts) for valuing this water (Morgan; Orr, 2015). It is also important to highlight that different approaches tend to find different water values (Young, 2005).

Only a small fraction of farmers that access water coming from resources under government control are charged for both surface and groundwater pumped for irrigation in Brazilian agriculture (ANA, 2018). The remaining farmers pay capital, maintenance, and operation costs of water withdrawal. Under this arrangement, water resources face overexploitation (Nikouei *et al.*, 2013), while rational management of water requires the knowledge of the value of the resource (Mesa-Jurado *et al.*, 2010; 2012). Without regulations of water use, the farmer could implement irrigation and so the potential value of irrigation

may be capitalized into the price of both currently irrigated land and dryland (Brozovic; Islam, 2010).

The main source of irrigation water in Brazil comes from the surface rather than groundwater (ANA, 2017; 2018) while much of the water used in irrigation comes from private sources and are not traded among economic agents (Ferrarini *et al.*, 2016). Because of the well-known common property problems of shared surface and groundwater sources, the Brazilian Water Agency is responsible for granting the water use to the farms across the twelve hydrologic basins spread among the country when this resource belongs to the government<sup>17</sup>. However, only six Federative Units charge the water used in irrigation: São Paulo, Minas Gerais, Rio de Janeiro, Paraná, Ceará and Paraíba. The total amount collected was approximately US\$ 171 million<sup>18</sup> in 2017 (ANA, 2018).

Given that irrigation has resulted in varying levels of depletion of water sources and also the lack of studies on irrigation value in Brazil, it is important for policy purposes and economic assessment tools to identify the overall value of this resource in the Brazilian agricultural production and understand how irrigation affects farmer's yields. Thus, the objective of this research is to fill in this gap in the literature seeking to answer the following questions: *What is the elasticity of yield when a hectare is converted into irrigation? How much of total gross yield per hectare could be achieved through irrigation? What is the value of irrigation adoption for Brazilian agricultural producers?*

We estimate the total gross value added by irrigation to agricultural production value using a rich dataset containing more than 4 million farm observations in Brazil, based on production value and irrigated hectares through production function approach. The extra production value attributable to irrigation at the farm level allows us to evaluate and obtain estimates of the additional revenue flow attributable to irrigation, giving a sense of how much is the value of irrigation adoption in the agriculture.

Our results show that the production value would increase by 64.8% due to irrigation adoption, with an incremental gross revenue due to irrigation averaged US\$1,492.15/ha. The value of irrigation adoption was estimated in US\$ 2.96 billion, which is based on total additional gross revenue when land is irrigated relative to non-irrigated land.

In the following section, we highlight different approaches to access the value of irrigation water. Section 3 and 4 we describe the theoretical framework and the empirical model, respectively. Results are shown in Section 5 and our final conclusions in Section 6.

---

<sup>17</sup> Figure A3 in the Appendix shows the Hydrologic Basins in Brazil.

<sup>18</sup> Value of 2006. Exchange Rate: 2.15 (dec, 2006)

## 2. Accessing the value of irrigation water

There are several ways to measure agriculture water value. In the case where water markets exist, the researcher is able to use approaches that will derive the water demand and supplying curves and thereby determining the optimal allocation and its price, which allow optimize the amount of water applied to crops based on the marginal productivity of that water (Johansson, 2005), where up to a certain point, more water implies more yield, but the increase in yield resulting from a marginal increase in water decreases as the total water input increases; this is known as a positive and diminishing marginal productivity of water (Frija *et al.*, 2014).

A review of the approaches to estimate the economic value of water can be found in Gibbons (1986), Johansson *et al.* (2002; 2005), Tsur *et al.* (2004) and Young (2005). A simple approach to measuring the value of irrigation is to compare sales values of irrigated land versus non-irrigated land, or to compare sales values of land over an aquifer versus land not over an aquifer (Brozovic; Islam, 2010; Hornbeck; Keskin, 2014). Relevant to our analysis are those approaches based on production function, which are a deductive method that involves the derivation of shadow prices where water or irrigated land is an input into production systems (Suárez *et al.*, 2018).

Alternative approaches are the Contingent Valuation (Adamowicz *et al.*, 1999; Carson *et al.*, 2001), Residual Method (Mesa-Jurado *et al.*, 2008; Ziolkowska, 2015), Hedonic Water Pricing (Faux and Perry, 1999; Latinopoulos *et al.*, 2004; Berbel and Mesa, 2007), or Choice Experiments (Gómez-Limón *et al.*, 2002; Rigby *et al.*, 2010). Recently the policymakers are interested in the implicit impacts of macroeconomic policies on the irrigated agricultural sector, especially those related to agricultural trade reform (Johansson, 2005). General Equilibrium Models (CGE) have been applied as an alternative model to access water demand in an inter-regional perspective (Ferrarini *et al.*, 2016); and also a combination of approaches implementing a multi-sector growth model through CGE and Residual Methods to estimate the stock value of irrigation water has been utilized (Santos; Spolador, 2018).

Crop-Water Functions can be used when the farmer is producing a single crop; and Profit Maximization when farmers seek to maximize profits, given market prices of water and output, allowing those farmers to choose water inputs optimally (Mesa-Jurado *et al.*, 2012). The Generalized Solutions can be used when the primal approach is generalized to multiple producers and multiple crops; and Constrained Profit Maximization when the provided water

is free of charge, but constrained to some volume, which allows identifying the willingness to pay (WTP) to relax the water constraints per unit of water (Johansson, 2005). Supply curves of water also can be estimated, which reflects the increasing available supply with increasing costs (Hussain *et al.*, 2007). When water supply is constrained and the producer is unable to acquire sufficient water to exhaust its marginal returns to production, the derived demand can be determined in terms of the shadow value for water (Tsur *et al.*, 2004).

### 3. Theoretical Framework

The approach to evaluating the value of irrigation in Brazilian agriculture is to estimate increased production value due to irrigation by farm-level yield function, which has as one of its arguments the fraction of irrigated land with crop and pastures (aggregated). The increased production value is obtained by differentiation of this function with respect to fraction irrigated.

Estimation of production functions can be improved by simultaneously estimating share equations that reflect producers' evaluation of the marginal product of inputs. In this case, we are assuming profit maximization and first order conditions allow estimation of a system of equations that includes production function and derived demand for inputs (or factor shares) allowing a more robust estimation (Mundlak, 2001). The profit maximizing decisions of price-taking producers can be represented as:

$$\max_{\mathbf{x}} \pi = p y - \mathbf{w}' \mathbf{x}; \quad y = f(\mathbf{x}, z); \quad p > 0, \mathbf{w} \gg 0 \quad (1)$$

where  $p y$  is the production value (revenue);  $\mathbf{x}$  is a vector of variables inputs,  $\mathbf{w}$  is a vector of input price, and  $z$  is a vector of environmental characteristics (e.g. weather). The input requirement set of the production function  $y = f(\mathbf{x}, z)$  must be closed and bounded, and this function is assumed to be monotone and quasi-concave (Varian, 1992). Under rational economic behavior, the first order conditions are given by differentiation of the profit by each of the inputs:

$$\frac{\partial \pi}{\partial x_k} = p \cdot \frac{\partial f(\mathbf{x}, z)}{\partial x_k} - w_k = 0 \quad k = 1, \dots, K \quad (2)$$

Given profit maximization and perfect competition, expressing equations (1) and (2) in logarithms we obtain production elasticities  $\varepsilon_k$  that also reflect the share of factor payments in output value,  $s_k$ :

$$\varepsilon_k(\mathbf{x}, z) \equiv \frac{\partial \ln f(\mathbf{x}, z)}{\partial \ln x_k} = \frac{\partial f(\mathbf{x}, z)}{\partial x_k} \cdot \frac{x_k}{f(\mathbf{x}, z)} = \frac{w_k}{p} \cdot \frac{x_k}{y} = s_k \quad k = 1, \dots, K \quad (3)$$

where  $s_k$  is the share of the input  $k$  in the total cost of production. The derivative of the log of the production function with respect to the log of the input  $k$  (i.e. the production elasticity of  $k$ ,  $\varepsilon_k$ ) is equal to the cost share of that input in the total cost, and  $\partial y / \partial x_i > 0$  due to monotonicity. These elasticities indicate the percentage change in production value per one percent change in each of the inputs.

As the irrigated land is measured in level, rather than logarithms of levels, the derivative of  $y$  with respect to  $x$  represents the semi-elasticity of response, which is interpreted as the percentage change in the production value per unit change in  $x$ . Multiplying the semi-elasticity of response by the output value we obtain the incremental gross value of production due to irrigation, and multiplying the incremental gross value by the irrigated land we obtain the average total gross value of irrigation adoption.

#### 4. Empirical Model

For the empirical application, the production function is assumed to follow a transcendental logarithmic functional form (Christensen et al., 1973). Assuming a Translog specification allows for more flexibility since it does not impose a priori restrictions on the structure of the technology (it allows for a non-linear relationship between the dependent variable and the factors of production) and provides a local second order approximation to any production frontier. The following Translog production function is estimated:

$$y_h = \alpha_0 + \sum_{i=1}^K \beta_i x_{ih} + \frac{1}{2} \sum_{i=1}^K \sum_{j=1}^K \beta_{ij} x_{ih} x_{jh} + \sum_{t=1}^T \gamma_t z_{th} + \frac{1}{2} \sum_{t=1}^T \sum_{t=1}^T \gamma_{tt} z_{th} z_{th} + \frac{1}{2} \sum_{i=1}^K \sum_{t=1}^T \phi_{it} x_{ih} z_{th} + \varepsilon_i \quad (4)$$

where  $y_h$  represents the logarithm of the output for  $h=1, \dots, H$  farmers;  $x$  is the logarithm of the input  $i, j=1, \dots, K$ ;  $z$  is the logarithm of climatic variables  $t=1, \dots, T$ , and  $\alpha_0, \beta_i, \beta_{ij}, \gamma_i, \gamma_{ij}, \phi_{ij}$  are parameters to be estimated. Our measure for output is the value of agricultural production. For inputs, we consider land, labor, expenses (purchased inputs), capital and the fraction of irrigated land. Under constant returns to scale, the output and all the

inputs have been scaled down by the land factor. Climatic variables are precipitation and temperature for different seasons. We also include dummies of Federative Units (States) and interactions of climatic variables with dummies representative of five Brazilian macro-regions to capture heterogeneity across the country.

We have included labor, expenses, and irrigated land share equations since they have observable prices and are part of the variable cost of the farmer. Given the Translog specification defined in equation (4) and the assumptions of profit maximization and perfect competition, the factor shares equations are:

$$S_i = \beta_i + \sum_{j=1}^k \beta_{ij}x_j + \sum_{t=1}^T \phi_{it}z_{th} + \varepsilon_i \quad (5)$$

$S_i$ :  $i$ th input cost divided by total revenue (production value) –  $p_i x_i / pq$

The labor cost is measured as total expenses in wages with the workforce in agriculture, and purchased inputs are measured as the total expenses related to several inputs. We do not have information about irrigated land sales/rent. Thus, to measure the price of irrigated land, first we evaluate the average land value by municipality for those farmers that use irrigation and we impute this average land value for those farmers that do not use irrigation (irrigators receive their own land value), then we multiply by 0.05 to obtain the irrigated land service price, which expresses the opportunity cost for owned land or approximate cash rental rate for leased land, which is normally around 2–6% of the land value (Ziolkowska, 2015).

To estimate the increase in the gross value of production per hectare,  $V$ , due to irrigation, we use the semi-elasticity with respect to irrigation,  $\varepsilon_h$ , and multiply by the yield,  $y_h$ , as described below:

$$V_h = \varepsilon_h y_h \quad (6)$$

where  $V_h$  is interpreted as the gross value of irrigation per hectare in the farm  $h$ . Suárez, Fulginiti and Perrin (2018) argue that the value of irrigation is thus reflected in the higher production if the producers are producing more valuable crops on the irrigated hectare. Multiplying the incremental gross values by the number of irrigated hectares in the farm provides an estimate of the average total gross value of irrigation adoption for all Brazilian farmers in 2006, i.e., the irrigation value.

The procedure to estimate our model fits a system of nonlinear equations by IFGNLS (Iterative Feasible Generalized Non-Linear Last Squares). It can be viewed as a nonlinear variant of Zellner's seemingly unrelated regression model (Zellner 1962; Zellner and Huang 1962; Zellner 1963) and is therefore commonly called nonlinear SUR or nonlinear SURE. Moreover, fitting the equations jointly allows us to impose cross-equation restrictions on the parameters and obtain more efficient estimates as well. Iterative FG-NLS estimation is equivalent to maximum likelihood estimation with multivariate normal disturbances.

Production elasticities are calculated at each data point (one for each farm) since we are using a Translog specification. Then we take the mean to evaluate the overall elasticity, and the Delta method is used to calculate standard errors.

#### 4.1. Data Source

The cross-sectional dataset used comes from the 2006 Agricultural and Livestock Census at farm level, which only can be accessed in the Brazilian Institute of Geography and Statistics (IBGE) headquarter in Rio de Janeiro, Brazil. The dataset contains information for more than 5 million farm observations.

To prepare the data for this research, we have excluded farmers that did not report area; farms settled in the urban areas; farms classified as special sectors - favelas, barracks, lodgings, boats, indigenous villages, nursing homes, etc.; farms belonging to rural settlements; farms which were considered as condominium, consortium or partnership, cooperative, public limited company or by quotas of limited liability, public utility institutions, government (Federal, state or municipal) or other condition; and farms which producer type is "not identified". We only have included those farms owned by an individual producer with maximizing behavior. Thus, 915,770 observations have been deleted (17.7% of the original sample), and the final sample is composed by 4,259,866 farm observations.

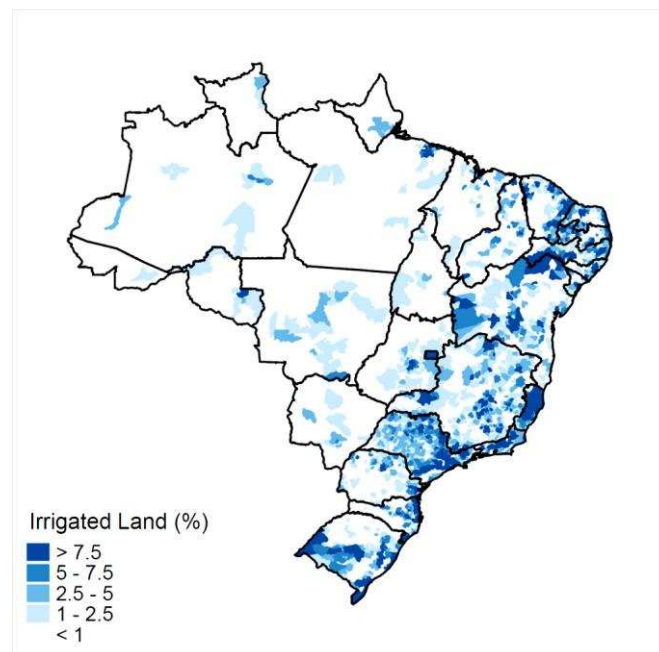
*The Output* represents the total value of production. *Land* is the sum of land used in crops and pastures (hectares); *Labor* is the sum of familiar and hired workers in agriculture; *Purchased Inputs* is the sum of expenses on fertilizers, correctives, agrochemicals, energy, animal medicines, transports, packages, seeds and animal feeds; and *Capital* is the asset value (buildings, land, vehicles, and others). *Irrigation* represents the fraction of irrigated land. The aggregation of the production value across crops is driven mainly by the fact that we do not have farm-level data on the hectares irrigated by crops, while we do have data on total hectares irrigated for all crops. Climatic variables are cumulative precipitation (millimeters)

and temperature (Celsius degree) averaged by municipality for the period of 2003-2006<sup>19</sup>, segregated by season – summer (December to January) and winter (June to August). Climatic Dataset was obtained from the Climate Research Unit – CRU/University of East Anglia<sup>20</sup>.

## 5. Results

Before presenting our estimates, it is worth to observe some characteristics of the variables used in our analysis and also interesting aspects of the irrigated agriculture and climate conditions in the heterogeneous Brazilian regions. Figure 3.1 illustrates the irrigated land as a fraction of planted land in crops and pastures in Brazilian municipalities.

**Figure 3.1 – Fraction of irrigated land, Brazil, 2006.**



**Source:** Author's elaboration based on 2006 Agricultural and Livestock Census

<sup>19</sup> To use climatic variables at the farm level, it would be necessary to obtain the longitude and latitude of the farm, which violates the confidentiality of the dataset provided by IBGE. In this sense, the assumption adopted in this research is that the climatic variables at the municipal level fit a good approximation for those that would be observed within the farm.

<sup>20</sup> We are grateful to Laís Rosa de Oliveira from "Natural and Environmental Resource Economics Research Group – PPGEA/UFV/Brazil" for work on the dataset.

There is great variability of irrigated land across the Federative Units: high values in the Southeast and Southern region; isolated irrigated spaces in the Northeast region and low values in the Midwest and North region. Table 3.1 shows the descriptive statistics of the variables averaged by region and for Brazil (after data exclusions)<sup>21</sup>.

The Midwest Region presents the highest average agricultural production value. Agriculture in this region has an advanced stage of mechanization, it is known as the agricultural frontier in the production of grains in Brazil. In addition, this region is more intensive in land, expenses, and capital when compared to the other Brazilian regions (Table 3.1). In the east, irrigation is required during a six-month dry season while it is free of winter temperature constraints. Most of the Midwest Region is *cerrado*, which is potentially productive after additives to the soil. Farmers are able to take advantage of rivers to complement their rain-fed cereal, soybeans, beans and cotton production with dry-season irrigated cropping (FAO, 2015).

The Southeast Region has the largest fraction of irrigated land, where 4.08% of land used in crops and pastures are irrigated (Table 3.1). The region is dominated by technically advanced commercial farmers, mainly in the extreme south. Winter irrigation allows the farmers to crop twice instead of once a year, rotating winter plantings of wheat, peas or beans with rain-fed summer crops, which include corn, cotton and sugarcane (FAO, 2015). Most of the perennial crops are coffee and orange production.

The South Region is specialized in irrigated rice production with flooding technique in the summer, where supplementary irrigation in this season can help farmers of crop failures in a dry year; on average it gives only a small increase over the rain-fed yields of the typical summer crops of the South: maize, beans, and soybean. There is a highly developed, commercially-oriented agriculture (FAO, 2015).

The North Region (where Amazon Forest is located) presented the highest average levels of precipitation in the summer season, while irrigation is needed in the winter season and it is limited to a small area of lowland rice. In the past few years, this region has presenting increases in land used in pastures as a result of the extensive livestock production observed in the region, mainly in Pará and Tocantins States. We can observe that North Region is more intensive in labor when compared to the others (Table 3.1).

The Northeast Region is known for the low quality of soils and several periods of drought with the lowest average rainfall value and the highest average temperature in the summer

---

<sup>21</sup> Because of data confidentiality, maximum and minimum values cannot be displayed.

season (Table 3.1); the region is highly dependent on irrigation. Water resources in most of the Northeast are a severe constraint to agriculture. One major river, Rio São Francisco (San Francisco River, in English), requires that its water be extracted by pumping, due to its topography. Although most of the semi-arid region in Brazil is in the Northeast Region (covering 1,133 municipalities in 2006), there are a great number of irrigated projects being developed to ensure production levels, mainly in fruit growing, horticulture and seed production (Moraes *et al.*, 2018). Some lowland areas are suitable for flooded rice, mainly in the humid coastal strip. Where water constraints can be overcome, the warm climate favors maize, beans, cotton, and sugarcane (FAO, 2015).

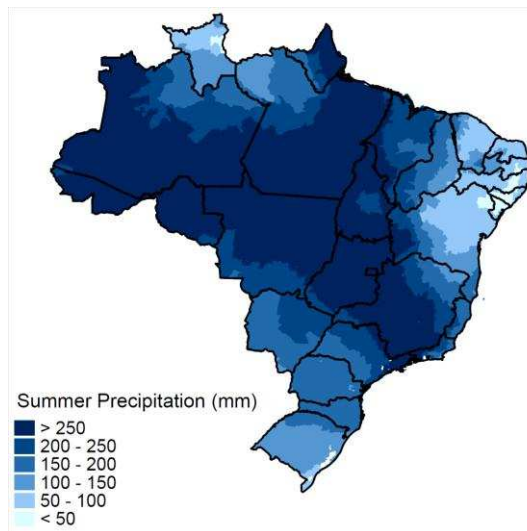
**Table 3.1 – Summary Statistics of the variables used in the production function, Brazil and Regions, 2006\***

Variable	Brazilian Regions					Brazil
	North	Northeast	Southeast	South	Mid-west	
<i>Value of Production (US\$)*</i>	9,012.32 (245,509)	4,663.00 (231,552)	18,426.44 (1,112,172)	18,131.10 (462,834)	39,628.46 (695,760)	12,166.33 (571,351)
<i>Land (ha)</i>	71.26 (416.83)	19.54 (134.92)	39.93 (168.10)	29.50 (125.86)	250.17 (1,008.89)	42.24 (299.40)
<i>Irrigation (fraction)</i>	0.0073 (7.0971)	0.0238 (13.3796)	0.0408 (16.1658)	0.0158 (10.1447)	0.0103 (7.7700)	0.0231 (12.7226)
<i>Labor (workers)</i>	3.13 (2.87)	2.67 (2.99)	2.75 (7.81)	2.59 (11.33)	2.75 (6.66)	2.71 (6.67)
<i>Purchases Inputs (US\$)*</i>	1,346.20 (101,031)	895.64 (313,912.9)	5,861.91 (1,387,667)	5,470.85 (342,745.5)	22,840.39 (3,190,093)	3,946.35 (984,351.4)
<i>Capital (US\$)*</i>	93,725.02 (2,385,148)	25,150.33 (717,422)	154,015.30 (1,953,673)	141,043.86 (1,689,948)	485,995.81 (5,001,374)	102,964.74 (1,848,856)
<i>Summer Precipitation (mm)</i>	275.36 (41.21)	105.69 (57.55)	229.74 (44.49)	150.29 (20.51)	267.34 (50.03)	161.12 (79.97)
<i>Winter Precipitation (mm)</i>	68.25 (60.24)	47.77 (48.56)	21.78 (12.19)	94.29 (21.00)	14.00 (13.52)	52.45 (46.91)
<i>Summer Temperature (°C)</i>	26.90 (0.55)	26.65 (0.94)	24.40 (1.46)	23.90 (1.24)	26.24 (0.94)	25.68 (1.65)
<i>Winter Temperature (°C)</i>	26.68 (1.14)	24.02 (2.03)	19.74 (1.82)	15.98 (1.10)	23.89 (1.69)	21.84 (3.92)
<i>Observations</i>	378,051	2,012,308	778,505	862,587	228,415	4,259,866

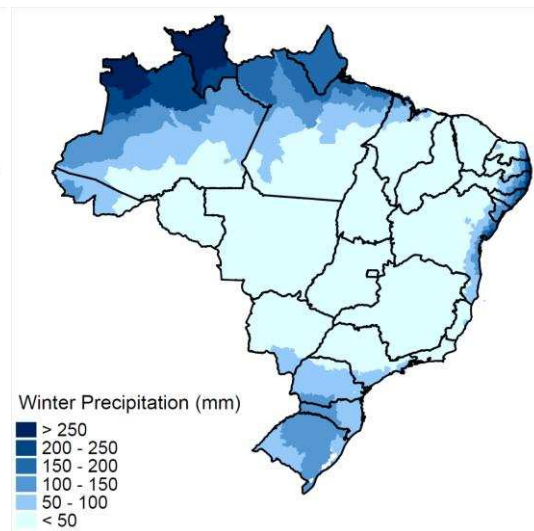
**Note:** \*: Values in thousands of 2006 U.S. dollars (Exchange rate = 2.15); Standard Deviation in ( ). **Source:** Research's results.

Figures 3.2a – 3.2d illustrate the climate by season (winter and summer) in Brazil for the period of 2003-2006. The North region has presented the highest average levels of precipitation in the summer season. Low rainfall levels are observed in winter season for the entire Brazil, except in the northern part of North Region; east of Northeast Region; and in the Rio Grande do Sul State in Southern Region. The temperature levels basically hold constant in the North and Northeast region in both seasons, while present great variability between summer and winter in the Southeast and South Regions and in the east part of the Midwest Region.

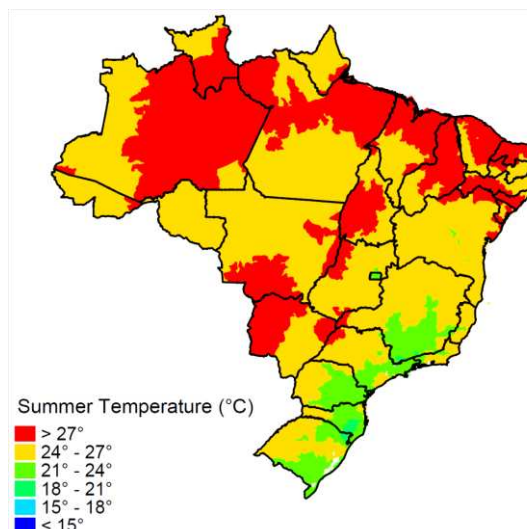
**Figure 3.2a – Summer precipitation**



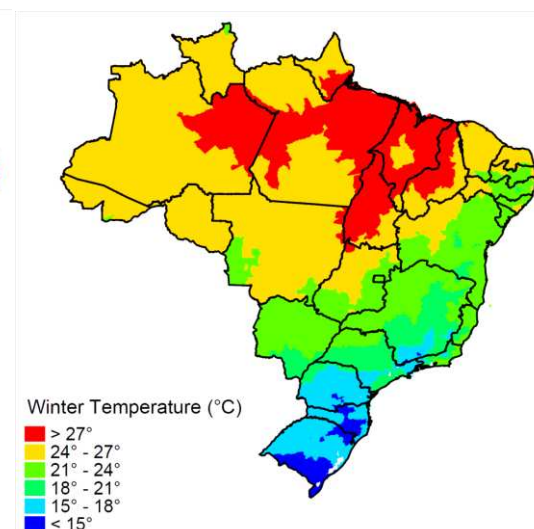
**Figure 3.2b – Winter precipitation**



**Figure 3.2c – Summer Temperature**



**Figure 3.2b – Winter Temperature**



Source: Author's elaboration

### 5.1. Elasticities and the Value of Irrigation Adoption

Following Trindade (2015) and Suárez, Fulginiti and Perrin (2018), after adding error terms and imposing symmetry in the second order parameters, the production function (Eq. 4) and the share equations (Eq. 5) for labor, expenses and irrigated land were simultaneously estimated as system of equations. We estimated 110 parameters (26 for Federative Units effects, and 84 for equation 4, twenty-four of which are shared with equation 5), and 94.5% of the parameters estimated are statistically significant. Since the translog specification allows the estimation of the elasticities for each data point, Table 3.2 displays average elasticities for land, labor, expenses, and capital; and semi-elasticity (percentage change in output value per unit change of variable) for irrigation, temperature, and precipitation. The standard errors and p-values are at their means. Table A5 in the Appendix shows the system of equations estimated.

**Table 3.2 – Average Production Elasticities for Translog Specification, 2006.**

<b>Variable</b>	<b>Elasticity</b>	<b>Standard-Error</b>
<i>Land</i>	0.1521***	0.0023
<i>Labor</i>	0.2097***	0.0019
<i>Expenses</i>	0.5005***	0.0018
<i>Capital</i>	0.1378***	0.0021
<i>Irrigation</i> <sup>#</sup>	0.6480***	0.0032
<b><i>Temperature</i><sup>#</sup></b>		
<i>Summer</i>	0.5869**	0.0709
<i>Winter</i>	-0.4633**	0.0496
<b><i>Precipitation</i><sup>#</sup></b>		
<i>Summer</i>	0.0286**	0.0052
<i>Winter</i>	0.0375**	0.0047

**Note:** \*\*, \*\*\* significant at 5% and 1%, respectively; # Semi-Elasticity:  $d\ln y/dx$ ;

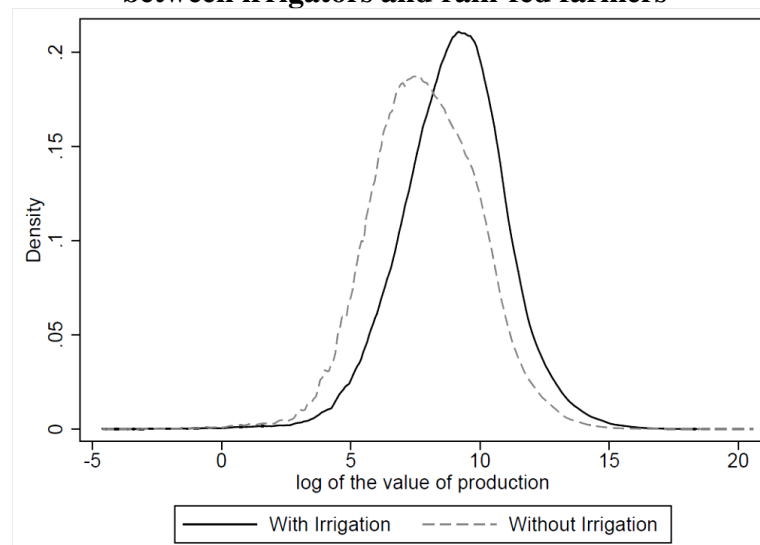
**Source:** Research results.

Evaluated at the average of the observations, the technology is monotone for all the inputs, but this is not true at each data point. The percentages of monotonicity violations are 10.45% for land, 12.95% for labor, 1.5% for expenses, 16.32% for capital, and 0% for irrigation.

The irrigation semi-elasticity indicates that changing a hectare from dryland to irrigated increases production value by 64.8%. Our estimate of irrigation semi-elasticity is higher than Trindade *et al.* (2015) estimates (0.23) and Suárez *et al.* (2018) estimates (0.511) for a semi-arid region in the United States. This result may be in part explained by the double harvest

observed in some crops and regions of Brazil. The negative coefficient for irrigation square implies that the yield boost from irrigation declines as the fraction of irrigated land increases within a farm. Figure 3.3 depicts the kernel density of the gross value of production between irrigators and non-irrigators, which gives a sense of the irrigation benefits and the capacity to shift the gross value of production.

**Figure 3.3 – Kernel density of Gross Value of Production (GVP) between irrigators and rain-fed farmers**



**Source:** Research results

In relation to climatic effects (Table 3.2), our results show that an increase in 1° Celsius would increase the yield in 0.58% in the summer and would decrease by 0.46% in the winter. This result is consistent if we consider that the summer season (December to February) is mostly rainy, and jointly with high temperatures provide suitable conditions for sowing and crop growing. On the other hand, in the winter season (June to August), which is mostly dry with low levels of humidity, this condition would become reverse. Anderson *et al.* (2016) identified agricultural regions within Brazil through yield-satellite index correlation analyses, where crop yields have been climatically sensitive to moisture deficits during the past decade, primarily in the southern and northeastern states. Our result for rainfall shows that, in general, increases in precipitation would increase yield, and the effect would be slightly stronger during the winter than in the summer season, which is expected.

Our estimates of the value of annual increment in gross production value per hectare due to irrigation (Equation 6) are summarized by Federative Unit and regions in column 4 of

Table 3.3. The incremental values in Brazil averaged US\$1,492.15/ha. The North, South and Southeast region present the highest incremental value per hectare, which is higher than the overall average.

The Northeast region shows the lowest yield response due to irrigation, which can be explained by the low quality of the soil and semi-arid climate, being this region highly dependent on irrigation. The high response to the humid-rainy North region is presumably due to the fact that, on average, irrigation adoption has been slower in this Region, reflecting the small fraction of irrigated land.

Multiplying the incremental gross value of production by the number of hectares irrigated and summing up to all farmers provides an estimate of the average total gross value of irrigation in 2006, and is summarized in column 7 of Table 3.3. The average value of irrigation in Brazilian agriculture is approximately US\$ 2.96 billion in 2006. We found the highest value of irrigation for the Southeast region (US\$1.09 billion), driven by irrigation value in São Paulo and Minas Gerais, where there are large areas of irrigated coffee, orange, corn, and sugarcane production. Given the results found in Chapter 2, where the change in the revenue for the selected grains (coffee, rice, soybean, beans, and corn) in the Southeast region exceeded US\$ 83 million (Table 2.6), we can affirm that the remaining amount generated by irrigation (Table 3.3) in the southeastern region is mainly due to orange, sugarcane, fruit plantations, and all other activities related to animal breeding.

The irrigation value for the Northeast region is around US\$900 million with the highest values for Pernambuco, Bahia and Ceará, where the former is driven mainly by sugarcane production in the coastal zone and fruit growing in São Francisco Basin. Bahia is driven by irrigated micro-regions in the western part with grain production, and the latter is due to several irrigated projects that have been developed in the last four decades.

Rio Grande do Sul in the South Region presents the highest irrigation value, around US\$410 million, followed by Santa Catarina, presumably due to irrigated rice production, while the irrigation value for Goiás (US\$95 million) in the Midwest region is driven by irrigated pastures and sugarcane. The values of irrigation for Mato Grosso and Mato Grosso do Sul are low as a result of the great response to droughts due to seeds genetical enhancement, mainly driven by the Brazilian Agricultural Research Corporation (Embrapa), mostly with soybeans, sorghum and corn production. The lowest irrigation values are for Roraima and Acre in the North Region, while Pará and Tocantins present the highest irrigation value in this region mainly due to irrigated pastures as a result of extensive cattle ranching.

Table 3.3 – Estimated Annual Average Irrigation Water Value by State, Brazil, 2006

Federative Unit	Observed Production Value	IR Semi-Elast.	Avg. Gross Value per Hectare Irrigated	Irrigated Hectares	Irrigated Fraction	Total Gross Value of Irrigation
	(US\$/ha)		(US\$/ha)	(Thousands hectares)	(%)	(Million US\$)
Rondônia	359.42	0.663	251.67	12.765	0.91	6.49
Acre	1,448.08	0.626	1,005.14	0.884	0.30	0.64
Amazonas	1,001.51	0.545	559.59	5.018	0.61	3.37
Roraima	4,637.30	0.588	3,753.80	2.481	0.44	0.50
Pará	5,057.27	0.608	3,893.48	21.447	0.81	28.92
Amapá	7,078.37	0.563	5,783.62	1.537	1.53	0.73
Tocantins	470.91	0.630	368.21	23.156	0.33	9.93
<b>North</b>	<b>3,964.57</b>	<b>0.615</b>	<b>2,793.37</b>	<b>67.291</b>	<b>0.73</b>	<b>50.57</b>
Maranhão	4,279.56	0.556	2,794.18	30.618	1.03	14.78
Piauí	992.19	0.544	650.00	21.977	1.28	31.37
Ceará	2,569.45	0.561	1,823.54	86.179	3.29	144.56
Rio G. Norte	1,233.64	0.583	927.64	25.926	2.31	22.59
Paraíba	1,150.24	0.609	790.52	32.341	1.90	39.44
Pernambuco	1,704.17	0.608	1,209.37	81.472	4.72	319.90
Alagoas	1,737.70	0.671	1,195.44	33.472	1.09	58.50
Sergipe	1,776.46	0.670	1,270.83	12.137	2.61	24.65
Bahia	756.35	0.616	522.46	191.149	2.10	243.40
<b>Northeast</b>	<b>1,645.45</b>	<b>0.598</b>	<b>1,131.86</b>	<b>515.275</b>	<b>2.38</b>	<b>899.18</b>
Minas Gerais	1,513.36	0.687	1,209.30	290.587	2.07	384.70
Espírito Santo	1,603.73	0.728	1,292.89	164.203	11.32	168.34
Rio de Janeiro	3,477.83	0.706	2,896.01	46.626	12.30	83.45
São Paulo	2,993.71	0.755	2,522.19	256.177	4.56	453.04
<b>Southeast</b>	<b>1,955.00</b>	<b>0.707</b>	<b>1,598.10</b>	<b>757.595</b>	<b>4.08</b>	<b>1,089.54</b>
Paraná	1,954.36	0.721	1,656.73	55.689	0.97	82.50
Santa Catarina	2,734.36	0.726	2,331.27	105.278	2.73	162.03
Rio G. do Sul	2,245.30	0.711	2,041.98	680.387	1.57	469.57
<b>South</b>	<b>2,233.24</b>	<b>0.717</b>	<b>1,956.84</b>	<b>841.355</b>	<b>1.57</b>	<b>714.10</b>
Mato G. Sul	454.31	0.695	356.32	42.412	0.69	24.33
Mato Grosso	375.20	0.654	273.68	95.140	0.56	69.57
Goiás	521.62	0.691	418.62	132.210	1.05	94.67
Fed. District	3,887.84	0.770	3,334.48	7.744	16.54	19.20
<b>Mid-West</b>	<b>503.78</b>	<b>0.681</b>	<b>396.61</b>	<b>277.507</b>	<b>1.02</b>	<b>207.78</b>
<b>Brazil</b>	<b>1,965.64</b>	<b>0.648</b>	<b>1,492.15</b>	<b>2,459.026</b>	<b>2.31</b>	<b>2,961.15</b>

Source: Research results.

It is important to highlight that our estimates are based on extra revenue per hectare (\$/ha). Studies that use the quantity of water applied in production functions to measure the value of irrigation water usually obtain returns in terms of \$/m<sup>3</sup> which is not strictly comparable to our estimates. Furthermore, we emphasize that we do not have data sources to estimate the additional costs of irrigated production versus non-irrigated production to be deducted from the values we estimate to obtain the net value of irrigation<sup>22</sup>, while we have estimates on total additional gross revenue when land is irrigated relative to non-irrigated land. The total cost of water would be measured by energy, operation, and maintenance costs for diversion and pumping at agricultural nodes (Cuadra *et al.*, 2019).

Are our irrigation water values estimates plausible, given results of other studies? Santos and Spolador (2018) combined General Equilibrium with Residual Method in a multi-sector growth model to estimate the stock value of irrigation water in Brazil in 2007 found a value of US\$9.6 billion, which is higher than our estimates, US\$2.96 billion. A production function was used in Carramaschi *et al.* (2000) to estimate the net irrigation value of horticulture and fruit growing in areas around the Federal District and found a net income of US\$1,779/ha; our gross estimate is higher, US\$3,334.48/ha. A yield function in response to water application using linear programming was estimated in Frizzzone *et al.* (1997) in an irrigated district in the São Francisco River Basin (Pernambuco State) obtaining an average shadow price of irrigated land of US\$1,115.20/ha which is close to our estimates for this State, of US\$1,209.37/ha.

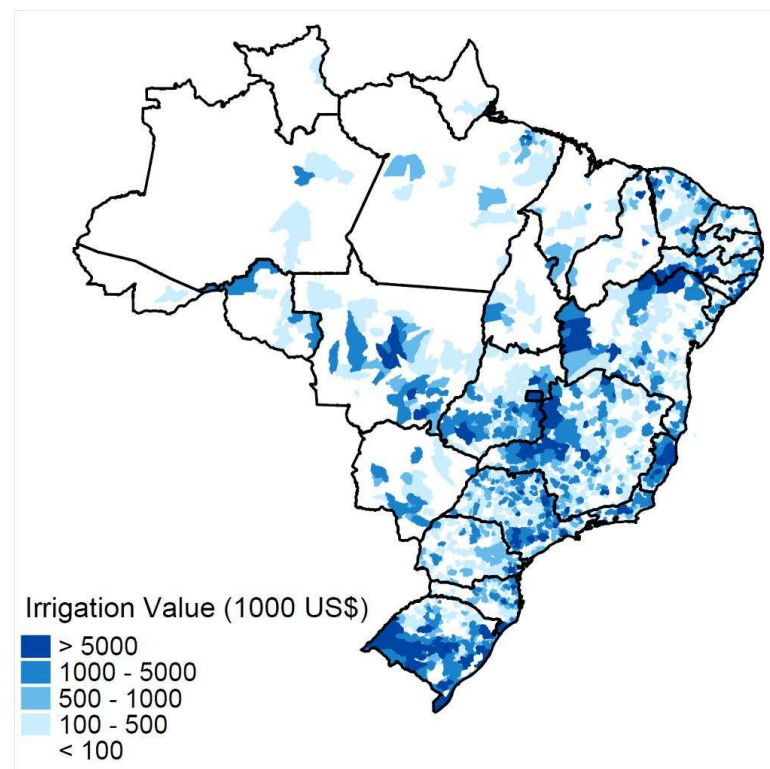
Nikouei *et al.* (2013) estimated the water value in Iran and found a value of US\$689.7 million/year in total revenue which is closer to our estimates to the well-irrigated South region, US\$714.1 million. They also estimated a total net income of US\$379.4 million/year where the average net income was US\$2.3 thousand/ha/year. The value of irrigation water estimated in Suárez *et al.* (2018) for the High Plains Aquifer in the USA is around US\$3.34 billion in 2007 which is close to our estimates for Brazilian agriculture, US\$2.97 billion. The total net benefit in irrigated production in England and Wales was estimated in Rey *et al.* (2016) to be around US\$854 million assuming no constraints in resource availability and optimal irrigation practices. The annual incremental benefit from irrigation was, on average, US\$226.96/ha in the findings of Viswanathan and Kumar (2016) for India. These previous results for different countries are close to our estimates for some of the Brazilian regions.

---

<sup>22</sup> The Irrigation and Drainage Practice Group (Esalq/University of São Paulo) had calculated the total cost of a sprinkler system to irrigate pastures in São Paulo. They found a cost by US\$1,166.84/ha/year. If we take this value as the cost of irrigation per hectare in Brazil and multiply by the total irrigated hectares given in Table 3.3, we found a total cost of irrigation of US\$2.87 billion/year. Then, our estimates of the irrigation net value would be around US\$91.86 million in 2006.

The Brazilian Gross National Product (GNP) in 2006 was US\$ 1.31 trillion, and the agricultural sector GNP was US\$312.68 billion, which represents 24% of total GNP (IBGE, 2006). Taking into account the total production value given by our data, this value is around US\$51.8 billion. Thus, our estimates of water irrigation value represent 5.73% of the total agricultural production value in 2006, 0.94% of agricultural sector GNP and 0.22% of Brazilian GNP, which is reasonable to consider given the results found in Santos and Spolador (2018), where that stock value of water used in irrigation would correspond to 0.22% of the value of the stock of physical capital for the entire Brazilian economy; equals to our estimate. However, as pointed out by authors, and also Resende Filho *et al.* (2015), from an economic point of view the value of water used in irrigation can be considered low in Brazil. Figure 3.4 depicts the value of irrigation estimates summed across all farmers within a municipality.

**Figure 3.4 – Irrigation water value, Brazil (2006)**



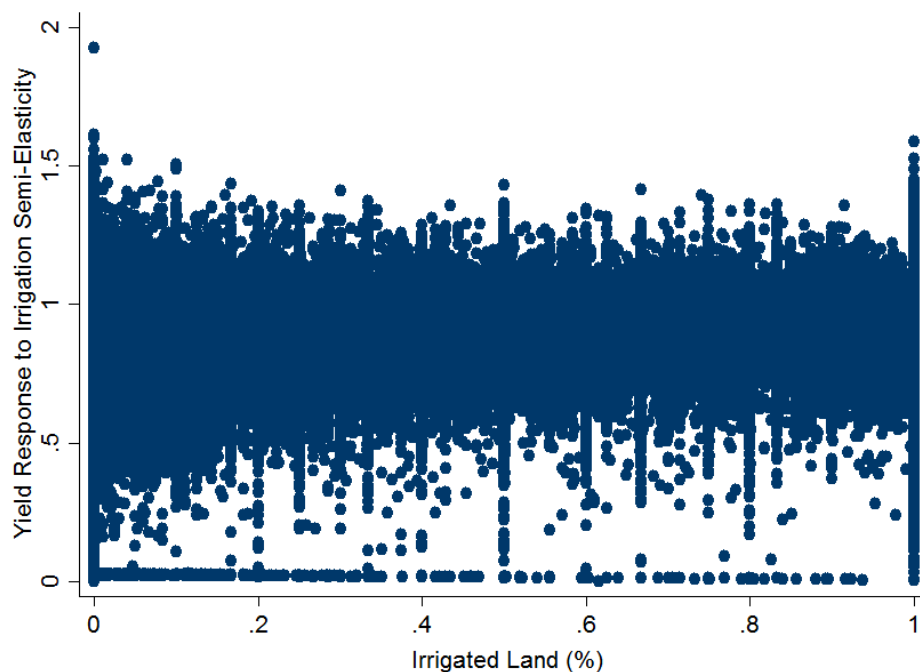
**Source:** Research results.

We can observe based on Figure 3.4 that the highest values of irrigation water are for those municipalities that present high fractions of irrigated land, and can be noted if we compare Figure 3.4 and Figure 3.1. Thus, we can conclude that irrigation water is more valuable in regions where irrigated agriculture is well developed, which makes sense.

### 5.2. Post estimation analysis

As highlighted by Young (2005), Frija *et al.* (2014) and Suárez *et al.* (2018), diminishing marginal productivity of irrigation is expected as irrigation increases. This relationship is unclear when we observe our irrigation semi-elasticity estimates and the fraction of irrigated land in Table 3.3; and remains unclear if we analyze a scatterplot of the irrigation response and irrigated land using the whole data collection. Figure 3.5 depicts a scatterplot of this relationship.

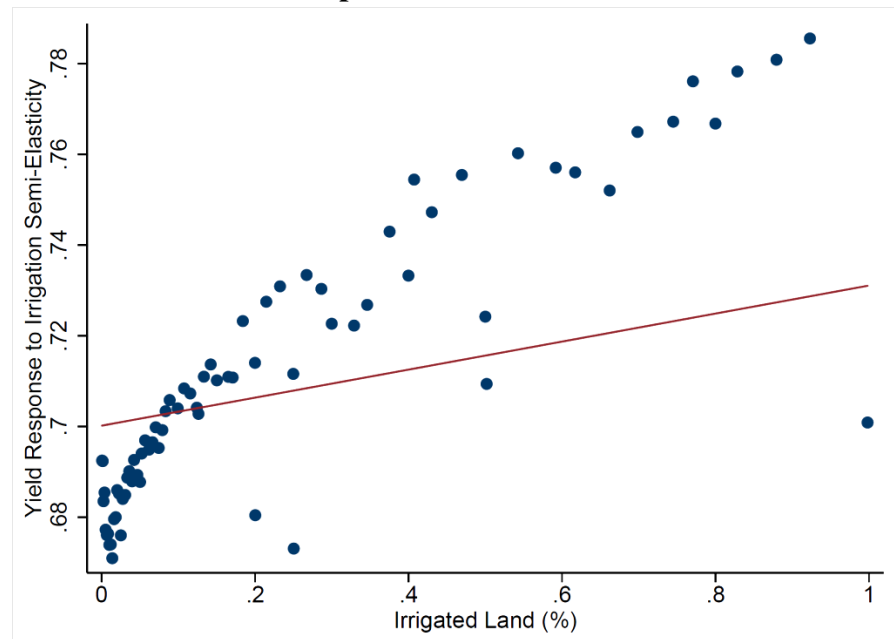
**Figure 3.5 – Scatterplot, Semi-elasticity of irrigation response estimated.**



**Source:** Research results.

As we have a large number of observations, a scatterplot that plots every data point became too crowded to interpret visually. An alternative way is to depict a binned scatterplot, which provides a non-parametric way of visualizing the relationship between two variables, where it groups the x-axis variable into equal-sized bins, computes the mean of the x-axis and y-axis variables within each bin, and then creates a scatterplot of these data points. The result is a non-parametric visualization of the conditional expectation function. Figure 3.6 depicts the binned scatterplot.

**Figure 3.6 – Binned scatterplot, Semi-elasticity of irrigation response estimated.**



**Source:** Research results.

Figure 3.6 shows that the irrigation response raises rapidly for low values of irrigated fraction, and slowly for high values, which support the intuition of diminishing marginal productivity of irrigation at the extensive margin within farms. We performed a binned scatterplot to evaluate whether this intuition holds for all macro-regions or not. The result seems to be the same for all Brazilian regions, except for the high values of irrigated fraction in the North, which may be explained, in part, by the low intensity and frequency of irrigation in the region due to great levels of precipitation observed as a result of the local-climate conditions generated by the Amazon Forest. Figures A4 in the Appendix show the result.

## 6. Conclusion

Brazil has shown significant incorporation of irrigated areas for several decades, where productivity gains can be explained in part by the implementation of efficient irrigation systems. However, the role of irrigated agriculture in the contribution to yield increase and the value of the irrigation has not been much analyzed in Brazilian agriculture.

This research aimed to estimate the average increases in gross value of production due to irrigation and also measure how much is the value of irrigation adoption in Brazil. We used a rich dataset containing more than 4 million farm observations. The dataset was obtained from

2006 Agricultural and Livestock Census, and a system of equations was estimated containing a production function and share equations for labor, expenses, and irrigated land.

A yield response due to irrigation averaging 0.648 was found and incremental gross revenue due to irrigation averaged US\$1,492.15/ha. The value of irrigation estimates is US\$ 2.96 billion, which is based on total additional gross revenue when land is irrigated relative to non-irrigated land. To obtain the net value the costs of irrigated production is required. Our estimates are consistent with diminishing marginal productivity of irrigation at the extensive margin within farms.

We found that irrigation is more valuable in regions where irrigated agriculture is well developed as in Rio Grande do Sul with irrigated rice production; São Paulo with orange, sugarcane and cotton production; and Espírito Santo and Minas Gerais in the production of coffee, corn, and beans.

In the Midwest region we can observe high values for areas producing soybean, sorghum, corn, and sugarcane; and in the Northeast Region in areas settled by the São Francisco Basin mainly in horticulture and fruit growing, and also in areas settled in the western part of Bahia, where soybean and grains in general has been harvested in the last years as a response of the development of MATOPIBA region (known as the new agriculture frontier in Brazil in the States of Maranhão, Tocantins, Piauí, and Bahia).

Farms settled in some municipalities located in Pernambuco and Alagoas presented high values of irrigation water due to irrigated sugarcane, and also in Ceará where several irrigated projects have been developed in the last four decades. Finally, we can observe isolated municipalities in the North region that presented high irrigation values, mainly settled in Tocantins and Pará with graze plantation, and flooded rice in Rondônia.

Public policies in the irrigation expansion could be driven in three ways: *(i)* in regions where irrigation response presents high values, but more use of water could be associated to a smaller production *vis-à-vis* another area with the same characteristics; *(ii)* or where the extra revenue per hectare due to irrigation is the highest compared to others regions; *(iii)* and also based where irrigation value is more valuable. Our estimates also allow obtaining some interesting results to support water price policy for irrigation among the twelve hydrological basins in Brazil, which the water price policy to pump water to irrigate must reflect the availability and the quality of the resource.

## FINAL REMARKS

The irrigation adoption has been receiving greater governmental attention as an instrument to support farmers to reduce dependency on variable rainfall and water availability and to mitigate and to adapt the adverse effects of climate change observed in the last decades. Although irrigation adoption is still low in Brazil, irrigated areas have remaining high in recent years. In fact, Brazil still has a lot of room to increase its use of irrigation which can largely improve the country's agricultural production. The main goal of this thesis was to identify the effect of irrigation on relevant aspects of Brazilian agriculture. We had focused on identifying the effect of irrigation on technical efficiency; in the supply of grain sector, demand for productive factors and revenue generation; and in the measurement of the value of irrigation in Brazilian agriculture.

Our results show that both irrigators and rain-fed farmers have presented low levels of technical efficiency, where irrigators are more efficient than rain-fed farmers, on average, in 2.51 percentage points, which implies that both groups can increase the production holding the same amount of inputs. The analysis by farm size showed that, in both groups, the small farmers are more efficient than the others, which corroborates with Schutz, who argued that small farmers are poor but efficient. However, the greatest difference in the technical efficiency between irrigators and non-irrigators was found for medium and large farms, which imply that irrigation technology had a significant effect on the efficiency gain for those sizes. Moreover, technical assistance, financing, and farmer's management experience have shown a positive effect on technical efficiency.

Nonetheless, we found that irrigation expansion affects positively grains supplies and labor input demand in the short-run in the most irrigated region in Brazil, the Southeast region. The change in grain sector revenue due to irrigation is 2.10% (around US\$ 83.45 million), where changes in the revenue of coffee, corn, and beans represent 97% of the total added revenue. We also found that output supplies and input demands respond differently to heterogeneous farm sizes when they facing irrigation expansion and short-term weather effects, being the agriculture in this region more affected by heat stress than water shortages. The analyses have shown that very small and small farmers were more capable to expand their supplies through irrigation technology than medium and large farmers since the small farmers are facing scarce resources in the production process and the latter are facing complexities in operating the irrigation systems. Hence, very small and small farmers could transform inputs into outputs more efficiently than the latter. These outcomes reinforce the

role of farm heterogeneity in technology adoption. Credit programs and specialized technical assistance could be provided by government policies at the micro-level, and reduced taxation to increase exports at the macro-level in order to increase farmers' revenue through irrigation technology.

Our results to the value of irrigation in Brazil showed a yield response due to irrigation averaging 0.648, which implies that converting a non-irrigated hectare to an irrigated would increase the yield by 64.8%. This result shows how agriculture in Brazil presents a great response to irrigation and farmers are able to crop twice a year. The incremental gross revenue due to irrigation was found to be US\$1,492.15/ha, on average, and the value of the irrigation adoption was US\$ 2.96 billion. This value is based on total additional gross revenue when land is irrigated relative to a non-irrigated land. Further estimation accounting the irrigation costs would give a sense of how much is the net value of irrigation in Brazil. Our findings reveal that irrigation is more valuable in regions where irrigated agriculture is well developed; and the water price policies to pump water from any resource to irrigate should account for quality and availability of water, but also in those areas where the return in terms of added revenue per hectare is higher.

It is important to highlight that the effective provision of rural extension services, credit market access, the increase in the skilled workforce in the farm, and projects that promote rural electrification and the existence of water resources within the farm would increase the irrigation technology adoption in Brazil. Those factors are an important research agenda of public policies in rural areas. The Empresa de Assistência Técnica e Extensão Rural (EMATER) – Technical Assistance and Rural Extension Company, in English – is the main governmental companies with the challenge of transmitting the necessary knowledge to farmers adopt new technologies in the Brazilian agriculture. EMATER prepares technical and credit fundraising projects at no cost to the familiar farmers, which represent more than 70% of the farmers in Brazil. EMATER also advises on the definition of the most suitable irrigation system for each type of exploration, helping farmers to obtain harvesting water grant and the environmental regularization in accordance with current legislation. Thus, an interesting and necessary research agenda is to identify how farmers perceive the climatic change and how they could mitigate and adapt their agricultural activities under climate anomalies using suitable technologies, like irrigation. Moreover, a new challenge should be embodied by the EMATER policy: the knowledge on how to convert the archaic irrigation system to a modern system to improve technical efficiency and irrigation efficiency in order to avoid overexploitation of water resources.

Notwithstanding, we suggest that those projects prepared by EMATER to easily request credits in the market might work jointly with the Programa de Incentivo à Irrigação e à Armazenagem (Moderinfra) – Irrigation and Storage Incentive Program, in English. Moderinfra was launched by the National Bank for Economic and Social Development (BNDES), which is the main program to provide credit to support the development of sustainable, economically and environmentally irrigated agriculture in order to minimize production risk and increase the supply of agricultural products. Moderinfra also provides support to expand the storage capacity of agricultural production by farmers; support the construction and expansion of facilities for the storage of agricultural machinery and implements, and the storage of agricultural inputs. Nevertheless, the interest rates of Moderinfra should be lower sufficiently to allow farmers to invest with a smaller risk.

Most of the fundings provided by public programs is based on some requirements, as bail or surety, pledge, fiduciary alienation, and mortgage. Thus, poor farmers settled in areas facing socioeconomic vulnerability, low quality of soils and water scarcity, as in the Northeast Region, should be encouraged to submit irrigation projects and take the benefits, for instance, of the Fundo Constitucional de Financiamento do Nordeste - FNE (Northeast Constitutional Financing Fund, in English). The Bank of Northeast is responsible to manage the FNE, which launched the FNE Irrigation, a program that provides funds to implement, expand, diversify, and modernize agricultural projects involving irrigation and drainage while complies the eco-efficiency criterion. The advantage of the FNE Irrigation for farmers grouped as very small and small is that they are able to require the maximum amount of the funding without compromise their assets, serving to exemplify how a program might be developed without excluding the poorest farmers.

Finally, we conclude that irrigation is able to increase labor demand. Thus, irrigation technology is an efficient tool in the employment generation and income in rural areas. As irrigation adoption can help farmers to ensure the production, achieve higher rates of productivity, generate income, alleviate poverty, increase food security in rural areas, and avoid overexploitation of water resources if the suitable irrigation system is implemented, we conclude that irrigation technology can help farmers to achieve rural development in a sustainable basis.

## REFERENCES

- ADAMOWICZ, W. L., P. C. BOXALL, J. J. LOUVIERE AND J. SWAIT, ‘Stated Preference Methods for Valuing Environmental Amenities’, in I. J. Bateman and K. G. Willis, eds., **Valuing Environmental Preferences: Theory and Practice of the Contingent Valuation Method in the USA, EC, and Developing Countries**. New York: Oxford University Press, pp. 460–479, 1999.
- AGÊNCIA NACIONAL DE ÁGUAS (Brasil). **Conjuntura dos recursos hídricos no Brasil: informe 2009**. Brasília, DF, 2009.
- ALVES, E. R. A.; VIEIRA FILHO, J. E. R. **O que se espera da irrigação no nordeste?** In: Diagnóstico e desafios da agricultura brasileira. VIEIRA FILHO, J. E. R. *et al.* 340 p. ISBN 978-85-7811-360-5. Rio de Janeiro, IPEA, 2019.
- ANA - AGÊNCIA NACIONAL DE ÁGUAS (Brasil). **Levantamento da agricultura irrigada por pivôs centrais no Brasil - 2014**. Brasília, DF, 2016.
- ANA - AGÊNCIA NACIONAL DE ÁGUAS (Brasil). **Atlas irrigação: uso da água na agricultura irrigada**. ISBN 978-85-8210-051-6. 86p. Brasília, 2017.
- ANA - AGÊNCIA NACIONAL DE ÁGUAS (Brasil). **Conjuntura dos recursos hídricos no Brasil 2018: informe anual**. 72p. Brasília, 2018.
- ANANG, B. T.; BACKMAN, S.; REZITIS, A . Production technology and technical efficiency: irrigated and rain-fed rice farms in northern Ghana. **Eurasian Economic Review**. 7:95–113, 2017.
- ANDERSON, M. C. *et al.* The Evaporative Stress Index as an indicator of agricultural drought in Brazil: An assessment based on crop yield impacts. **Remote Sensing of Environment**, v. 174, p. 82–99, 2016.
- BABATUNDE, R. O., SALAMI, M. F., MUHAMMED, B. A. Determinants of yield gap in rain-fed and irrigated rice production systems – evidence from household survey in Kwara State, Nigeria. *J. Agribus. Rural Dev.*, 1(43), 25–33, 2017.
- BALL, V. E. Modeling Supply Response in a Multiproduct Framework. **American Journal of Agricultural Economics**, 70(4), 813.doi:10.2307/1241922, 1988.
- BARROS, E. DE S.; COSTA, E. DE F.; SAMPAIO, Y. Análise de eficiência das empresas agrícolas do pólo Petrolina/Juazeiro utilizando a fronteira paramétrica Translog. **Revista de Economia e Sociologia Rural**, v. 42, n. 4, p. 597–614, 2004.
- BATTESE, G. E. Frontier production functions and technical efficiency: a survey of empirical applications in agricultural economics. **Agric Econ**, 7:185–208, 1992
- BATTESE, G. E.; COELLI, T. J. Prediction of firm-level technical efficiencies with a generalized frontier production function and panel data. **Journal of Econometrics**, v. 38, n. 3, p. 387–399, 1988.

BATTESE, G. E.; COELLI, T. J. A Model for Technical Inefficiency Effects in a Stochastic Frontier Production Function for Panel Data. **Empirical Economics**, v. 20, p. 325–332, 1995.

BERBEL, J.; MESA, P. Valoración del agua de Riego por el método de precios quasi-hedónicos: aplicación al Guadalquivir. **Econ Agrar Recurs Nat** 7, 127-144. [In Spanish]. 2007.

BINSWANGER, H.; YANG, M.C.; BOWERS, A., MUNDLAK, Y. On the determinants of cross-country aggregate agricultural supply. **Journal of Econometrics**. 36 111-131, North-Holland, 1987.

BRASIL, Lei nº 12.787, de 11 de janeiro de 2013. **Dispõe sobre a Política Nacional de Irrigação**. Available: at: <https://bit.ly/2mpi2Ry>. Access: 10/04/2019.

BRAVO-URETA, B. E.; SOLIS, D.; MOREIRA, V.H.; MARIPANI, J.; THIAM, A.; RIVAS, T. Technical efficiency in faming: a meta-regression analysis. **Journal of Productivity Analysis**, 27:57–72, 2007.

BRAVO-URETA, B. E.; GREENE, W.; SOLÍS, D. Technical efficiency analysis correcting for biases from observed and unobserved variables: an application to a natural resource management project. **Empirical Economics**, v. 43, n. 1, p. 55-72, 2012.

BROZOVIC, N.; ISLAM, S. **Estimating the value of groundwater in irrigation**. In Agricultural and Applied Economics Association Annual Meeting, Denver, Colorado, pp. 34., 2010.

BURSZTYN, M. **O Poder dos Donos: Planejamento e Clientelismo no Nordeste**. Rio de Janeiro/Fortaleza: Banco do Nordeste, 2008.

CAREY, J. M.; ZILBERMAN, D. A Model of Investment under Uncertainty: Modern Irrigation Technology and Emerging Markets in Water. **American Journal of Agricultural Economics** 84:171-83, 2002.

CARRAMASCHI, E. C. *et al.* O preço da água para irrigação: um estudo comparativo de dois métodos de valoração econômica - contingente e dose-resposta. **Cadernos de Ciência & Tecnologia**, Brasília, v.17, n.3, p.59-81, set./dez. 2000.

CARSON R. T.; FLORES, N. E.; MEADE, N. F. Contingent Valuation: Controversies and Evidence. **Environmental and Resource Economics** 19: 173–210, 2001.

CASTRO, E. R.; TEIXEIRA, E. C. Rural credit and agricultural supply in Brazil. **Journal of Agricultural Economics**, 43 293–301, 2012.

CHAMBERS, R. G. **Applied production analysis: a dual approach**. Cambridge: Cambridge University Press, 331p, 1988.

CHRISTENSEN, L. R., JORGENSON, D. W., LAU, L. J. (1973). Transcendental logarithmic production frontiers. **The review of economics and statistics**, 28-45, 1973.

CHRISTOFIDIS, D. O futuro da irrigação e a gestão das águas. **Revista Item**, v. 1, n. 80, p. 40-47, 2008.

CHRISTOFIDIS, D. **Política Nacional de Irrigação**. Lei nº 12.787, de 11 de janeiro de 2013. Transferência de Gestão dos Projetos Públicos de Irrigação. Ministério da Integração Nacional (MI). Brasília, 12 de novembro de 2013. Available at: <https://bit.ly/2IGXm7a.b>

CLIMATIC RESEARCH UNIT – CRU/University of East Anglia. Available on: <http://www.cru.uea.ac.uk/>.

COELLI, T. J. Recent developments in frontier modeling and efficiency measurement. **Australian Journal of Agricultural Economics** 39:219–245, 1995.

CUADRA, S. V. ; VICTORIA, D. C.; FERRARINI, A. S. F. ; FERREIRA FILHO, J. B. S.; HORRIDGE, M. The Expansion of Irrigated Agriculture in Brazil and Potential Regional Limitations. **Fields Institute Communications**. 1ºed.: Springer New York, p. 139-158., 2019.

CUNHA, D. A. et al. Effects of climate change on irrigation adoption in Brazil. **Acta Scientiarum - Agronomy**, v. 36, n. 1, p. 1–9, 2014.

CUNHA, D. A.; COELHO, A. B.; FÉRES, J. G. Irrigation as an adaptive strategy to climate change: An economic perspective on Brazilian agriculture. **Environment and Development Economics**, (1), 57-79. doi:10.1017/S1355770X14000102, 2015.

DIWERT, W. E., MORRISON, C. "Export Supply and Import Demand Functions: A Production Theory Approach." In: Feenstra, R. ed., *Empirical Methods for International Trade*. Cambridge, Mass.: MIT Press, 1989.

DINH, H.; DONOGHOE, M.; HUGHES, N.; GOESCH, T. **A micro-simulation model of irrigation farms in the southern Murray-Darling Basin**. Department of Agriculture and Water Resources – ABARES, Australian Government. Working Paper, 2018.

DRIDI, C.; KHANNA, M. Irrigation Technology Adoption and Gains From Water Trading under Asymmetric Information. **American Journal of Agricultural Economics**, v. 87, n. 2, p. 289-301, 2005.

DROOGERS, P. **Adaptation to climate change to enhance food security and preserve environmental quality: example for southern Sri Lanka** Agricultural Water Management., 66, pp. 15-33, 2004.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA – EMBRAPA. Evolução da Política de Crédito Rural Brasileira. **Embrapa Cerrados**. Ministério da Agricultura, Pecuária e Abastecimento – MAPA. v. 1, p. 65, 2010.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA – EMBRAPA. **Tecnologias de produção de soja – Região Central do Brasil 2014**. Londrina: Embrapa Soja, 265p. ; 21cm. – (Sistemas de Produção/Embrapa Soja, ISSN 2176- 2902; n.16), 2013.

EVANS, R. G.; SADLER, E. J. Methods and technologies to improve efficiency of water use. **Water Resources Research**, v. 44, n. 7, p. 1–15, 2008.

FAUX, J.; PERRY, G. Estimating irrigation water value using hedonic price analysis: A case study in Malheur County, Oregon. **Land Economics**, 75(3):440-452. 1999.

FERRARINI, S. F. A.; FERREIRA FILHO, J. B.; HORRIDGE, M. **Water demand prospects in brazil: a sectoral evaluation using an inter-regional CGE Model**. Presented at the 19<sup>th</sup> Annual Conference on Global Economic Analysis, Washington DC, USA, 2016.

FIGUEIREDO, A. M. R. ; TEIXEIRA, E. C. Response of agricultural production to prices in the Brazilian Midwest: An analysis of spatial econometrics for the period 1975-1995/1996 (In Portuguese). **Revista de Estudos Sociais**, n.8, p. 72-104, 2002.

FINGER R.; HEDIGER, W.; SCHMID, S. Irrigation as adaptation strategy to climate change – a biophysical and economic appraisal for Swiss maize production. **Climate Change**, 105, pp. 509-528, 2011.

FOOD AND AGRICULTURE ORGANIZATION – FAO. 2017. **Information on Brazilian and world agricultural production**. Available at <<http://www.fao.org/faostat/en/#data/QV>> Accessed on Nov of 2018.

\_\_\_\_\_. **Information System on Water and Agriculture – AQUASTAT**. Available in: <<http://www.fao.org/nr/water/aquastat/main/index.stm>>. Accessed: may, 17 of 2019. 2015.

FOSTER, A.D.; M.R. ROSENZWEIG. “Learning by Doing and Learning from Others: Human Capital and Technical Change in Agriculture.” **Journal of Political Economy** 103:1176-1209. 1995.

FOSTER, A.D.; M.R. ROSENZWEIG. “Microeconomics of Technology Adoption.” **Annual Review of Economics** 2:395-424. 2010.

FREITAS, C. O.; TEIXEIRA E. C.; BRAGA, M. J. **Technical efficiency and farm size: an analysis based on the Brazilian agriculture and livestock census**. Italian Review of Agricultural Economics 74(1): 33-48. doi: 10.13128/REA-25478. 2019.

FREITAS, C. O. **Three Essays on the Effect of Rural Extension in the Brazilian Agricultural Sector**. Viçosa, MG. Tese (Doutorado em Economia Aplicada). Universidade Federal de Viçosa, 2017.

FRIJA, A.; CHEBIL, A.; SPEELMAN, S.; BUYSSE, J.; VAN HUYLENBROECK, G. Water use and technical efficiencies in horticultural greenhouses in Tunisia. **Agricultural Water Management**, v. 96, n. 11, p. 1509-1516, 2009.

FRIJA, I.; FRIJA, A.; CHEBIL, A.; M’HAMED, H. C, SPEELMAN, S.; MAKHLOUF, M. Marginal Water Productivity of Irrigated Durum Wheat in Semi-Arid Tunisia. **Journal of Agricultural Science**; Vol. 6, No. 10; 2014.

FRIZZONE, J. A.; COELHO, R. D.; DOURADO-NETO, D.; SOLIANI, R. Linear Programming Model to optimize the water resource used in irrigation projects: An application

to Senador Nilo Coelho Project. **Sci. Agric., Piracicaba**, 54 (Especial edition), p.136-148, 1997.

GEBREHAWERIA G.; REGASSA E. N.; STEIN, H. Technical Efficiency of Irrigated and Rain-Fed Smallholder Agriculture in Tigray, Ethiopia: A Comparative Stochastic Frontier Production Function Analysis. **Quarterly Journal of International Agriculture** 51, No. 3: 203-226, 2012.

GENIUS, M.; KOUNDOURI, P.; NAUGES, C.; TZOUVELEKAS, V. Information Transmission in Irrigation Technology Adoption and Diffusion: Social Learning, Extension Services, and Spatial Effects, **American Journal of Agricultural Economics**, 96, issue 1, p. 328-344. 2014.

GIBBONS, D. C. **The economic value of water**. DC Resources for the Future, Inc, Washington DC, USA. 118 pp., 1986.

GÓMEZ-LIMÓN, J. A., ARRIAZA, M. AND BERBEL, J. (2002). Conflicting implementation of agricultural and water policies in irrigated areas in the EU. **Journal of Agricultural Economics** 53: 259– 281.

GORMAN, W. M. Tricks with Utility Functions. In: **Essays in Economic Analysis**. M. J. Artis and A. R. Nobay, eds. (New York: Cambridge University Press), 1976.

GREENE, W. A stochastic frontier model with correction for sample selection. **Journal of Productivity Analysis**, v. 34, n. 1, p. 15-24, 2010.

HAINMUELLER, J. Entropy balancing for causal effects: A multivariate reweighting method to produce balanced samples in observational studies. **Political Analysis**, v.20, n.1, p. 25-46, 2012.

HAJI, J. Production efficiency of smallholders' vegetable-dominated mixed farming system in Eastern Ethiopia: a non-parametric approach. **Journal of African Economies** 16, 1–27, 2007.

HAJIME, K.; KENICHI, K.; MOHAMED, K. Technical efficiency among irrigated and non-irrigated olive orchards in Tunisia. **African Journal of Agricultural Research**, v. 11, n. 45, p. 4627–4638, 2016.

HECKMAN, J. Sample selection bias as a specification error. **Econometrica**, v. 47, p. 153-161, 1979.

HELFAND, S. M.; LEVINE, E. S. Farm size and the determinants of productive efficiency in the Brazilian Center-West. **Agricultural Economics**, v. 31, n. 2–3 SPEC. ISS., p. 241–249, 2004.

HORNBECK, R.; KESKIN, P. The Historically Evolving Impact of the Ogallala Aquifer: Agricultural Adaptation to Groundwater and Drought. **American Economic Journal: Applied Economics** 6 (1): 190–219. 2014.

HUGHES, N. et al. Productivity pathways: climate- adjusted production frontiers for the Australian broadacre cropping industry. **Australian Agricultural and Resource Economics Society**, 2011.

HUFFMAN, W. E.; EVENSON, R.E. Supply and Demand Functions for Multiproduct U.S. Cash Grain Farms: Biases Caused by Research and Other Policies. **American Journal of Agricultural Economics**, v. 71, n.3, 1989.

HUSSAIN, I.; TURRAL, H.; MOLDEN, D.; AHMAD, M. Measuring and enhancing the value of agricultural water in irrigated river basins. **Irrigation Science** 25:263–282, 2007.

HUSSAIN, I.; HANJRA, M. A. Irrigation and poverty alleviation: review of the empirical evidence. **Irrigation and Drainage**, 53: 1–15, 2004.

IGLESIAS, A.; GARROTE, L. Adaptation Strategies for agricultural water management under climate change in Europe. **Agricultural Water Management**, 155, p.113–124, 2015.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA – IBGE. **Censo Agropecuário 2006**. Rio de Janeiro, 2009. Vol. 1. p.1-777. Available at: <https://bit.ly/33Py7Ap> . Accessed on May, 2017.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE), 2017. Information on Brazilian agricultural land irrigated. Available at <<http://www2.sidra.ibge.gov.br/bda/tabela/listabl.asp?c=855&z=t&o=11>> Accessed on November of 2018.

JIANG, N.; SHARP, B. Technical efficiency and technological gap of New Zealand dairy farms: a stochastic meta-frontier model. **Journal of Productivity Analysis**, v. 44, n. 1, p. 39–49, 2015.

JOHANSSON, R. C. **Micro and macro-level approaches for assessing the value of irrigation water**. Washington D.C.: World Bank, (Working Paper 3778), 2005.

JOHANSSON, R. C.; TSUR, Y.; ROE, T. L.; DOUKKALI, R. M.; DINAR, A. “Pricing irrigation water: a review of theory and practice,” **Water Policy**. 4: 173-199, 2002.

KAGIN, J.; TAYLOR, J. E.; YÚNEZ-NAUDE, A. Inverse Productivity or Inverse Efficiency? Evidence from Mexico. **The Journal of Development Studies**, v. 388, n. December, p. 1–16, 2015.

KARAGIANNIS, G.; TZOUVELEKAS, V.; XEPAPADEAS, A. Measuring irrigation water efficiency with a stochastic production frontier. **Environmental and Resource Economics**. 26, 57–72, 2003.

KOUNDOURI, P.; NAUGES, C.; TZOUVELEKAS, V. Technology Adoption under Production Uncertainty: Theory and Application to Irrigation Technology. **American Journal of Agricultural Economics**, v. 88, n. 3, p. 657-670, 2006.

KRASACHAT, W. Technical Inefficiency of Chili Farms in Thailand. Annual Conference of the Agricultural Economics Society, the Royal Dublin Society, Dublin, Ireland, 2017.

KURUKULASURIYA P. *et al.* Will African agriculture survive climate change? **World Bank Economic Review** 20(3):367–388, 2006.

LANDAU, E. C. *et al.* **Variação geográfica do tamanho dos módulos fiscais no Brasil**. Sete Lagoas: Embrapa Milho e Sorgo, 199 p. (Documentos/Embrapa Milho e Sorgo, ISSN 1518-4277; 146), 2012.

LATINOPOULOS, P., TZIAKAS, V. Y MALLIOS, Z. Valuation of irrigation water by the hedonic price method: a case study in Chalkidiki, Greece. **Water, Air & Soil Pollution: Focus**, 4:253-262, 2004.

LAU, Lawrence J. A characterization of the normalized restricted profit function. **Journal of Economic Theory**, v. 12, n. 1, p. 131-163, 1976.

LEVIDOW, L.; ZACCARIA, D.; MAIA R.; VIVAS, E.; TODOROVIC, M.; SCARDIGNO, A. Improving water-efficient irrigation: Prospects and difficulties of innovative practices. **Agricultural Water Management**, 146, 84–94, 2014.

LIMA, J. E. F. W.; FERREIRA, R. S. A.; CHRISTOFIDIS, D. O uso da irrigação no Brasil. O estado das águas no Brasil. **Agência Nacional de Energia Elétrica**, 1999.

LIPTON, M.; LITCHFIELD, J.; FAURÈS, J-M. The effects of irrigation on poverty: a framework for analysis. **Water Policy**, 5, p. 413–427, 2003.

LOBELL, D. B.; CASSMAN, K. G.; FIELD, C. B.; Crop yield gaps: Their importance, magnitudes, and causes, **Annual Review of Environmental Resources**. 34, 179–204, doi:10.1146/annurev.environ.041008.093740, 2009.

LOPEZ, R. Estimating Substitution and Expansion Effects Using a Profit Function Framework. **American Journal of Agricultural Economics**. 66:358-67. 1984.

\_\_\_\_\_. Structural Implications of a Class of Flexible Functional Forms for Profit Functions. **International Economics Review**. 26:593-601. 1985.

MARRA, M.; PANNELL, D. J.; GHADIM, A. A. The Economics of Risk, Uncertainty and Learning in the Adoption of New Agricultural Technologies: Where are we on the Learning Curve? **Agricultural systems**, v. 75, n. 2, p. 215-234, 2003.

McFADDEN, D. **Duality of production, cost, and profit function**. In: McFADDEN, D.; FUSS, M. Production economics: a dual approach to theory and applications – the theory of production. Amsterdam: North Holland, 1978.

McKAY, LLOYD, LAWRENCE, D.; VLASTUIN, C. Profit, Output Supply, and Input Demand Functions for Multiproduct Firms: The Case of Australian Agriculture. **International Economic Review**. 24:323-39.1983.

MAKOMBE, G. *et al.* An analysis of the productivity and technical efficiency of smallholder irrigation in Ethiopia. **Water SA** Vol. 43 No. 1 Jan. 2017

MAKOMBE, G.; KELEMEWORK, D.; AREDO, D. A comparative analysis of rainfed and irrigated agricultural production in Ethiopia. **Irrigation and Drainage System**, 21:35–44, 2007.

MARETH, T. *et al.* Technical efficiency in dairy farms: Research framework, literature classification and research agenda. **International Journal of Productivity and Performance Management**, v. 66, n. 3, p. 380–404, 2017.

MARIANO, J. L.; PINHEIRO, G. M. T. L. Eficiência técnica da agricultura familiar no projeto de irrigação do baixo Açu ( RN ). **Revista Econômica do Nordeste**, v. 40, n. 2, p. 283–296, 2009.

MARRA, M.; PANNELL, D. J.; GHADIM, A. A. The Economics of Risk, Uncertainty and Learning in the Adoption of New Agricultural Technologies: Where are we on the Learning Curve? **Agricultural systems**, v. 75, n. 2, p. 215-234, 2003.

MELESSE, K. A.; AHMED, M. H. A comparative stochastic frontier analysis of irrigated and rain-fed potato farms in Eastern Ethiopia. **J. Agribus. Rural Dev.**, 4(38), 769–781. 2015.

MESA-JURADO, M. A.; BERBEL, J.; ORGAZ, F. Estimating marginal value of water for irrigated olive grove with the production function method. **Spanish Journal of Agricultural Research**, 8(S2), S197-S206, 2010.

MESA-JURADO, M. A.; MARTIN-ORTEGA, J.; RUTO, E.; BERBEL, J. The economic value of guaranteed water supply for irrigation under scarcity conditions. **Agricultural Water Management** 113, 10– 18, 2012.

MKANTHAMA *et al.* Technical efficiency of rain-fed and irrigated rice production in Tanzania. **Irrigation and Drainage**. 67: 233–241, 2018.

MINISTÉRIO DA INTEGRAÇÃO NACIONAL - MIN. **A irrigação no Brasil: situação e diretrizes**, 2008.

MINISTÉRIO DO MEIO AMBIENTE – MMA (Ministry of Environment). **Cadernos Setoriais de Recursos Hídricos: Agropecuária**. Secretaria de Recursos Hídricos, Brasília, 2006.

MOOLMAN, C. E.; BLIGNAUT, J. N.; EYDEN, R. Modelling the marginal revenue of water in selected agricultural commodities: A panel data approach. **Agrekon**, Vol 45, N° 1, 2006.

MORAES, M. M. G. A.; BIEWALD, A.; CARNEIRO, A. C. G.; SILVA, G. N. S.; POPP, A.; LOTZE-CAMPEN, H. The impact of global change on economic values of water for Public Irrigation Schemes at the São Francisco River Basin in Brazil. **Regional Environmental Change**, 18:1943–1955, 2018.

MORGAN, A. J.; ORR, S. The Value of Water: A framework for understanding water valuation, risk and stewardship. **International Finance Corporation – World Bank Group**, 56p. 2015.

- MUNDLAK, Y. **Production and supply**. Handbook of agricultural economics, 1, 3-85. 2001.
- MUNDLAK, Y., R. BUTZER, AND D. F. LARSON. **Heterogeneous technology and panel data: The case of the agricultural production function**. Policy Research Working Paper 4536, World Bank. 2008.
- MURTAZA, G.; THAPA, G. B. Factors affecting technical efficiency of small-scale apple farms in Balochistan Plateau, Pakistan. **Journal of Mountain Science**, v. 14, n. 4, p. 782–794, 2017.
- NEVES, M. C. R. **A influência das cooperativas na atividade agropecuária dos municípios do Sul e Sudeste brasileiros**. Tese de Doutorado. 96p. Universidade Federal de Viçosa, MG, 2016.
- NIKOU EI, A.; WARD, F. A. Pricing irrigation water for drought adaptation in Iran. **Journal of Hydrology**, 503, 29–46, 2013.
- NJUKI, E.; BRAVO-URETA, B. E. Climatic Variability and Irrigation : An Analysis of Irrigation Efficiency Patterns in U.S. Counties. In: **Agricultural & Applied Economics Association Annual Meeting**, Boston, Massachusetts, 2016.
- O'DONNELL, C.J.; RAO, D.S.P.; BATTESE, G.E. Metafrontier frameworks for the study of firm-level efficiencies and technology ratios. **Empir. Econ.** 34:231–255, 2008.
- OKADA, M., IIZUMI, T., SAKAMOTO, T., KOTOKU, M., SAKURAI, G., HIJIOKA, Y., & NISHIMORI, M. Varying benefits of irrigation expansion for crop production under a changing climate and competitive water use among crops. **Earth's Future**, 6, 1207–1220. <https://doi.org/10.1029/2017EF000763>, 2018.
- OPATA, P. I.; NWEZE, N. J.; EZEIBE, A. B.; MALLAM, M. Efficiency of irrigated and rain-fed rice (*oryza sativa*) producers in fadama agriculture, nigeria. *Expl Agric.*: p. 1-13, 2018.
- OZDOGAN, M. Exploring the potential contribution of irrigation to global agri-cultural primary productivity. **Glob. Biogeochem. Cycles**, 25. <http://dx.doi.org/10.1029/2009GB003720>, 2011.
- PEREDA, P. C. **Long-and short-run climate impacts on Brazil: theory and evidence for agriculture and health**. Tese (Doutorado em Teoria Econômica) - Faculdade de Economia, Administração e Contabilidade, Universidade de São Paulo, São Paulo, 2012. <https://doi:10.11606/T.12.2012.tde-15032013-163013> . Accessed in: 2019-04-10. 2012
- PEREIRA, L.S. Irrigation demand management to cope with drought and water scarcity. In Rossi G.; Cancelliere A.; Pereira L.S.; Oweis T.; Shatanawi M.; Zairi A. (Eds). **Tools for drought mitigation in Mediterranean regions**, 44 Kluwer, 2003.
- RADA, N.; HELFAND, S.; MAGALHÃES, M. Agricultural productivity growth in Brazil: Large and small farms excel. **Food Policy**. Vol. 84, p. 176-185, 2019.

RESENDE FILHO, M. A.; CORREA, J. S. O.; TORRES, M. O. Water Pricing in Brazil: Successes, Failures and New Approaches. In: DINAR, A. POCHAT, V.; ALBIAC-MURILLO, J. **Water Pricing Experiences and Innovations**. New York: Springer, 2015.

REY, D. *et al.* Modelling and mapping the economic value of supplemental irrigation in a humid climate. **Agricultural Water Management**, 173, p.13–22, 2016.

RIGBY, D., ALCON, F., BURTON, M., 2010. Supply uncertainty and the economic value of irrigation water. **Eur. Rev. Agric. Econ.** 37 (1), 97–117.

ROMERO, P.; GARCIA, J.; BOTIA, P. Cost-benefit analysis of a regulated deficit-irrigated almond orchard under subsurface drip irrigation conditions in South-eastern Spain. **Irrigation Science** 24, 175-184, 2006.

ROSENZWEIG, C., STRZEPEK, K., MAJOR, D., IGLESIAS, A., YATES, D., HOLT, A., HILLEL, D. Water availability for agriculture under climate change: five international studies. **Glob. Environ. Change**, 14, 345–360, 2004.

ROSENZWEIG, C. *et al.* Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. **Proc Natl Acad Sci** 111(9):3268–3273, 2014.

SANTOS, P. F. A.; SPOLADOR, H. F. S. **Valor da água destinada à irrigação das lavouras brasileiras em um modelo multissetorial de crescimento econômico**. In: 46º Encontro Nacional de Economia, 2018, Rio de Janeiro. 46º Encontro Nacional de Economia - ANPEC, 2018.

SCHAIBLE, D. G.; AILLERY, P. M. Water Conservation in Irrigated Agriculture: Trends and Challenges in the Face of Emerging Demands. **Economic Research Service**, n. 99, p. 1–60, 2012.

SCHLENKERA W.; ROBERTS B. M. J. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. **PNAS**. 106 (37) 15594-15598; <https://doi.org/10.1073/pnas.0906865106>. 2009.

SCHOENGOLD, K.; ZILBERMAN, D. The Economics of Water, Irrigation, and Development, ch. 58, p. 2933-2977 in Evenson, Robert and Pingali, Prabhu: **Handbook of Agricultural Economics**, Elsevier, 2007.

SCHUCK, E. C. *et al.*; Adoption of More Technically Efficient Irrigation Systems as a Drought Response. **Water Resources Development**, Vol. 21, No. 4, 651–662, 2005.

SCHULTZ, T. W. **A transformação da agricultura brasileira**. Tradução de J. C. Teixeira Rocha. Rio de Janeiro: Zahar Editores, 1965, 207p.

SCHURING, J., HUFFMAN, W.E., FAN, X. **The Impact of Public and Private R&D on Farmers' Production Decisions: 1960-2004**. In: 2011 Annual Meeting, July 24-26, 2011, Pittsburgh, Pennsylvania. Agricultural and Applied Economics Association, 2011.

SEPASKHAH, A. R.; AKBARI, D. Deficit irrigation under variable seasonal rainfall. **Biosystems Engineering**, 92(1), 97-106, 2005.

SHUMWAY, C.R.; SAEZ, R. R.; GOTTRET, P. E. Multiproduct Supply and Input Demand in U.S. Agriculture. **American Journal of Agricultural Economics**, v.70, 1988.

SILVA, J. S.; FERREIRA, O. F.; LIMA, J. R. F. Eficiência Técnica dos Produtores de Manga do Vale do São Francisco. **Revista de Economia e Agronegócio**, v. 15, p. 27–47, 2017.

SIPIÄINEN, T.; LANSINK, A. O. Learning in switching to organic farming. NJF Report 1. 2005.

SOUSA, E. P. DE; JUSTO, W. R.; CAMPOS, A. C. Eficiência Técnica da Fruticultura Irrigada no Ceará. **Revista Economica do Nordeste**, v. 44, n. 4, p. 851–866, 2013.

SPEELMAN, S.; D’HAESE, M.; BUYSSE, J.; D’HAESE, L. A measure for the efficiency of water use and its determinants, a case study of small-scale irrigation schemes in North-West Province, South Africa. **Agricultural Systems** 98, 31–39, 2008.

STUBBS, M. Irrigation in U.S. Agriculture: On-Farm Technologies and Best Management Practices. **Congressional Research Service**, 7-5700, p. 1-34, 2016.

TERRESTRIAL HYDROLOGY RESEARCH GROUP – Civil and Environmental Engineering Department of Princeton University. Available on: <https://bit.ly/32I5Kmo>

SUÁREZ, F. G. **Essays on the Economic Value of the High Plains Aquifer**. PhD Dissertation, University of Nebraska Lincoln. Available at digital commons: [unl.edu/dissertations/AAI3604717/](http://unl.edu/dissertations/AAI3604717/), 2013.

SUÁREZ, F. G.; FULGINITI, L. E.; PERRIN, R. K. What is the use value of irrigation water from the High Plains Aquifer? **American Journal of Agricultural Economics**, Vol. 101, Issue 2, March 2019, Pages 455–466, 2018.

TEGEGNE, B.; TADESSE, G.; ZEMEDU, L. Technical efficiency in irrigated small-scale agriculture : empirical evidence from onion farming in Kobo district of Northeast Ethiopia. **Journal of Agricultural Economics and Development**, v. 3, n. 3, p. 35–46, 2014.

THIAM, A.; BRAVO-URETA, B. E.; RIVAS, T. E. Technical efficiency in developing country agriculture: a meta-analysis. **Agricultural Economics**, 25, p. 235-243, 2001.

TIRUNEH, W. G.; CHINDI, A.; WOLDEGIORGIS, G. Technical efficiency determinants of potato production : A study of rain-fed and irrigated smallholder farmers in Welmera district, Oromia, Ethiopia. **Journal of Development and Agricultural Economics**, v. 9, n. August, p. 217–223, 2017.

TUBIELLO, N. N. Climate variability and agriculture: perspectives on current and future challenges. **Impact of climate change, variability and weather fluctuations on crops and their produce markets**. B. Knight, Cambridge, p 47–66, 2005.

TURRAL, H.; SVENDSEN, M.; FAURES, J. M. Investing in irrigation: Reviewing the past and looking to the future. **Agricultural Water Management**. 97, 551–560, 2010.

TRINDADE, F. U.S. **Crop Yield Redux: Weather Effects versus Human Inputs**. In: Agricultural Association and Western Agricultural Economics Association Annual Meeting, CA, July 26-28, 2015.

TSUR, Y.; DINAR, A.; DOUKKALI, R. M; ROE, R. Irrigation water pricing: policy implications based on international comparison. **Environ Dev Econ** 9, 735-755, 2004.

ULLAH, A.; PERRET, S. R. Technical- and environmental-efficiency analysis of irrigated cotton-cropping systems in Punjab, Pakistan using data envelopment analysis. **Environmental Management**, v. 54, n. 2, p. 288–300, 2014.

VAN PASSEL S.; MASSETTI, E.; MENDELSON, R. A Ricardian analysis of the impact of climate change on European agriculture. **Environmental Resource Economics** 67(4):725–760, 2017.

VANDERLUGT, B. P. "Climate Change and Idaho Agriculture: Is Farm Size a Determinate of Adaptive Capacity?," **McNair Scholars Research Journal**: Vol. 7 : Iss. 1, Article 16. 2011.

VANSCHOENWINKEL, J.; VAN PASSEL, S. Climate response of rainfed versus irrigated farms: the bias of farm heterogeneity in irrigation. **Climatic Change**. 147: 225, 2018.

VARIAN, H. R. **Microeconomic Analysis**, Third Edition. New York, NY: W. W. Norton & Company, Inc., 1992.

VILLANO, R.; BRAVO-URETA, B. E.; SOLÍS, D.; FLEMING, E. Modern rice Technologies and productivity in the Phillippines: disentangling technology from managerial gaps. **Journal of Agricultural Economics**, v. 66, n.1, p. 129-154, 2015.

VISWANATHAN, P. K.; KUMAR, M. D. **Micro Irrigation Systems in India: Emergence, Status and Impacts**. Springer, 2016.

VRACHIOLI, M.; STEFANO, S.; TZOUVELEKAS, V. Impact Evaluation of New Irrigation Technology in Crete: Correcting for Selectivity Bias. In: **30<sup>th</sup> International Conference of Agricultural Economists**, Vancouver, 2018.

YOUNG, R. A.. **Determining the economic value of water. Concepts and methods**, DC. Resources for the Future, Washington, DC, USA. 356 pp., 2005.

WATTO, M.; MUGERA, A. Wheat farming system performance and irrigation efficiency in Pakistan: a bootstrapped metafrontier approach. **Intl. Trans. in Op. Res.**, 26: 686-706. doi:10.1111/itor.12314, 2019.

WIJETUNGA, C. S. Rice production structures in Sri-Lanka: the normalized translog profit function approach. **Asian Journal of Agriculture and Rural Development**. Vol. 6(2), 21-35, 2016.

WORLD BANK. Impactos e externalidades sociais da irrigação no semi-árido brasileiro. Brasília. Série Água Brasil, v.5. 2004.

ZELLNER, A. An efficient method of estimating seemingly unrelated regressions and tests for aggregation bias. **Journal of the American Statistical Association**, n. 57 p. 348-368, 1962.

\_\_\_\_\_. Estimators for seemingly unrelated regression equations: Some exact finite sample results. **Journal of the American Statistical Association** 58: 977–992. 1963

ZELLNER, A., AND D. S. HUANG.. Further properties of efficient estimators for seemingly unrelated regression equations. **International Economic Review** 3: 300–313. 1962.

ZELLNER, A., AND H. THEIL. Three stage least squares: Simultaneous estimate of simultaneous equations. **Econometrica** 29: 54-78. 1962

ZIOLKOWSKA, J.R. Shadow Price of Water for Irrigation—A Case of the High Plains. **Agricultural Water Management** 153: 20–31. 2015.

ZOUGMORE, R.; MANDO, A.; STROOSNIJDER, L. Benefits of integrated soil fertility and water management in semi-arid West Africa: an example study in Burkina Faso. **Nutrient Cycling in Agroecosystems**, 18, p. 17-27, 2010.

**APPENDIX**

**Table A 1 – Climatic Semi-Elasticities for the Brazilian Regions, 2006.**

	Total Sample ( <i>Pooled</i> )				Irrigators				Rain-fed			
	Temperature		Precipitation		Temperature		Precipitation		Temperature		Precipitation	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
<b>North</b>	0.294 <sup>***</sup> (0.0799)	-0.298 <sup>***</sup> (0.0754)	0.001 <sup>ns</sup> (0.0012)	0.017 <sup>***</sup> (0.0031)	0.224 <sup>*</sup> (0.1369)	-0.334 <sup>***</sup> (0.1198)	-0.0001 <sup>ns</sup> (0.0015)	0.010 <sup>*</sup> (0.0055)	0.384 <sup>***</sup> (0.0879)	-0.291 <sup>***</sup> (0.0621)	0.004 <sup>***</sup> (0.0013)	0.019 <sup>***</sup> (0.0029)
<b>Northeast</b>	-0.079 <sup>*</sup> (0.0463)	0.056 <sup>*</sup> (0.0353)	0.001 <sup>ns</sup> (0.0009)	0.019 <sup>***</sup> (0.0055)	-0.092 <sup>*</sup> (0.0558)	0.036 <sup>ns</sup> (0.0429)	0.0003 <sup>ns</sup> (0.0013)	0.021 <sup>***</sup> (0.0066)	0.011 <sup>ns</sup> (0.0506)	-0.020 <sup>ns</sup> (0.0367)	0.002 <sup>**</sup> (0.0009)	0.026 <sup>***</sup> (0.0051)
<b>Southeast</b>	-0.139 <sup>***</sup> (0.0387)	0.125 <sup>***</sup> (0.0333)	0.002 <sup>***</sup> (0.0006)	0.021 <sup>***</sup> (0.0037)	-0.105 <sup>*</sup> (0.0584)	0.105 <sup>**</sup> (0.0489)	0.003 <sup>***</sup> (0.0008)	0.020 <sup>***</sup> (0.0041)	-0.122 <sup>***</sup> (0.0331)	0.117 <sup>***</sup> (0.0289)	0.002 <sup>***</sup> (0.0004)	0.022 <sup>***</sup> (0.0038)
<b>South</b>	-0.042 <sup>ns</sup> (0.0315)	0.043 <sup>ns</sup> (0.0408)	-0.003 <sup>***</sup> (0.0009)	-0.002 <sup>**</sup> (0.0010)	0.0007 <sup>ns</sup> (0.0376)	-0.016 <sup>ns</sup> (0.0496)	-0.001 <sup>ns</sup> (0.0012)	-0.001 <sup>ns</sup> (0.0015)	-0.082 <sup>**</sup> (0.0352)	0.136 <sup>***</sup> (0.0465)	-0.003 <sup>***</sup> (0.0010)	0.002 <sup>**</sup> (0.0011)
<b>MidWest</b>	0.288 <sup>***</sup> (0.0687)	-0.239 <sup>***</sup> (0.0505)	0.004 <sup>***</sup> (0.0014)	-0.021 <sup>*</sup> (0.0133)	0.227 <sup>**</sup> (0.1133)	-0.173 <sup>*</sup> (0.0930)	0.0028 <sup>ns</sup> (0.0024)	-0.018 <sup>ns</sup> (0.0219)	0.383 <sup>***</sup> (0.0660)	-0.298 <sup>***</sup> (0.0422)	0.005 <sup>***</sup> (0.0013)	-0.009 <sup>ns</sup> (0.0118)

**Source:** Research results

**Note:** \*\*\* p-value<0.01, \*\* p-value<0.05, \* p-value<0.1, ns: Non-significative.

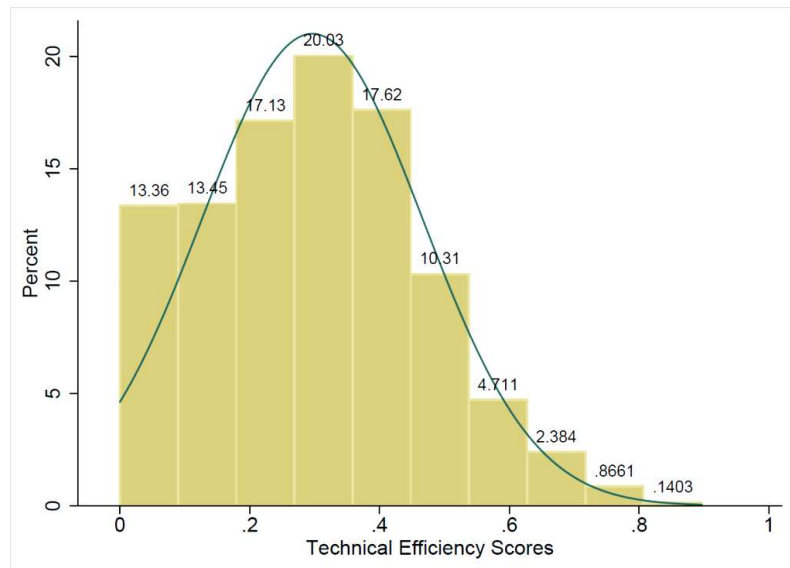
*Sample Selection***Table A 2 – Estimation of the selection equation (Probit) for irrigation adoption, after balancing the sample**

<b>Variable</b>	<b>Marginal Effect (dy/dx)</b>	<b>Standard-Error</b>	<b>Estat. Z</b>	<b>p-value</b>
<i>Gender</i>	0.00206	0.0003690	5.58	0.000
<i>Age</i>	0.00077	0.0000480	15.97	0.000
<i>Age2</i>	-7.43E-06	0.0000005	-16.37	0.000
<i>Read and write</i>	-0.01132	0.0007554	-14.99	0.000
<i>Do not read and write</i>	-0.02243	0.0007223	-31.06	0.000
<i>Literate</i>	-0.01635	0.0008422	-19.41	0.000
<i>Incomplete elementary</i>	-0.00668	0.0006614	-10.1	0.000
<i>Complete Elementary</i>	0.00315	0.0007123	4.43	0.000
<i>Agric. Technician</i>	0.00956	0.0010204	9.37	0.000
<i>High School</i>	0.00586	0.0007204	8.14	0.000
<i>Exp_1</i>	0.00519	0.0007868	6.6	0.000
<i>Exp_1to5</i>	0.00661	0.0003350	19.73	0.000
<i>Exp_5to10</i>	0.00277	0.0003199	8.67	0.000
<i>Private Extension</i>	-0.00856	0.0003608	-23.72	0.000
<i>Governmental Extension</i>	0.01973	0.0003453	57.14	0.000
<i>Co-op Membership</i>	-0.00795	0.0002336	-34.05	0.000
<i>Television</i>	0.00561	0.0002690	20.84	0.000
<i>Telephone</i>	0.01805	0.0002662	67.81	0.000
<i>Internet</i>	0.01820	0.0007853	23.17	0.000
<i>Energy</i>	0.03873	0.0003172	122.12	0.000
<i>Financing</i>	-0.00883	0.0002826	-31.23	0.000
<i>Qualif.</i>	0.01529	0.0004906	31.17	0.000
<i>Urban</i>	-0.00293	0.0003558	-8.25	0.000
<i>Agr. Practice</i>	0.00186	0.0002423	7.67	0.000
<i>Water Resource</i>	0.03337	0.0003220	103.63	0.000
<i>Agrochemicals</i>	0.04416	0.0002558	172.61	0.000
<i>Soil pH</i>	0.02455	0.0003287	74.68	0.000
<i>Fertilizers</i>	0.09043	0.0002928	308.81	0.000
<i>Value of Land</i>	-1.42E-09	0.0000000	-16.66	0.000
<i>Agr. Family</i>	-0.00713	0.0003031	-23.51	0.000
<i>Owner</i>	-0.00319	0.0004382	-7.28	0.000
<i>Tenant</i>	0.00736	0.0006383	11.53	0.000
<i>Partner</i>	-0.00113	0.0007716	-1.46	0.145
<i>Summer precipitation</i>	-0.00024	0.0000031	-78.41	0.000
<i>Winter precipitation</i>	-0.00038	0.0000056	-68.87	0.000
<i>Summer temperature</i>	-0.00560	0.0001974	-28.39	0.000
<i>Winter temperature</i>	0.00473	0.0001185	39.91	0.000
<i>Summer Prec. Stand. Dev.</i>	0.00022	0.0000062	35.91	0.000

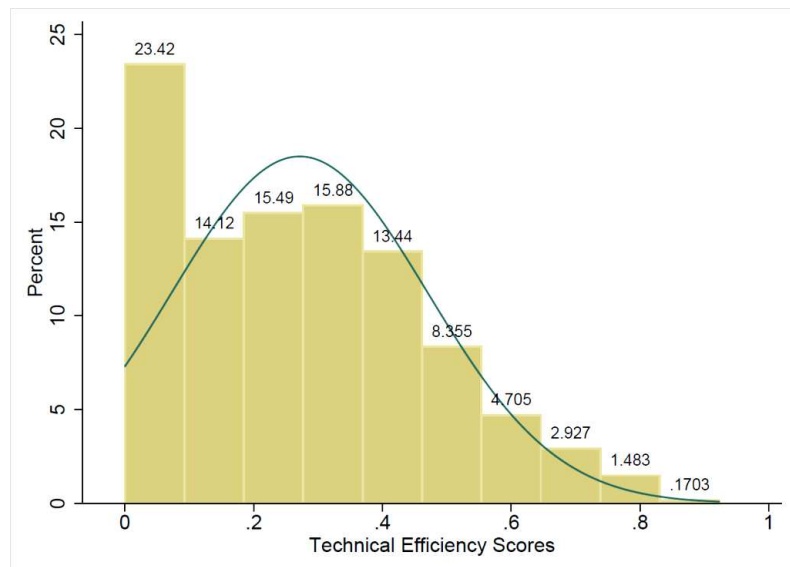
<i>Winter Prec. Stand. Dev.</i>	-0.00045	0.0000101	-43.91	0.000
<i>Summer Temp. Stand. Dev.</i>	0.01652	0.0004981	33.16	0.000
<i>Winter Temp. Stand. Dev.</i>	-0.06200	0.0006704	-92.48	0.000
<i>N° Obs.</i>	4,259,865			
<i>Log Likelihood</i>	-798547.93			
<i>Chi<sup>2</sup></i>	389230.58			0.000
<i>Pseudo R<sup>2</sup></i>	0.196			

**Source:** Research results

**Figure A 1 – Distribution of estimated technical efficiency**



**(a) Irrigators**



**(b) Rain-fed**

Source: Research results

**Figures A 2 - Production (in tons) for selected grains in Brazilian Southeast region, 2006**

Figure A2.a – Coffee

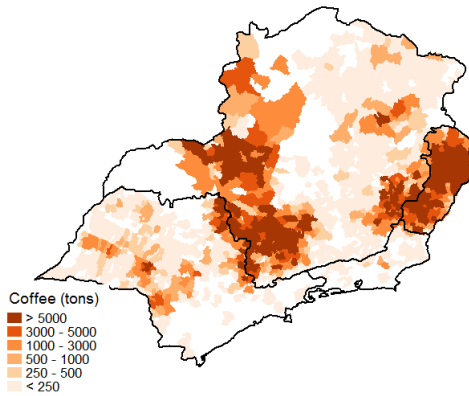


Figure A2.b – Rice

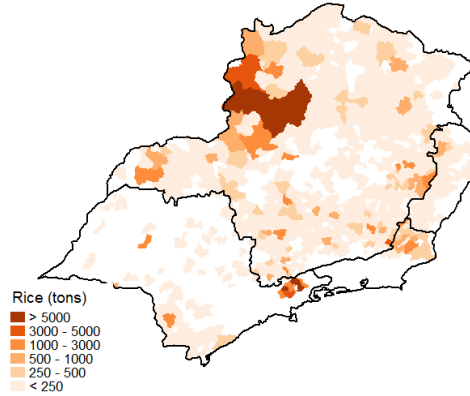


Figure A2.c – Soybeans

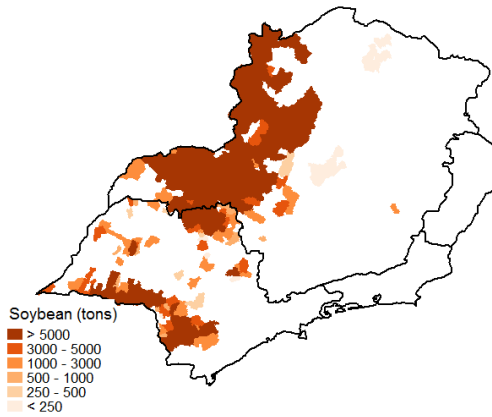


Figure A2.d – Corn

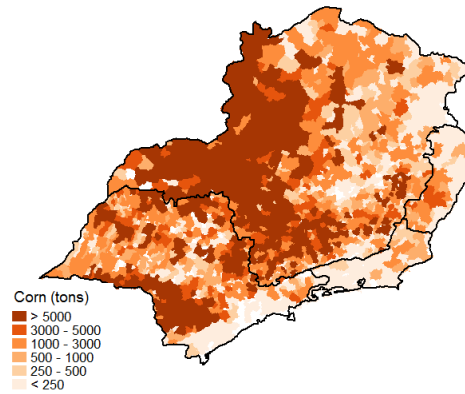


Figure A2.e – Beans

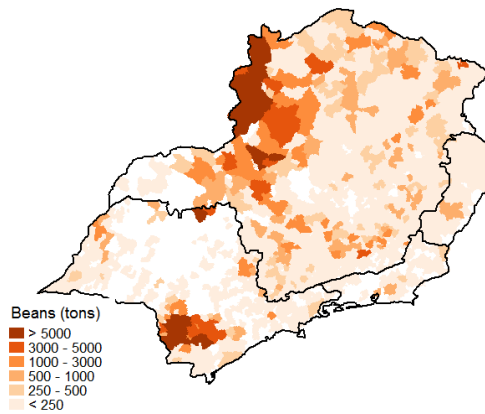


Table A 3 – Grain Supply and Input Demand Equations in Southeast region, Brazil, 2006.

<i>Variables</i>	Output Supply					Input
	Coffee	Rice	Soybean	Corn	Bean	Labor
<i>p1</i>	237.1871*** (12.5214)	-16.3755 <sup>NS</sup> (20.8448)	-183.0001*** (53.6699)	-625.3649*** (60.9206)	-24.8791** (11.1147)	0.0436*** (0.0038)
<i>p2</i>	-16.3755 <sup>NS</sup> (20.8448)	1015.276*** (246.6951)	-2354.449*** (445.1497)	10.1286 <sup>NS</sup> (136.1506)	-49.2114 <sup>NS</sup> (75.5130)	-0.0100 <sup>NS</sup> (0.0106)
<i>p3</i>	-183.0001*** (53.6699)	-2354.449*** (445.1497)	42651.1*** (1574.9760)	-648.7753** (346.3680)	2.4930 <sup>NS</sup> (191.5486)	0.6636*** (0.0272)
<i>p4</i>	-625.3649*** (60.9206)	10.1286 <sup>NS</sup> (136.1506)	-648.7753* (346.3680)	693.7592 <sup>NS</sup> (1703.6650)	-283.861*** (78.9701)	-0.0362 <sup>NS</sup> (0.0236)
<i>p5</i>	-24.8791** (11.1147)	-49.2114 <sup>NS</sup> (75.5130)	2.4930 <sup>NS</sup> (191.5486)	-283.861*** (78.9701)	240.485*** (48.1722)	0.0373*** (0.0056)
<i>p10</i>	0.0436*** (0.0038)	-0.0100 <sup>NS</sup> (0.0106)	0.6636*** (0.0272)	-0.0362 <sup>NS</sup> (0.0236)	0.0373*** (0.0056)	7.95E-06*** (2.42E-06)
<b><i>Fixed Factors</i></b>						
<i>z1</i>	1.96E-04*** (7.53E-05)	8.23E-06 <sup>NS</sup> (1.26E-04)	-1.34E-05 <sup>NS</sup> (3.26E-04)	3.50E-04 <sup>NS</sup> (2.13E-03)	-3.72E-06 <sup>NS</sup> (6.84E-05)	-4.77E-08* (2.85E-08)
<i>z2</i>	62.5505*** (3.8785)	10.4217 <sup>NS</sup> (6.5118)	-15.0855 <sup>NS</sup> (16.8050)	71.0428 <sup>NS</sup> (109.7959)	-4.2893 <sup>NS</sup> (3.5235)	0.0051*** (0.0015)
<i>z3</i>	96.2335*** (7.5063)	5.3961 <sup>NS</sup> (12.5952)	6.3900 <sup>NS</sup> (32.5063)	382.6413** (212.8487)	6.7154 <sup>NS</sup> (6.8152)	-0.0205*** (0.0028)
<i>z4</i>	257.7269*** (53.9493)	200.5731** (90.5277)	31.6815 <sup>NS</sup> (233.6308)	957.1279 <sup>NS</sup> (1529.7210)	174.8044*** (48.9824)	-0.1053*** (0.0204)
<i>z5</i>	83.1049* (51.9388)	88.9441 <sup>NS</sup> (87.1683)	-125.1323 <sup>NS</sup> (224.9632)	-951.2528 <sup>NS</sup> (1472.7460)	-62.6399 <sup>NS</sup> (47.1693)	0.0124 <sup>NS</sup> (0.0197)
<i>a2</i>	11857.93*** (2868.105)	2852.172 <sup>NS</sup> (4812.441)	-25771.08** (12420.08)	-256291.8*** (81327)	11215.19*** (2603.969)	-5.4942*** (1.087)

<i>a3</i>	20313.16*** (4256.805)	-87.2729 <sup>NS</sup> (7143.209)	-418259.9*** (18436.9)	86487.68 <sup>NS</sup> (120702)	40780.96*** (3864.998)	-13.1342*** (1.6133)
<i>a4</i>	163150*** (7407.539)	-117668.1*** (12430.5)	-2316783*** (32083.83)	-287931.5 <sup>NS</sup> (210044.3)	195602.5*** (6725.8)	-42.992*** (2.8074)
<i>a2z1</i>	1.11E-02*** (3.15E-04)	2.05E-04 <sup>NS</sup> (5.29E-04)	4.78E-03*** (1.37E-03)	9.60E-03 <sup>NS</sup> (8.94E-03)	-1.32E-04 <sup>NS</sup> (2.86E-04)	-1.98E-06*** (1.19E-07)
<i>a3z1</i>	2.10E-03*** (1.12E-04)	-3.46E-05 <sup>NS</sup> (1.88E-04)	2.40E-03*** (4.85E-04)	6.53E-03** (3.17E-03)	1.74E-04* (1.02E-04)	-4.37E-07*** (4.24E-08)
<i>a4z1</i>	1.05E-03*** (8.76E-05)	-8.38E-04*** (1.47E-04)	1.40E-02*** (3.80E-04)	1.58E-02*** (2.48E-03)	1.81E-03*** (7.96E-05)	-6.32E-07*** (3.32E-08)
<i>a2z2</i>	63.7137*** (8.4555)	-3.2739 <sup>NS</sup> (14.1883)	8.1967 <sup>NS</sup> (36.6177)	963.7885*** (239.7569)	-21.0420*** (7.6771)	0.0018 <sup>NS</sup> (0.0032)
<i>a3z2</i>	571.2809*** (13.3906)	21.9892 <sup>NS</sup> (22.4701)	706.3508*** (57.9928)	617.1521* (379.6981)	-119.8448*** (12.1581)	-0.0570*** (0.0051)
<i>a4z2</i>	1617.1430*** (26.1705)	124.2051*** (43.9150)	4387.87*** (113.3403)	4111.4860*** (742.0749)	-704.2726*** (23.7615)	-0.1784*** (0.0099)
<i>a2z3</i>	-76.1709*** (8.4825)	-4.3482 <sup>NS</sup> (14.2331)	78.8125** (36.7332)	-122.8964 <sup>NS</sup> (240.5306)	3.2843 <sup>NS</sup> (7.7014)	0.0176*** (0.0032)
<i>a3z3</i>	-57.6595*** (7.7513)	-4.6168 <sup>NS</sup> (13.0062)	277.0977*** (33.5669)	-137.6884 <sup>NS</sup> (219.7967)	8.1930 <sup>NS</sup> (7.0376)	0.0156*** (0.0029)
<i>a4z3</i>	-94.0971*** (7.5213)	-37.3156*** (12.6203)	425.6049*** (32.5709)	-187.3928 <sup>NS</sup> (213.2741)	40.4355*** (6.8287)	0.0195*** (0.0029)
<i>a2z4</i>	174.4308*** (57.2829)	-24.5363 <sup>NS</sup> (96.1224)	86.9426 <sup>NS</sup> (248.0704)	39.7278 <sup>NS</sup> (1624.275)	159.4746*** (52.0097)	0.0565*** (0.0217)
<i>a3z4</i>	68.1900 <sup>NS</sup> (54.5081)	-140.5016 <sup>NS</sup> (91.4651)	935.6539*** (236.0499)	1375.104 <sup>NS</sup> (1545.5750)	167.0578*** (49.4895)	0.0649*** (0.0207)
<i>a4z4</i>	-241.3475*** (53.9857)	481.8641*** (90.5888)	60.2487 <sup>NS</sup> (233.7883)	-487.9634 <sup>NS</sup> (1530.7530)	-24.1616 <sup>NS</sup> (49.0154)	0.0946*** (0.0205)

<i>a2z5</i>	-882.1122*** (97.8245)	-110.7523 <sup>NS</sup> (164.1418)	965.4737** (423.6239)	6517.139** (2773.8820)	-392.2485*** (88.8158)	0.2203*** (0.0371)
<i>a3z5</i>	-3898.966*** (149.0971)	-105.8356 <sup>NS</sup> (250.1999)	13544.29*** (645.7776)	-7264.308* (4227.552)	-1188.227*** (135.3768)	0.8085*** (0.0565)
<i>a4z5</i>	-14958.79*** (279.5599)	5038.0280*** (469.1296)	74213.61*** (1210.839)	-5974.35 <sup>NS</sup> (7926.987)	-5614.854*** (253.8349)	2.5929*** (0.1060)
<i>Minas Gerais</i>	3825.0810*** (154.9543)	754.6797*** (260.2711)	-2614.705*** (671.8567)	-6993.655 <sup>NS</sup> (4392.85)	-484.2076*** (140.8017)	-0.8568*** (0.0587)
<i>Espírito Santo</i>	4433.4440*** (211.6656)	399.0537 <sup>NS</sup> (355.2584)	-3007.007*** (917.0609)	-16632.94*** (5997.26)	-977.2576*** (192.2009)	-1.3904*** (0.0802)
<i>Rio de Janeiro</i>	2302.796*** (411.627)	1555.532** (691.3852)	-5645.326*** (1784.238)	-18200.3 <sup>NS</sup> (11671.77)	-1009.79*** (374.0896)	-0.5027*** (0.1560)
<i>Intercept</i>	-12008.5*** (1543.267)	-3765.191 <sup>NS</sup> (2590.227)	7101.879 <sup>NS</sup> (6684.779)	23234.85 <sup>NS</sup> (43757.29)	2570.99* (1401.629)	-2.6016*** (0.5849)

**Note:** Following the theory, Labor input was estimated with a negative labor quantity as dependent variable. NS: non-significant; \*\*\* significant at 1% level; \*\* significant at 5% level, \* significant at 10% level. Standard-Errors in ( ).

**Table A 4 – Output and input elasticity with respect to non-irrigated land and irrigated land, Southeast, 2006.**

	Coffee	Rice	Soybean	Corn	Bean	Labor
<b><i>Rain-fed</i></b>						
<i>Very Small</i>	0.0703*** (0.0054)	0.0308 <sup>NS</sup> (0.0719)	-0.0008 <sup>NS</sup> (0.0042)	0.6494* (0.3612)	0.0286 <sup>NS</sup> (0.0290)	0.0079*** (0.0011)
<i>Small</i>	0.0151*** (0.0030)	0.0057 <sup>NS</sup> (0.0368)	0.0067*** (0.0013)	0.0313** (0.0137)	0.0330*** (0.0120)	0.0008** (0.0004)
<i>Medium</i>	0.0052*** (0.0002)	0.0012 <sup>NS</sup> (0.0051)	0.0093*** (0.0002)	0.0097*** (0.0022)	0.0326*** (0.0039)	0.0008*** (0.0001)
<i>Large</i>	0.00006*** (0.00001)	-0.0224*** (0.0005)	0.0016*** (7.77e-06)	0.0009*** (0.00006)	0.0288*** (0.0002)	0.0001*** (0.00001)
<b><i>Irrigation</i></b>						
<i>Very Small</i>	0.259*** (0.0542)	0.5107** (0.2305)	0.0054 <sup>NS</sup> (0.0402)	0.4949 <sup>NS</sup> (0.7910)	1.100*** (0.3083)	0.0376*** (0.0073)
<i>Small</i>	0.0949*** (0.0042)	0.2942*** (0.0542)	0.0078 <sup>NS</sup> (0.0055)	0.2949* (0.1620)	0.4958*** (0.0260)	0.0129*** (0.0019)
<i>Medium</i>	0.0382*** (0.0009)	0.0717*** (0.0155)	0.0102*** (0.0003)	0.0502*** (0.0047)	0.4387*** (0.0090)	0.0068*** (0.0004)
<i>Large</i>	0.0005*** (0.00006)	0.1279*** (0.0006)	0.0006*** (0.00005)	0.0024*** (0.0002)	0.0252*** (0.0003)	0.0009*** (0.00006)

**Note:** Parameters are significant at \*\*\*: 1%; \*\*: 5%; NS: Non-Significant; Standard errors in ( ).

**Source:** Research results.

**Figure A 3 – Hydrological Basins, Brazil, 2006.**



Source: Adapted from ANA (2018) and Ferrarini *et al.* (2016)

**Table A 5 – Coefficients of the System of Equations, Brazil, 2006.**

<b>Variables</b>	<b>Coefficients</b>	<b>Standard-Error</b>	<b>p-value</b>
<b>Production Function</b>			
<i>Labor</i>	0.3526	0.05688	0.000
<i>Expenses</i>	1.2763	0.05295	0.000
<i>Capital</i>	0.2790	0.05753	0.000
<i>Irrigation</i>	0.1427	0.00681	0.000
<i>Summer temperature</i>	68.6712	5.96873	0.000
<i>Winter temperature</i>	-7.2994	3.38402	0.031
<i>Summer precipitation</i>	-5.0006	0.56398	0.000
<i>Winter precipitation</i>	-2.2576	0.16038	0.000
<i>Labor</i> <sup>2</sup>	0.0544	0.00048	0.000
<i>Expenses</i> <sup>2</sup>	0.0458	0.00046	0.000
<i>Capital</i> <sup>2</sup>	-0.0820	0.00047	0.000
<i>Irrigation</i> <sup>2</sup>	-0.0005	0.00001	0.000
<i>Labor x Expenses</i>	-0.0827	0.00029	0.000
<i>Labor x Capital</i>	0.0172	0.00040	0.000
<i>Labor x Irrigation</i>	0.0015	0.00006	0.000
<i>Expenses x Capital</i>	0.0036	0.00038	0.000
<i>Expenses x Irrigation</i>	0.0004	0.00004	0.000
<i>Capital x Irrigation</i>	-0.0011	0.00005	0.000
<i>Summer.temp</i> <sup>2</sup>	-67.1987	3.37108	0.000
<i>Winter.temp</i> <sup>2</sup>	-42.7363	1.53501	0.000
<i>Summer.prec</i> <sup>2</sup>	0.4589	0.02556	0.000
<i>Winter.prec</i> <sup>2</sup>	-0.0232	0.00148	0.000
<i>Summer.temp x Winter.temp</i>	44.9933	2.12989	0.000
<i>Summer.temp x Summer.prec</i>	0.7357	0.26196	0.005
<i>Summer.temp x Winter.prec</i>	2.0261	0.08467	0.000
<i>Winter.temp x Summer.prec</i>	-0.0258	0.15523	0.868
<i>Winter.temp x Winter.prec</i>	-1.6171	0.04716	0.000
<i>Summer.prec x Winter.prec</i>	0.1462	0.00401	0.000
<i>Labor x Summer.temp</i>	-0.4112	0.02372	0.000
<i>Expenses x Summer.temp</i>	0.3060	0.02234	0.000
<i>Capital x Summer.temp</i>	0.0345	0.02412	0.152
<i>Irrigation x Summer.temp</i>	-0.0427	0.00300	0.000
<i>Labor x Winter.temp</i>	0.3413	0.00887	0.000
<i>Expenses x Winter.temp</i>	-0.7064	0.00849	0.000
<i>Capital x Winter.temp</i>	0.1545	0.00879	0.000
<i>Irrigation x Winter.temp</i>	0.0087	0.00131	0.000
<i>Labor x Summer.prec</i>	0.0680	0.00129	0.000
<i>Expenses x Summer.prec</i>	0.0297	0.00109	0.000
<i>Capital x Summer.prec</i>	-0.0072	0.00130	0.000
<i>Irrigation x Summer.prec</i>	0.0011	0.00017	0.000

<i>Labor x Winter.prec</i>	0.0165	0.00056	0.000
<i>Expenses x Winter.prec</i>	-0.0142	0.00048	0.000
<i>Capital x Winter.prec</i>	-0.0023	0.00054	0.000
<i>Irrigation x Winter.prec</i>	0.0009	0.00007	0.000
<i>Summer.temp x North</i>	5.9873	0.49457	0.000
<i>Winter.temp x North</i>	-5.7296	0.35754	0.000
<i>Summer.prec x North</i>	0.5835	0.07484	0.000
<i>Winter.prec x North</i>	0.5206	0.01729	0.000
<i>Summer.temp x Northeast</i>	0.7176	0.41589	0.084
<i>Winter.temp x Northeast</i>	0.2511	0.27605	0.363
<i>Summer.prec x Northeast</i>	0.3185	0.07297	0.000
<i>Winter.prec x Northeast</i>	0.2261	0.01643	0.000
<i>Summer.temp x Southeast</i>	-4.1845	0.40115	0.000
<i>Winter.temp x Southeast</i>	0.3836	0.29307	0.191
<i>Summer.prec x Southeast</i>	-0.5442	0.07237	0.000
<i>Winter.prec x Southeast</i>	0.1101	0.01755	0.000
<i>Summer.temp x South</i>	7.1760	0.59968	0.000
<i>Winter.temp x South</i>	-9.1493	0.45796	0.000
<i>Summer.prec x South</i>	0.1734	0.08301	0.037
<i>Winter.prec x South</i>	0.3087	0.02982	0.000
<i>Uf-1</i>	-5.8988	1.18876	0.000
<i>Uf-2</i>	-5.6324	1.18812	0.000
<i>Uf-3</i>	-4.9688	1.19064	0.000
<i>Uf-4</i>	-6.5636	1.18508	0.000
<i>Uf-5</i>	-5.0095	1.19018	0.000
<i>Uf-6</i>	-5.4320	1.18796	0.000
<i>Uf-7</i>	-4.9700	1.19524	0.000
<i>Uf-8</i>	-4.4826	0.99729	0.000
<i>Uf-9</i>	-4.6643	0.99789	0.000
<i>Uf-10</i>	-4.5957	0.99691	0.000
<i>Uf-11</i>	-5.0861	0.99702	0.000
<i>Uf-12</i>	-5.1630	0.99684	0.000
<i>Uf-13</i>	-5.1978	0.99696	0.000
<i>Uf-14</i>	-5.2255	0.99633	0.000
<i>Uf-15</i>	-5.7101	0.99649	0.000
<i>Uf-16</i>	-5.5553	0.99600	0.000
<i>Uf-17</i>	14.6946	0.90964	0.000
<i>Uf-18</i>	14.7740	0.90989	0.000
<i>Uf-19</i>	14.2994	0.90992	0.000
<i>Uf-20</i>	14.0601	0.91026	0.000
<i>Uf-21</i>	1.3721	1.14532	0.231
<i>Uf-22</i>	1.2859	1.14519	0.262
<i>Uf-23</i>	1.3562	1.14454	0.236
<i>Uf-24</i>	-0.5160	0.04866	0.000

<i>Uf-25</i>	-0.5581	0.04579	0.000
<i>Uf-26</i>	-0.4831	0.04329	0.000
<i>Constant</i>	-85.6457	6.57541	0.000

---

***Share Equations***


---

<b><i>Labor</i></b>	<b>Coefficients</b>	<b>Standard-Error</b>	<b>p-value</b>
<i>Labor</i>	0.0544	0.00048	0.000
<i>Expenses</i>	-0.0827	0.00029	0.000
<i>Capital</i>	0.0172	0.00040	0.000
<i>Irrigation</i>	0.0015	0.00006	0.000
<i>Summer temperature</i>	-0.4112	0.02372	0.000
<i>Winter temperature</i>	0.3413	0.00887	0.000
<i>Summer precipitation</i>	0.0680	0.00129	0.000
<i>Winter precipitation</i>	0.0165	0.00056	0.000
<i>Constant</i>	0.3526	0.05688	0.000

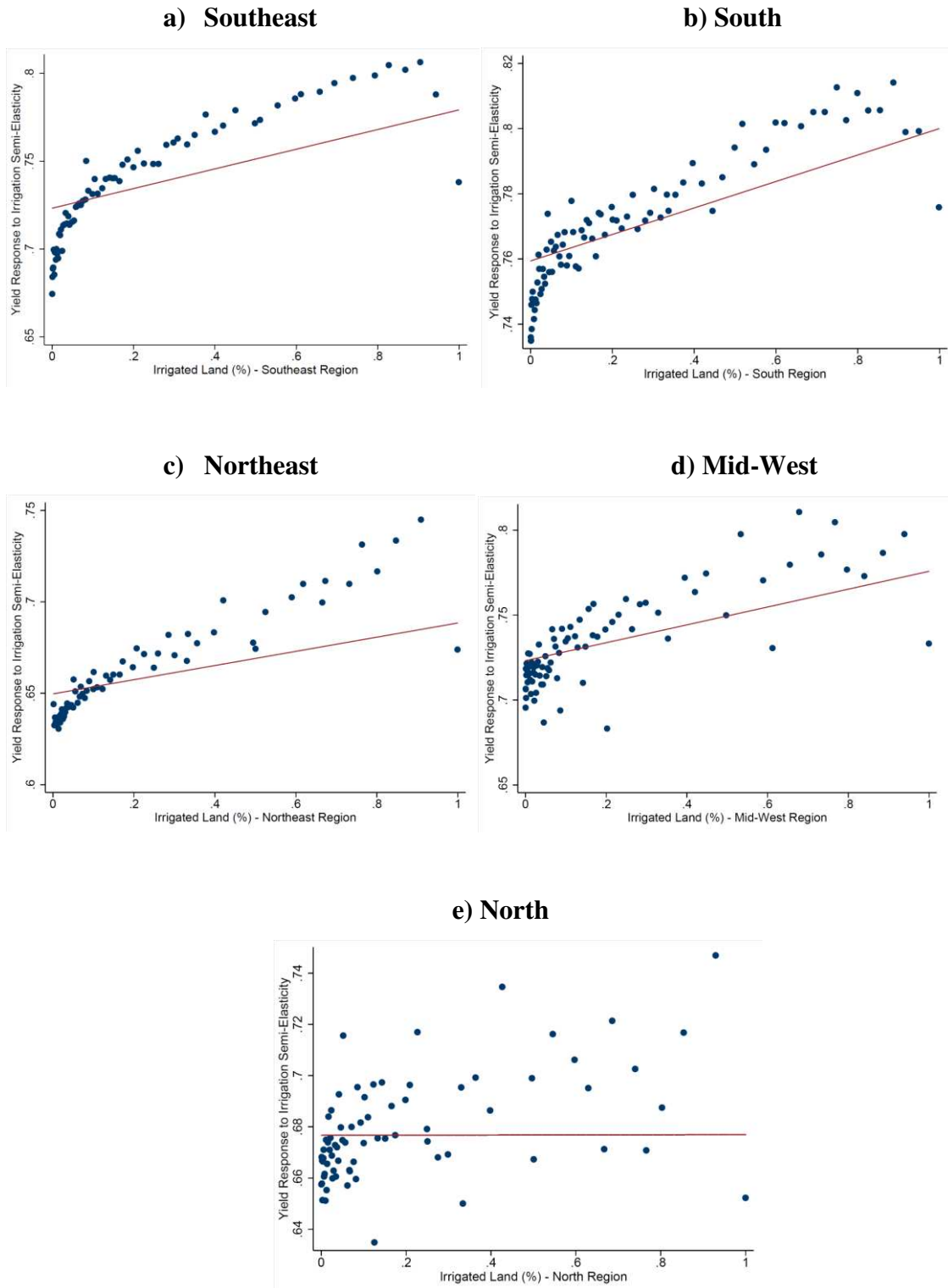
<b><i>Expenses</i></b>	<b>Coefficients</b>	<b>Standard-Error</b>	<b>p-value</b>
<i>Labor</i>	-0.0827	0.00029	0.000
<i>Expenses</i>	0.0458	0.00046	0.000
<i>Capital</i>	0.0036	0.00038	0.000
<i>Irrigation</i>	0.0004	0.00004	0.000
<i>Summer temperature</i>	0.3060	0.02234	0.000
<i>Winter temperature</i>	-0.7064	0.00849	0.000
<i>Summer precipitation</i>	0.0297	0.00109	0.000
<i>Winter precipitation</i>	-0.0142	0.00048	0.000
<i>Constant</i>	1.2763	0.05295	0.000

<b><i>Irrigated Land</i></b>	<b>Coefficients</b>	<b>Standard-Error</b>	<b>p-value</b>
<i>Labor</i>	0.0015	0.00006	0.000
<i>Expenses</i>	0.0004	0.00004	0.000
<i>Capital</i>	-0.0011	0.00005	0.000
<i>Irrigation</i>	-0.0005	0.00001	0.000
<i>Summer temperature</i>	-0.0427	0.00300	0.000
<i>Winter temperature</i>	0.0087	0.00131	0.000
<i>Summer precipitation</i>	0.0011	0.00017	0.000
<i>Winter precipitation</i>	0.0009	0.00007	0.000
<i>Constant</i>	0.1427	0.00681	0.000

<b>Equation</b>	<b>Obs.</b>	<b>Parms</b>	<b>RMSE</b>	<b>R-sq</b>	<b>Chi2</b>	<b>p-value</b>
<i>Production</i>	4259866	86	2.097199	0.39690	2.81E+06	0.0000
<i>Labor</i>	4259866	8	866.9707	0.00000	118533.7	0.0000
<i>Expenses</i>	4259866	8	8484.132	0.00000	190211.4	0.0000
<i>Irrigation</i>	4259866	8	406.5759	0.00000	5910.26	0.0000

**Source:** Research results.

Figures A 4 – Binned Scatterplot, Semi-elasticity of irrigation by region, Brazil, 2006.



Source: Research results.