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By:  
Karelys Guzman-Finol  
Sandy Dall'erba  
Angela C. Lyons  
Jorge Eiras-Barca

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Karelys Guzman-Finol  
[kguzmafi@banrep.gov.co](mailto:kguzmafi@banrep.gov.co)  
Banco de la República

Sandy Dall'erba  
[dallerba@illinois.edu](mailto:dallerba@illinois.edu)  
University of Illinois at Urbana-Champaign

Angela C. Lyons  
[anglyons@illinois.edu](mailto:anglyons@illinois.edu)  
University of Illinois at Urbana-Champaign

Jorge Eiras-Barca  
[jeiras@tud.uvigo.es](mailto:jeiras@tud.uvigo.es)  
Defense University Center at the Spanish Naval  
Academy

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## Abstract

We estimate the effects of annual temperature and precipitation on rice yields in Colombia from 1987 to 2016. The analysis explores the degree of variation in response to climate changes across the country's diverse topography. Since there are two growing seasons in Colombia, the effects of the weather conditions for these two seasons are independently investigated. Additionally, rice yields are projected for two periods (2046-2065 and 2081-2100) based on the RCP 4.5, 6.5, and 8.0 of future climate scenarios. We found a positive effect of rainfall and temperature on yields, although one variable attenuates the effect of the other. The early season temperature and the later season precipitation were the main drivers of the yield. Effects were larger in departments with higher altitudes. Projections show that temperature and precipitation changes will cause rice yields to increase by 10% over 2046-2065, and 2081-2100, with respect to the reference period 1987-2016.

*Keywords:* rice yields, irrigation, rainfed, temperature, precipitation, climate change

*JEL classification:* R11, Q15, Q18

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# Efecto de la variabilidad climática en el rendimiento del arroz en Colombia

Karelys Guzman-Finol  
[kguzmafi@banrep.gov.co](mailto:kguzmafi@banrep.gov.co)  
Banco de la República

Sandy Dall'erba  
[dallerba@illinois.edu](mailto:dallerba@illinois.edu)  
University of Illinois at Urbana-Champaign

Angela C. Lyons  
[anglyons@illinois.edu](mailto:anglyons@illinois.edu)  
University of Illinois at Urbana-Champaign

Jorge Eiras-Barca  
[jeiras@tud.uvigo.es](mailto:jeiras@tud.uvigo.es)  
Defense University Center at the Spanish Naval  
Academy

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## Resumen

En este documento estimamos los efectos de la temperatura y la precipitación en el rendimiento del arroz en Colombia, utilizando datos anuales a nivel departamental entre 1987 y 2016. El análisis explora como estos efectos varían de acuerdo a la altitud media del departamento y al periodo en el que se miden las variables. Adicionalmente, realizamos proyecciones del rendimiento del arroz para los periodos 2046-2065 y 2081-2100, con base en los escenarios RCP 4.5, 6.5, y 8.0 de cambio climático. Encontramos que la temperatura y la precipitación tienen un efecto positivo en el rendimiento del arroz, aunque cada variable atenúa el efecto de la otra. La temperatura del primer semestre y la precipitación del segundo semestre fueron los principales impulsores del rendimiento anual. Los efectos fueron más considerables en los departamentos con mayor altitud promedio. Las proyecciones muestran que (todo lo demás constante) los cambios en la temperatura y la precipitación harán que el rendimiento aumente en un 10% en los periodos 2046-2065 y 2081-2100, con respecto al periodo de referencia (1987-2016).

*Palabras Clave:* arroz, rendimiento, secano, temperatura, precipitación, cambio climático

*Clasificación JEL:* R11, Q15, Q18

## 1 Introduction

Current and future food security worldwide is deeply connected to the supply side, specifically the country's agricultural productivity. Crop yields are one of the preferred measures used to determine productivity within the agricultural sector. Because there is limited land available for food production, current agricultural policies focus on how higher yields can be achieved to obtain higher production amounts with the least amount of land possible. Therefore, crop yields are critical to allowing a country to sustain adequate food security levels in the short and long run.

Rice is the number one staple food for the world's poorest and undernourished people. The grain makes up 20 percent of the world's dietary energy supply—more than wheat (19 percent) and maize (5 percent) (FINAGRO, 2014; Rebolledo et al., 2018). Therefore, rice production is critical to global food security. However, the world's annual rough rice production will have to increase markedly over the next 30 years to keep up with population growth (Lomax, 2017; Seck et al., 2012). To achieve this, the sector should work on varietal development, improved rice production methods, and coping with climate change (Seck et al., 2012). The downside of rice production is that it is a significant user of land and water (Lomax, 2017), and this could be a source of concern for two reasons (Seck et al., 2012). First, the arable land in the world is becoming scarcer and more degraded. Second, the average water availability per person in big rice producers like China and India is lower than in other countries (Water Scarcity Clock, 2023).

Colombia is a South American country where rice is an economically and socially important commodity, and it has a privileged position in terms of land and water availability. According to the Food and Agriculture Organization of the United Nations -FAO- (2002), approximately half of the land that could go into agricultural production is located in seven tropical countries, including Colombia<sup>1</sup>. Also, the average water availability per person in Colombia by 2020 was greater than 1,700 m<sup>3</sup>, while in China and India, this one was less than 500 m<sup>3</sup> (Water Scarcity Clock, 2023). Colombia is one of the most important rice producers in South America. In 2021, its production was 3.3 million tons, only below Peru (3.5) and Brazil (11.6). In terms of rice yield, Colombia is farther below in the South American ranking. In 2021, its average yield was 6.11 tons/ha, while in Uruguay and Peru, on top of that list were 9.40 tons/ha and 8.32 tons/ha, respectively (FAO, 2002), which shows that the Colombian rice sector has the potential to keep growing and improve its productivity.

Rice is the food most consumed in Colombia by individuals between 2 and 64 years of age (ICBF, 2006). On the supply side, around 500,000 families make a living in the rice sector (Portafolio, 2019). In 2018, the rice sector comprised 9.4% of the national cultivated area. During the same year, its value chain generated 2.7% of the direct jobs in rural areas and 5.1% of the indirect ones (DANE, 2017a; Portafolio, 2018). Rice is

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<sup>1</sup> The others are Angola, Argentina, Bolivia, Brazil, Democratic Republic of Congo and the Sudan.

considered one of the 15 fundamental products for the development of the agricultural sector in Colombia due to its contribution to food security, rural employment, and domestic trade (FINAGRO, 2014).

Yet, Colombia faces several challenges when it comes to rice production. First, the production of rice is mainly intended for domestic consumption. Colombia does not export rice regularly. Between 2019 and 2021, the average rice production in Colombia was 3.2 million tons, of which 69% was allocated for domestic consumption. Imports of paddy and white rice were 11% of the national production (FEDEARROZ, 2023) and came mainly from the United States and Peru. Since Colombia meets its demand for rice mainly from domestic production, consumer welfare is highly susceptible to changes in price. A 20% increase in the price of rice implies that the indigence rate increases from 10.4% to 10.8% and the poverty rate increases from 32.7% to 33.6% nationwide (Fedesarrollo & ANDI, 2013). The effect is especially marked in rural areas where a 20% increase in the price of rice increases the incidence of indigence from 22.7% to 23.5% and the incidence of poverty from 46.9% to 47.9% (Fedesarrollo & ANDI, 2013). Rice consumption is higher in the rural areas than in the urban areas.

Second, the demographic composition of rice producers in Colombia raises additional concerns. The latest figures show that 49% of producers are over 50 years of age and only 11% have a university education (DANE, 2016a). These socio-demographic trends suggest that Colombia could face challenges with its ability to produce rice in the short and long run and even sustain current production levels. The seriousness of the situation is magnified by the fact that producers' low earnings continue to augment inequalities between urban and rural populations, especially when it comes to producers' ability to create sustainable livelihoods for themselves and their families. In the future, Colombia is likely to see further reductions in the number of rice producers, as more of the younger generation is likely to leave the rural areas to complete a college degree and pursue careers with better income prospects.

Lastly, national aggregate figures suggest that Colombia is already experiencing stagnation in the rice sector. Between 2000 and 2016, the area planted increased by an average of 2% annually, while the yields remained almost constant at an average of 6 tons per hectare per year (DANE, 2016b). In fact, in 2014 Colombia ranked only 11 out of the 23 Latin American and Caribbean countries when it came to rice yields (Rebolledo et al., 2018). Since the initiation of the free trade agreement in 2012, farmers, industry leaders, and academics have argued that the sector lacks greater productivity and is not prepared to compete internationally, especially with the United States (Chica, Tirado, & Barreto, 2016; MINAGRICULTURA; 2018; Portafolio, 2019).

The productivity of a crop depends on its fertilization and nutrition. The climate (temperature, solar radiation, precipitation, and humidity) affects the absorption and availability of nutrients. According to the National Federation of Rice Farmers (referred to in Spanish as FEDEARROZ), temperature influences the growth rate of rice from germination to 3-5 weeks thereafter (FEDEARROZ, 2015). If the temperature

increases, the rate of growth will increase. Beyond 3-5 weeks, the temperature has little effect on growth. During the reproductive phase, the ideal temperature range is between 21 and 35 °C. Near and during the flowering period, temperatures below 20 °C or above 35 °C make the plant sterile. The plant's requirements for nutrients increase with temperature.

Water availability is crucial for growing rice. While most crops require 2,000 to 7,000 m<sup>3</sup> of water per hectare, rice cropping needs up to 22,000 m<sup>3</sup> when it is cultivated using irrigation (DNP, n.d). There are two rice production systems in Colombia: rainfed and irrigated. The rainfed system depends on the occurrence, intensity, and frequency of precipitation. For the irrigated system, the source of water is the irrigation districts, but the distribution of the precipitation throughout the year is still a key factor. While the initial stages of the growing season should coincide with the period when there are the highest levels of precipitation, the harvest season should coincide with the dryer conditions (DNP, n.d).

In this study, we focus on the effect of temperature and precipitation variations on rice yields. Specifically, we assess the role of weather conditions on rice yields in Colombia between 1987-2016. The yields summarize how well farmers perform during a determined period. We build a panel over a sample of departments that produce 99% of the nation's paddy rice using data that were collected between 1987 and 2016. In addition to running the estimates for the overall sample, we explore how the sensitivity of the yields to the climatic variables varies across highland and lowland departments (heterogeneity in space), and how the results change if the weather is measured over the growing seasons instead of the entire year (time heterogeneity). Finally, we forecast rice yields for two periods (2046-2065 and 2081-2100) based on future temperature and precipitation estimated using RCP 4.5, 6.5, and 8.0 climate scenarios<sup>2</sup>.

This paper contributes in three key ways to the growing literature that investigates the impacts of weather and climate change on crop production in developing countries. First, our paper uses a finer spatial scale and a larger sample than previous studies on rice production in Colombia. Previous studies such as Cortés and Alarcón (2016) focused on Cundinamarca only (a department located in Colombia's main rice-growing region), while BID, CEPAL, and DNP (2014) focused on four departments that represented only 7.7% of the total planted area in the country. We provide estimates for twenty departments. Second, our study provides new and stronger evidence of the relationship between weather and rice yields, as we estimate both the magnitudes of the temperature and precipitation effects on rice yields. Our projections for future rice yields are the third major contribution of this paper. We project rice yields in each of the producing regions in Colombia for the rest of the 21st century. While previous work on Colombia has used the Special Report on

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<sup>2</sup> RCP is the acronym for Representative Concentration Pathway which is used to describe a set of scenarios used to predict how future global warming will contribute to climate change. These are based on key variables such as future greenhouse gas emissions, developments in technology, changes in energy generation and land use, global and regional economic circumstances, and population growth (Vuuren et al., 2011; IDEAM et al., 2015).

Emissions Scenarios (SRES) to examine various climate change scenarios, we use the more updated version of these scenarios, the Representative Concentration Pathways (RCP).

In the past, extreme events in Colombia have affected the production of rice, causing economic losses for farmers. For instance, in 2010-2011, *La Niña* brought heavy rains, floods, and landslides (Arias, Martínez, & Vieira, 2015), resulting in the GDP growth rate falling by 0.2 percentage points. Agriculture has been the most impacted economic sector. According to CEPAL (2012), losses incurred by rice farmers in 2010-2011 represented 38% of the gross value of production lost among all temporary crops. In the second half of 2014, some regions of the country lost 35% of the rice that had been planted due to *El Niño*, which significantly decreased rainfall over the region (DANE, 2015). Floods and droughts were the cause of 44% of losses in planted areas in 2016 (DANE, 2016a). Between 2016 and 2017, planted areas that were lost due to flooding increased by 209% (DANE 2018b). Therefore, anomalous weather events have increasingly been affecting rice production in Colombia.

As this study will show, temperature and precipitation have had a positive effect on rice yields for the period 1987-2016. When the effects for each growing season are examined separately, temperature is found to have a larger impact on yields in the early season, while precipitation has a larger impact in the later season. In terms of spatial heterogeneity, significant differences are observed between departments with higher and lower altitudes. Finally, projections using various climate change scenarios reveal that rice yields are likely to increase in 15 out of the 20 producing regions in 2046-2065 and 2081-2100. On average, we anticipate that rice yields will increase by 10% compared to yields for the period 1987-2016.

The remainder of this paper proceeds as follows. The next section provides a review of the literature focusing on the sensitivity of rice yields to weather conditions. After describing the data and methodology used to assess the impact of weather on yield variations, we present the estimation results. We then predict future rice yields based on projections of temperature and precipitation in Colombia. Some concluding remarks and future research directions are provided in the last section.

## **2 Literature Review**

The use of panel data to measure the relationship between weather and economic outputs is increasingly common in the literature (Deschenes & Greenstone, 2011; Dell, Jones, & Olken, 2014; Dall'erba, Chen & Nava, 2021). Previous research has used year-to-year variation in the climatic variables to identify their economic impacts on agricultural productivity. These studies provide evidence of unanticipated weather events (e.g., weather shocks) rather than climate changes, which correspond to the expected average weather conditions (Blanc & Reilly, 2017). When the farmers decide how much and when to plant, they rely on their expectations about the weather. The panel approach identifies the net effect of weather shocks on the outcome of interest (Dell et al., 2014), which makes it a more suitable approach to answering our research question.

There is consensus within the literature about which climatic variables should be used to estimate the impact of climate change on rice yields. Temperature (minimum, maximum, mean), precipitation, and solar radiation are the most commonly used variables (Yao, Xu, Lin, Yokozawa, & Zhang, 2007; Zhang, Zhu, & Wassmann, 2010; Liu et al., 2016). Other authors have also considered relative humidity (Zhou, Li, Dong, & Wenxiang, 2013) and wind speed (Yu, Zhang, & Huang, 2014). The relevance of each variable can vary across regions and periods under study. For example, in northeast China, the growing season's minimum temperature was found to be the main driver of rice yields (Zhou et al., 2013). However, in southern China, Liu et al. (2016) concluded that rice yields depend positively on temperature and negatively on solar radiation and precipitation. In Colombia, Banco Interamericano de Desarrollo et al. (2014) and Ramírez-Villegas et al. (2012) included only temperature and precipitation. In some cases, the effects of climatic variables on yields can change across the crop's development. For example, Delerce et al. (2016) found that one of the varieties of crops analyzed in some Colombian municipalities was positively affected by nighttime temperatures in the reproductive stage and accumulated solar radiation during the ripening stage.

While crop yields are affected by climatic variables, they also can be affected by non-climatic variables. The effects of non-climatic factors on rice yields have been captured in various ways. Zhou et al. (2013) found that average yield changes were significantly impacted by climatic variables, as well as crop management, use of fertilizers, increases in CO<sub>2</sub>, improvements in technology, and other non-climatic factors. Liu et al. (2016) included a time trend in their regression models to capture the impacts of non-climatic factors and found that time trends significantly affected crop yields. The magnitude of non-climatic effects can also vary. In northeast China, approximately 92.8% of the increase in rice yields was ascribed to non-climatic factors (Zhou et al., 2013); while in southern China, non-climatic factors accounted for approximately 60% and 70% of the variability for early and late rice yields, respectively (Liu et al., 2016). For the cultivars analyzed by Delerce et al. (2016) in Colombia, the climatic factors explained 54% to 94% of the spatio-temporal variability in yields.

Among all the non-climatic factors, the price of rice is often assumed to be endogenous, and therefore it has been disregarded in the analysis of crop yields. Prices have also not been included as part of the control variables when evaluating the weather effects on rice yields in the international literature (Yao, Xu, Lin, Yokozawa, & Zhang, 2007; Zhang et al., 2010; Zhou et al., 2013; Yu et al., 2014; Liu et al., 2016) and in the Colombian literature (Delerce et al., 2016). Moreover, researchers such as Berry and Schlenker (2011) have found that net yield-price elasticities for U.S. crops are close to zero<sup>3</sup>. As it is suggested in the previous literature, we do not include the price of rice as a control variable in our estimations.

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<sup>3</sup> The authors estimated net yield-price elasticities which combine two effects. First, when a crop price increases, there is a more intensive use of existing land (positive effect on yields). Second, if the new land called into production is less productive than previous land, this has been found to have a negative effect on yields (Berry & Schlenker, 2011).

### 3 Data and Descriptive Analysis

Geographically, Colombia is divided into 32 departments. Data on the total number of hectares of rice harvested, the total amount of rice produced, and rice yields are collected at the department level from the *Information and Communication Network of the Colombian Agricultural Sector* (AGRONET, 2017). The data have been collected annually since 1987. Our sample tracks 20 rice-producing departments from 1987 to 2016 (the period under analysis). For this study, we measure rice yields by the total tons of rice produced per harvested hectare as follows:

$$Y_{it} = \frac{[(Y_{irrigation_{it}} * Hectares_{irrigation_{it}}) + (Y_{rainfed_{it}} * Hectares_{rainfed_{it}})]}{Total\ Hectares_{it}} \quad (1)$$

Data for monthly mean temperature and precipitation are reported by the weather stations from the *Institute of Hydrology, Meteorology and Environmental Studies*, also known by its Spanish acronym, IDEAM, which is a government agency of the *Ministry of Environment and Sustainable Development in Colombia*<sup>4</sup>. The station-level data for temperature and precipitation are averaged across departments to match with the geographical unit for the rice data. Temperatures are reported in terms of Celsius. Precipitation is reported as cumulative rainfall in meters per year. Delerce et al. (2016) also examine the relationship between weather and rice yields for some cultivars in Colombia using cumulative rainfall during the year instead of mean rainfall. We also construct annual measures for temperature and precipitation since information on rice yields is only available annually for Colombia.

There are two rice production seasons in Colombia. The first one spans the first six months of the year while the second spans the rest of the year (FEDEARROZ, 2017). Most rice production traditionally occurs in the first half of the year. In 2016, 68.8% of the annual planted area, and 25.8% of the annual production was carried out in the first half of the year (FEDEARROZ, 2017). In the second half of the year, these percentages were reversed, since a good part of the cultivated area in the first six months was harvested in the late season. The share of rice planted in the second half of the year was 31.2%, which comprised 74.2% of annual production (FEDEARROZ, 2017). Because rice is grown all year long in Colombia, our main analysis is conducted at the annual level rather than seasonally. Other researchers have used growing-degree-days to capture weather variability in countries such as the U.S. (e.g., Schlenker & Roberts, 2009). However, Colombia does not experience significant variations in temperature and precipitation throughout the year. It is located near the equator and so it only has two seasons: dry and rainy (Bohorquez-Penuela & Otero-Cortes, 2020).

To estimate periods of anomalous weather, dummy variables are constructed to indicate if precipitation and temperature were above the upper 90<sup>th</sup> percentile or below the lower 10<sup>th</sup> percentile of the entire distribution

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<sup>4</sup> Note that the dataset is not available publicly. It was requested by the authors and is available to other researchers upon request.

for each department. A similar approach was used by Dall'erba and Domínguez (2016) to determine the impacts of extreme rainfall and temperature events on farmland values in the Southwestern United States.

Additionally, a set of indicators is used to capture key macroeconomic characteristics for each department. We include Gross Domestic Product (GDP) per capita, obtained from the *National Administrative Department of Statistics of Colombia* (DANE, 2018a, 2018c), and geographic characteristics on altitude and surrounding area for each department, taken from the municipal panel catalog of the University of the Andes Foundation (UNIANDES, 2018). Altitude is recorded in meters above sea level (m.a.s.l.). Finally, we also include population density (population per km<sup>2</sup>).

Table 1 reports the department-level summary statistics for the key variables included in our analysis. The mean temperature in the departments that produce rice in Colombia was 24.83°C between 1987 and 2016, while the average precipitation was two meters per year. On average, more than 21 thousand hectares of rice were harvested per year in Colombia, which resulted in 110,991 tons of rice being produced. The average rice yield was 4.90 tons per hectare per year.

**Table 1 Department-level summary statistics for the Colombian rice sector**

Variables	Mean	Std. Dev.	Min	Max
Temperature (°C), T	24.83	3.22	15.81	29.59
Precipitation (m/year), P	2.12	1.00	0.49	6.17
Area harvested (hectares)	21,181	28,194	50	132,000
Production (tons)	110,991	163,864	170	838,220
Yield (tons per hectare)	4.90	0.98	2.29	7.70
Number of departments	20			

Decisions on how much rice to plant, where to plant, and when to plant are highly dependent on the availability of water. Between 1987 and 2016, irrigated and rainfed agricultural systems were the systems most commonly used to produce rice in Colombia. With the rainfed system, farmers rely on rainfall for water, whereas with the irrigated system, farmers apply water from other sources such as freshwater from streams, rivers and lakes, or groundwater. The irrigated system is the predominant method used but requires more investment in the construction of water resource management systems. The rainfed system requires less investment but can only be used in regions that experience an unimodal pattern of rainfall (DANE, 2017b).

FEDEARROZ (2017) classifies the departments in Colombia into five regions based on their agronomic and economic characteristics. These regions are referred to as *Central*, *Llanos*, *Bajo Cauca*, *Santanderes*, and *Costa Norte* (see Appendix 1). Table 2 presents the summary statistics for our key variables and highlights some of the differences across these five regions. In Centro, Santanderes, and Costa Norte, more than 80% of the planted hectares rely on irrigation, whereas in the regions of Cauca and Llanos, the rainfed system is predominant. On average, these two regions are responsible for 95% of the total hectares cultivated with the

rainfed system in the country. The yields produced by the irrigated system are higher than those produced by the rainfed system in every region.

**Table 2 Regional-level summary statistics on the Colombian rice sector**

Variables (average per year)	Centro	Llanos	Bajo Cauca	Santanderes	Costa Norte
Area harvested (hectares)	23,382	42,098	13,999	14,678	9,318
Percentage of hectares cultivated with irrigation	0.84	0.28	0.13	0.87	0.99
Yield from irrigated system (tons per hectare)	6.31	4.93	4.96	5.31	4.89
Yield rainfed system (tons per hectare)	4.78	4.62	3.91	2.40	2.95
Production (tons)	148,887	200,411	56,739	75,999	44,149
T (Celsius)	21.82	26.06	26.36	21.74	27.91
P (m/year)	2.28	3.00	2.05	1.80	1.32
Altitude (masl)	1,041	299	415	1,369	63
Number of departments	6	4	4	2	4

Figure 1 shows how the total hectares of rice planted, the total amount of rice produced, and the amount of rice produced per hectare have changed over time via both the rainfed and irrigated agricultural systems. Although irrigation is the predominant production system in the country, Figure 1 shows that, in the last ten years, an increasing share of rice production has come from rainfed systems. According to FEDEARROZ (2017), the increase in the area cultivated with rainfed systems has negatively affected national yields, because the quality of the soil used is not necessarily the best for rice cultivation. Since 1987, an average of 394,063 hectares of rice have been planted annually in Colombia; 65% of these hectares have been cultivated with irrigation and 35% with rainfall. The average yield per year in the rainfed areas has only been 4.3 tons of rice per hectare, compared to 5.7 in the irrigated areas. The bottom graph in Figure 1 shows that the gap in yields per hectare between the irrigated and rainfed systems increased until 2000, then decreased between 2000 and 2004. After that year, changes in the gap were less consistent, up until 2011 when the gap narrowed.

**Figure 1 Harvested area, production, and average yields by the production system**

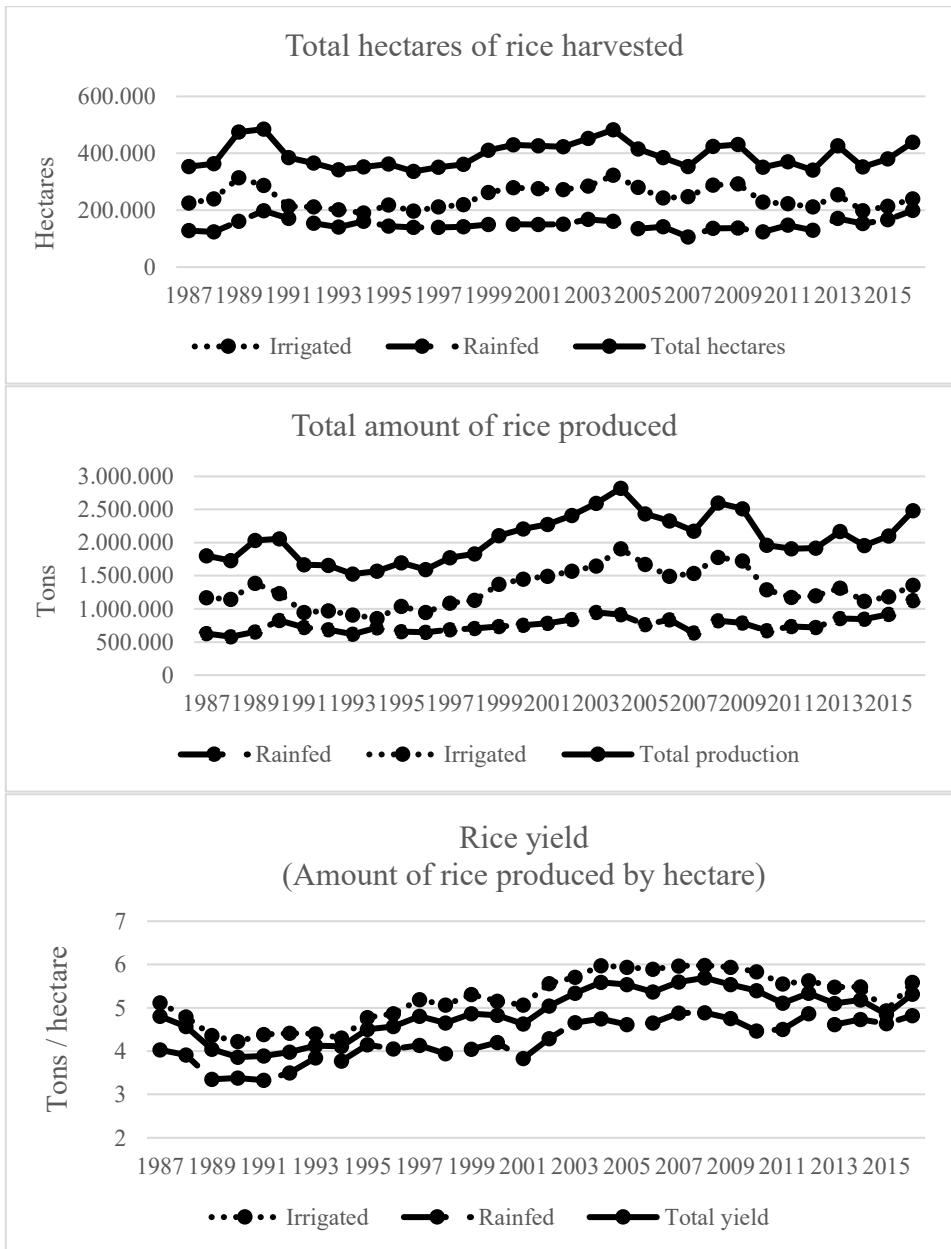


Figure 2 shows how annual temperature and precipitation have varied over time. The average temperature has been fairly stable over this period, hovering between 24 °C and 25 °C. However, there has been a steady increase in average temperature levels since 2010. Between 1987 and 2016, the average temperature increased by 0.58°C. Although the change in precipitation over this same period was found to be negligible, there was considerable variation from year to year. Annual means of precipitation amounts tended to be between 1,700 and 2,700 mm. Some of the variations in precipitation were a result of *El Niño* which took place in 1986-87, 1991-92, 1997-98, and 2014, and *La Niña* which occurred in 1988-89, 1999-00, 2005, and 2010-11 (IDEAM, 2007; CEPAL, 2012). Events such as *La Niña* resulted in considerable economic losses for Colombia, especially in terms of the volumes of rice that had wilted, died, and could not be harvested. The affected areas saw significant decreases in crop yields (CEPAL, 2012).

**Figure 2 Cumulative precipitation and average temperature (Celsius) in Colombian rice producer departments**

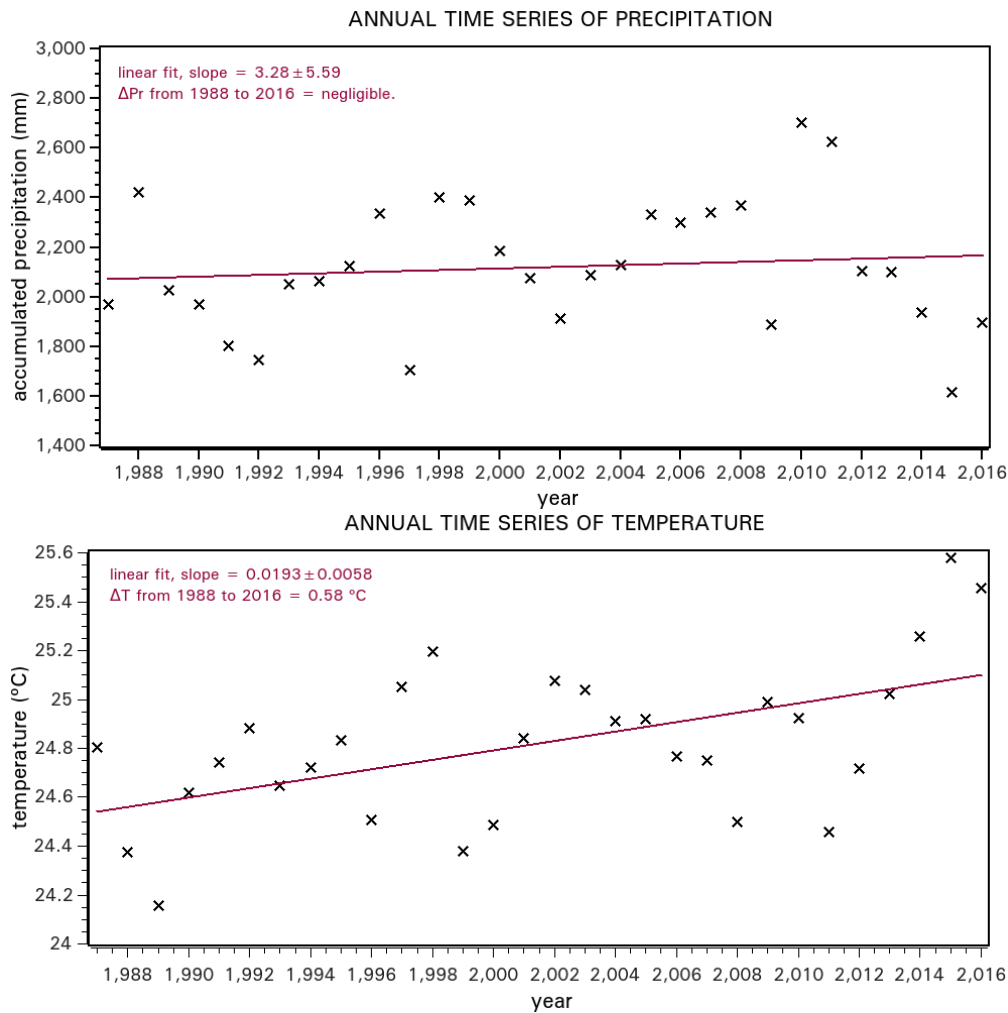


Figure 3 presents the results for the non-parametric local polynomial regressions related to the yields and the weather without imposing a linear model or using more controls (Sheahan & Barrett, 2017). Accordingly, the relationship between temperature and yields is non-linear, while the relationship between precipitation and yields is positive. The graph indicates that departments with an average temperature of approximately 20 °C have the lowest yields in the sample.

**Figure 3 Local linear non-parametric regression of rice yields (tons per hectare) by annual temperature and precipitation**



#### 4 Econometric Model and Results

To empirically examine the effects of the weather variables on rice yields, we estimate the following panel data model:

$$y_{it} = W_{it}'\beta + X_{it}'\gamma + \theta_{Rt} + \alpha_i + \varepsilon_{it}, \quad (2)$$

where  $i = \{1, \dots, 20\}$ ,  $t = \{1987, \dots, 2016\}$ ,  $R = \{1, \dots, 5\}$ , and  $\varepsilon_{it} \sim (0, \sigma_\varepsilon^2 I_n)$ .

In this model, the dependent variable,  $y_{it}$ , is rice yields in the  $i^{th}$  department in year  $t$ . The independent variables are represented by the vector,  $W_{it}$ , which is a vector of weather variables. This includes temperature, precipitation, and anomalous weather events (upper and lower 10% of each department's variable distribution as described earlier). The squared values for temperature ( $T_{it}$ ) and precipitation ( $P_{it}$ ) are included to capture their non-linear effects on yields. Additionally, an interaction term between temperature and precipitation ( $T_{it} * P_{it}$ ) is included since one might influence the effect that the other has on yields. An additional vector,  $X_{it}$ , is included to control for non-climatic factors such as GDP per capita and population density. GDP per capita is a proxy for the economic growth of the department. The more economic growth a department experiences, the more rice farmers can access resources to invest in infrastructure and technology that, in turn, could increase

yields. Population density is a proxy for the rurality level of the department<sup>5</sup>. Areas with higher population densities are likely to be associated with more urbanized regions that have easier access to labor and other production inputs, which could favor productivity.

The fixed effects at the department level,  $\alpha_i$ , account for all the unobserved variables, like the soil characteristics, that are constant over the studied period. Equation (2) also includes a regional time-fixed effect,  $\theta_{Rt}$ , that captures unobserved effects shared by all the departments of the same region in a specific year. The models are estimated using a balanced panel.

Table 3 reports the results from the OLS estimation and the associated heteroscedasticity-consistent standard errors<sup>6</sup>. Column (1) presents the results for Model (1) without the fixed effects. The model includes temperature, precipitation, and squared terms for each of the variables. It does not include controls for the fixed effects and macroeconomic characteristics. The findings show that temperature significantly increases yields, but at a decreasing rate, whereas precipitation significantly decreases yields, but at an increasing rate. Columns (2)-(4) present the results for the fixed-effect models. The models include the same variables as Model (1) – namely, temperature and precipitation. Additionally, Model (2) includes departmental fixed effects and regional time-fixed effects. Model (3) includes both fixed effects and macroeconomic characteristics (GDP per capita and population density). The effect of anomalous weather episodes is included in Model (4). Finally, Model (5) includes the interaction term,  $T_{it} * P_{it}$ , which takes into account the relationship between these two variables. To calculate the marginal effects of temperature and precipitation on yields for Model (5), which includes the interaction term, we took the derivative of the function in Equation (2) with respect to  $T_{it}$  and  $P_{it}$ , at their mean values<sup>7</sup>.

According to the results in column (5), temperature and precipitation have a positive effect on rice yields. However, because the coefficient of the interaction term is negative and significant, each variable attenuates the effect of the other. In other words, the effect of precipitation depends on temperature and vice versa. The significant squared temperature term indicates non-linear yield responses to changes in temperature. When  $T_{it}$

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<sup>5</sup> There are other variables potentially related to rice yields (e.g., investment in infrastructure, labor intensity, research, technology, soil preparation, and the use of chemical pesticides and fertilizers) that are not observable annually at the department level in Colombia. This might be considered a limitation of this study. However, note that regional time-fixed effects and fixed effects at the department level are included in the models to disentangle the effects of the weather conditions from possible sources of omitted variable bias (Dell et al., 2014).

<sup>6</sup> The estimations have robust standard errors. I am clustering the standard errors at the department level (the unit of study), which accounts for heteroskedasticity problems because accommodates and adjusts for the correlation of observations within values of panelvar.

<sup>7</sup> The marginal effect of T =  $\delta Y / \delta T = \beta_1 + (2\beta_2 * \bar{T}) + \beta_3 * \bar{P}$ , where  $\beta_1$ ,  $\beta_2$  and  $\beta_3$  are the estimated coefficients for T and T<sup>2</sup>, and T\*P, respectively. All of them are variables in the  $W_{it}$  vector.  $\bar{T}$  and  $\bar{P}$  are specific values for temperature and precipitation. In our models, we use the means values for  $\bar{T}$  and  $\bar{P}$ . In the same way, the marginal effect of P =  $\delta Y / \delta P = \beta_4 + (2\beta_5 * \bar{P}) + \beta_3 * \bar{T}$ , where  $\beta_4$ ,  $\beta_5$  and  $\beta_3$  are the estimated coefficients for P and P<sup>2</sup>, and T\*P, respectively. All of them are variables in the  $W_{it}$  vector.

and  $P_{it}$  are at their mean values (25 °C, 2.12 m/year) an additional degree of Celsius increases yields by 0.04 tons per hectare, and an additional meter of rain per year increases yields by 0.09 tons per hectare.

**Table 3 Effects of annual temperature and precipitation on rice yields**

	(1)	(2)	(3)	(4)	(5)
T	0.834*** (0.184)	0.868** (0.364)	0.758** (0.325)	0.903** (0.374)	1.242*** (0.302)
P	-0.865*** (0.176)	-0.378 (0.233)	-0.326 (0.259)	-0.144 (0.264)	1.352* (0.708)
T*P					-0.051** (0.020)
T <sup>2</sup>	-0.020*** (0.004)	-0.016** (0.008)	-0.014* (0.007)	-0.016** (0.008)	-0.022*** (0.006)
P <sup>2</sup>	0.116*** (0.030)	0.055 (0.034)	0.050 (0.037)	0.035 (0.040)	-0.007 (0.041)
Anomalous high T				-0.125 (0.113)	-0.123 (0.113)
Anomalous low T				0.029 (0.097)	0.028 (0.097)
Anomalous high P				-0.134 (0.123)	-0.131 (0.121)
Anomalous low P				0.129 (0.099)	0.171 (0.106)
GDP per capita			-0.005 (0.006)	-0.004 (0.006)	-0.002 (0.006)
Population density			-0.005** (0.002)	-0.005** (0.002)	-0.005*** (0.001)
Department fixed effects	No	Yes	Yes	Yes	Yes
Region*year fixed effects	No	Yes	Yes	Yes	Yes
Observations	555	555	555	555	555
R-squared	0.13	0.73	0.73	0.73	0.74
Adjusted R-squared	0.13	0.62	0.63	0.63	0.64
Number of departments		20	20	20	20

Robust standard errors in parentheses

\*\*\* p<0.01, \*\* p<0.05, \* p<0.1

The coefficient associated with GDP per capita is not significant, but population density was found to be negatively correlated with rice yields, which means that we find higher yields in areas where the population density is lower. One way to think about this is that, in more urban areas, there is higher competition for the water that is available and a larger population using water, which in turn might lower the water and other resources available for rice production. The negative relationship between population density and yields is likely explained by the fact that rice production takes place in more rural areas, which are less inhabited.

An alternative approach to capturing the time dynamics of weather on rice yields is to include a time trend. An example of a time trend could be the knowledge and experience farmers acquire when dealing with new weather conditions and how they learn to make adjustments to maintain or increase their yields. This process is assumed to be homogenous across all departments within the country. We test the robustness of our findings in Table 3 by re-estimating Equation (2) with a linear time trend,  $\delta Trend$ , instead of a spatially-specific time fixed effect ( $\theta_{Rt}$ ). The equation is specified as follows:

$$y_{it} = \beta W_{it} + \gamma X_{it} + \delta \text{Trend} + \alpha_i + \varepsilon_{it}. \quad (3)$$

The variable *Trend* is assigned numerical values. For every department *i*, we assign a value of 1 for the year 1987, a value of 2 for 1988, and so on. The last observation for department *i* is in 2016 which has a value of 30. The vectors of control variables,  $W_{it}$  and  $X_{it}$ , are the same as those included in Equation (2).

Table 4 displays the results. The magnitude and sign of the coefficients for the climatic variables do not change significantly concerning the estimates presented in Table 3 for Equation (2). Therefore, our results are robust regardless of whether a regional time-fixed effect or a time trend is included in the models. According to Model (4) in Table 4, When  $T_{it}$  and  $P_{it}$  are at their mean values (25 °C, 2.12 m/year), an additional degree of Celsius per year increases yields by 0.14 tons per hectare; while an additional meter of rain per year, increases yields by 0.37 tons per hectare. The coefficient associated with the linear time trend (*Trend*) indicates that yields follow a positive trend through the period under study. As we mentioned, Equation (3) assumes that the trend is homogenous across all departments within the country. This assumption, however, does not hold for all departments in Colombia<sup>8</sup>. Moreover, the adjusted R-squared in Tables 3 and 4 suggests that the model in Equation (2) is more appropriate than the one in Equation (3)<sup>9</sup>.

Departments are divided into municipalities. Given this, one might question why the analysis was conducted at the department level and not at the municipality level, since the latter is a smaller geographic unit. We estimated the regressions at the municipal level for the period 2007-2016 using the available data. We did not find a significant relationship between the climatic variables and rice yields. The reason is that the political division between municipalities does not necessarily correspond to geographical limits. For example, two small municipalities located next to each other might not exhibit enough climatic differences. Therefore, climatic variations across municipalities may not be significant enough to explain part of the variation in rice yields. For this reason, the geographical unit must be larger in geographical size.

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<sup>8</sup> We calculated the trend for every department and these are different for each of them. These results are available from the authors upon request.

<sup>9</sup> Some concerns might arise because the percentage of hectares cultivated with irrigation is not included as a control variable in our models. However, the decision to produce rice with a rainfed or irrigated system depends on precipitation and the rain pattern (unimodal or bimodal), which are likely to be highly correlated with the percentage of hectares cultivated with irrigation. For this reason, we decided not to include it as a control variable in our models. If it is included, the signs and magnitude of the coefficients associated with the temperature and precipitation do not change significantly, especially to the estimations presented in Column 5 of Table 3. The full estimation results are available from the authors upon request.

**Table 4 Robustness check: Effects of annual temperature and precipitation on rice yields with a time trend common to all departments**

Variables	1	2	3	4
T	1.079*** (0.362)	0.988** (0.376)	1.151** (0.456)	1.788** (0.777)
P	0.438* (0.252)	0.473* (0.251)	0.456 (0.264)	2.457*** (0.702)
T*P				-0.070*** -0.021
T <sup>2</sup>	-0.021** (0.008)	-0.019** (0.008)	-0.020** (0.009)	-0.030** (0.014)
P <sup>2</sup>	-0.041 (0.040)	-0.043 (0.040)	-0.036 (0.042)	-0.083** (0.031)
Anomalous high T			-0.292* (0.140)	-0.299** (0.135)
Anomalous low T			-0.029 -0.091	-0.036 -0.084
Anomalous high P			-0.110 -0.095	-0.136 -0.099
Anomalous low P			-0.071 (0.114)	-0.021 (0.112)
GDP per capita		-0.026** (0.011)	-0.025** (0.011)	-0.023* (0.011)
Population density		-0.004* (0.002)	-0.003 (0.002)	-0.003** (0.002)
Trend	0.048*** (0.004)	0.056*** (0.006)	0.057*** (0.006)	0.059*** (0.006)
Constant	-10.41** (4.294)	-8.872* (4.561)	-12.20* (5.883)	-22.00* (10.75)
Observations	555	555	555	555
Department fixed effects	Yes	Yes	Yes	Yes
R-squared	0.39	0.41	0.42	0.44
Adjusted R-squared	0.38	0.40	0.41	0.43
Number of coddep	20	20	20	20

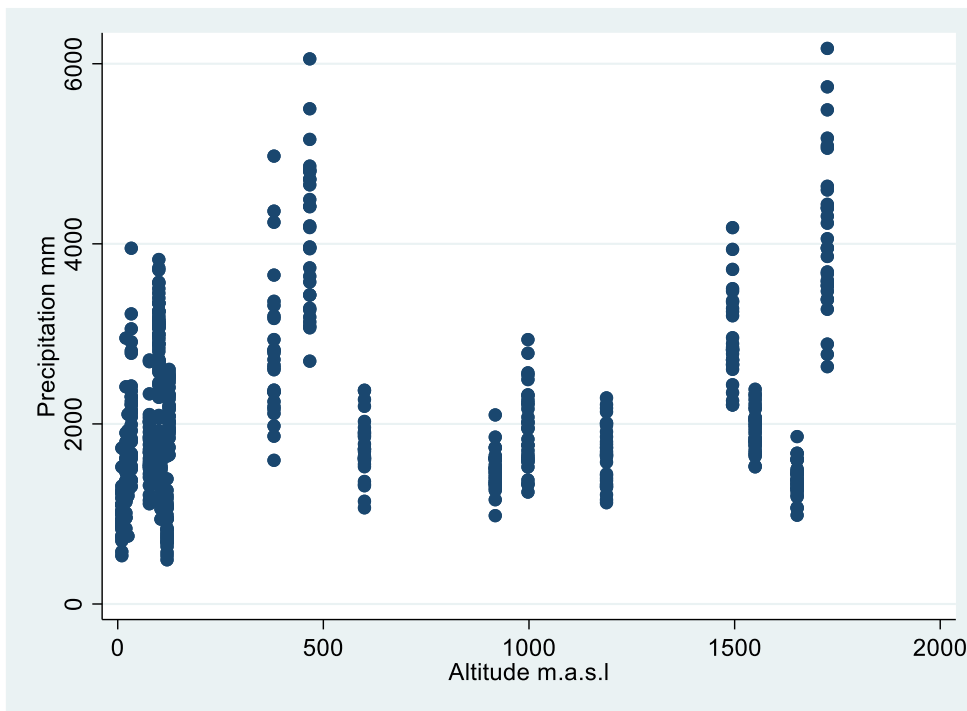
Robust standard errors in parentheses

\*\*\* p<0.01, \*\* p<0.05, \* p<0.1

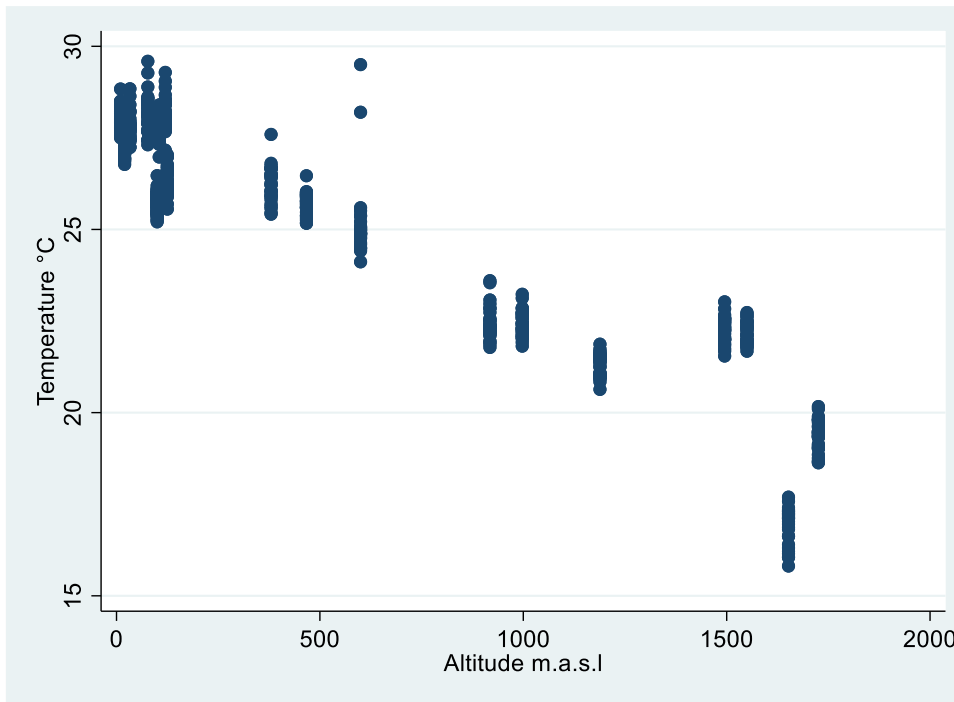
#### 4.1 Heterogeneity in space: The role of altitude

In Colombia, rice is produced at sea level up to 2,000 m.a.s.l (AGROPINOS, 2022). Throughout the country, a negative relationship between altitude and temperature has been observed such that high-altitude areas present lower temperatures. However, the relationship between altitude and precipitation might not be as clear, since there could be a high variance in precipitation among areas with the same elevation. In our data, the correlation between temperature and altitude is -0.93, while that between precipitation and altitude is 0.22. Both correlation coefficients are significant at the 5% level or better. As it is countrywide, the relationship between precipitation and altitude is weaker than its relationship with temperature among the rice-producing areas. This is more evident graphically (see Figures 4 and 5).

**Figure 4** Precipitation (mm) and altitude (m.a.s.l) in rice-producing departments (1987-2016)



**Figure 5 Temperature (°C) and altitude (m.a.s.l) in rice-producing departments (1987-2016)**



Given the country’s topography, the effect of temperature and precipitation could vary between lowland and highland departments<sup>10</sup>. Table 5 presents some descriptive statistics for departments whose altitude is above or below the median value for our sample of departments in Colombia (1,112 m.a.s.l.). Note that 15 of the 20 departments are (on average) below sea level. Also, note that the difference in mean temperature is higher than the difference in mean precipitation and yields.

**Table 5 Summary statistics by altitude**

Altitude dummy variable	Altitude (MSL)	T (Celsius)	P (m/year)	Yield (tons per ha)	Departments
=1 (altitude>median altitude of the country)	1,522.20	20.41	2.41	4.91	5
=0 (altitude<median altitude of the country)	273.27	26.33	2.02	4.90	15

To separate the marginal effects for departments with altitudes above and below the median sea level, we estimated Equation (2), interacting each independent variable with a dummy equal to 1 if the department altitude is higher or equal to the median value of the altitude in the sample. The Chow test results indicate that the null hypothesis of no structural change is rejected (p-value = 0.000).

<sup>10</sup> Dall’erba and Dominguez (2016) found this form of spatial heterogeneity to be highly significant among Southwestern counties in the United States.

Results show that temperature and precipitation have a positive effect in both the highlands and the lowlands (see Table 6). However, the interaction term is no longer significant for departments with higher altitudes, which means that temperature does not attenuate the effects of precipitation in those areas (and vice versa). One of the meteorologists working at Fedearroz (the National Rice Producers Association in Colombia) explained that in elevated areas (more than 500 m.a.s.l) high luminosity (instead of precipitation) is the key variable to ensuring high yields since in many cases the water is provided by the irrigation systems. Then, higher precipitations do not weaken the positive effects of solar radiation (associated with higher temperatures).

In departments with higher elevation, when  $T_{it}$  and  $P_{it}$  are at their mean values (20.41 °C, 2.41 m/year), an additional degree of Celsius per year increases yields by 0.14 tons per hectare; while an additional meter of rain per year increases yields by 0.44 tons per hectare (Table 6). In departments with lower elevation, when  $T_{it}$  and  $P_{it}$  are at their mean values (26.33 °C, 2.02 m), an additional degree of Celsius per year increases yields by 0.02 tons per hectare; while an additional meter of rain per year increases yields by 0.11 tons per hectare. The larger magnitudes of the effects of temperature in the highlands versus the lowlands is supported by Ramírez-Villegas et al. (2012) who conclude that higher temperatures in the highlands shorten the growth cycle, allowing farmers to plant more frequently to increase revenue.

**Table 6 Effects of annual temperature and precipitation on rice yields by altitude**

	Higher altitude	Lower altitude
T	1.302** (0.573)	2.614** (1.112)
P	-1.42 (1.019)	3.161* (1.583)
T*P	0.050 (0.042)	-0.116* (0.062)
T <sup>2</sup>	-0.029* (0.016)	-0.044** (0.021)
P <sup>2</sup>	0.091** (0.035)	-0.023 (0.043)
Anomalous high T	-0.084 (0.154)	-0.152 (0.143)
Anomalous low T	0.105 (0.281)	-0.021 (0.127)
Anomalous high P	-0.313*** (0.107)	-0.076 (0.142)
Anomalous low P	-0.203 (0.213)	0.312** (0.111)
GDP per capita	0.036 (0.032)	-0.003 (0.006)
Population density	-0.011 (0.010)	-0.006*** (0.001)
Region*year and department fixed effects		Yes
Adjusted R-squared		0.64

Robust standard errors in parentheses  
\*\*\* p<0.01, \*\* p<0.05, \* p<0.1

#### 4.2 Heterogeneity in time: The two growing seasons of Colombia

After investigating spatial heterogeneity's role, we now test for the possible presence of heterogeneity in time. Indeed, while Colombian farmers plant rice throughout the year, the volume planted varies from month to month. Moreover, planting and harvesting periods are different across regions (FEDEARROZ, 2021; DNP, 1980). Therefore, it is likely that the weather conditions experienced during some periods of the year are more likely to have an impact on yields than others.

To evaluate the effects of weather on rice yields during the growing season, it would be necessary to use historical information on the hectares planted per month, so as to identify the months that are most critical to the growing stages of rice. However, these data are not available for the whole period under analysis. Information for 2000-2016 indicates that, the trimesters of March to May and September to November, are the ones with the highest percentage of planted areas in the year (DANE 2016c, 2018b). Based on this information, we assume that these are the key periods to consider for the entire sample. Table 7 presents the results for the estimations of Equation (2), where key periods conditions are used instead of annual temperature and

precipitation. In this equation,  $T_{mm}$  and  $T_{sn}$  represent the annual early (March-May) and late season (September-November) temperatures respectively. Similarly,  $P_{mm}$  and  $P_{sn}$  represent the annual early and late season amounts of precipitation.

**Table 7 Effects of the growing season temperature and precipitation on rice yield**

	(1)	(2)	(3)
Tmm	0.675** (0.320)	0.742** (0.297)	0.671** (0.285)
Tsn	0.407 (0.372)	0.408 (0.354)	0.392 (0.385)
Pmm	-0.688 (1.128)	-0.456 (1.159)	-0.350 (1.102)
Psn	3.254** (1.434)	3.560** (1.307)	3.761** (1.442)
Tmm*Pmm	0.009 (0.042)	0.006 (0.043)	0.006 (0.041)
Tsn*Psn	-0.162*** (0.045)	-0.164*** (0.043)	-0.170*** (0.047)
Tmm <sup>2</sup>	-0.014* (0.007)	-0.014** (0.006)	-0.013** (0.006)
Tsn <sup>2</sup>	-0.006 (0.007)	-0.006 (0.006)	-0.006 (0.007)
Pmm <sup>2</sup>	0.176 (0.160)	0.132 (0.179)	0.098 (0.170)
Psn <sup>2</sup>	0.193 (0.219)	0.109 (0.207)	0.083 (0.220)
Anomalous high T		-0.066 (0.109)	-0.071 (0.111)
Anomalous low T		0.049 (0.101)	0.047 (0.091)
Anomalous high P		-0.033 (0.110)	-0.030 (0.109)
Anomalous low P		0.116 (0.096)	0.104 (0.099)
GDP per capita			-0.008 (0.006)
Population density			-0.005*** (0.002)
Region*year fixed effects	yes	yes	yes
Department fixed effects	yes	yes	yes
Observations	555	555	555
Adjusted R-squared	0.63	0.63	0.64
Number of Departments	20	20	20

Standard errors in parentheses

\*\*\* p<0.01, \*\* p<0.05, \* p<0.1

The results in Table 7 show that early-season temperature (indexed as “ $mm$ ”) and late-season precipitation (indexed as “ $sn$ ”) are the most significant factors impacting rice yields. When  $T_{mm}$  and  $P_{mm}$  are at their mean values (24.99 °C, 606.06 m/year), an additional degree of Celsius per year increases yields by 0.03 tons per hectare (See Column (3) of Table 7). During the first semester of the year, precipitation does not appear to have a statistically significant effect on yields. Neither is there any attenuation of the effects between temperature and precipitation. These results could be explained by the regional distribution of the planting areas and the timing of the rice-growing stages in Colombia.

Approximately 65% of hectares cultivated with rice are planted in the early season under the rainfed system (FEDEARROZ, 2017, 2018). Most of the area planted is located in Llanos Orientales, where there is just one rainy season that goes between March (or April) and October (FEDEARROZ, 2021; FEDEARROZ 2011). Thanks to this unimodal wet season, Llanos Orientales plants rice mainly with a rainfed system during the first half of the year. The other regions (Costa Norte, Centro, Bajo Cauca, and Santanderes) plant rice evenly throughout the year thanks to having two rainy seasons per year or their irrigation systems. However, the vegetative stage of rice growth takes place during the first 45 days (on average) after planting the seeds. According to the meteorologist from Fedearroz, the plant is less sensitive to weather variations at this stage. This could explain the small coefficient for temperature and the insignificant one associated with precipitation for the trimester considered.

As for the results in the late season, we find that when  $T_{sn}$  and  $P_{sn}$  are at their mean values (24.66 °C, 660.52 m/year), an additional meter of precipitation per year decreases yields by 0.43 tons per hectare. It is important to notice that the direct effect of precipitation is positive, but it is attenuated by the temperature, as the coefficient associated with the interaction term is negative and significant.  $T_{sn}$  does not appear to have a statistically significant effect on yields. This could be explained partially by the length of the rice cycle in Colombia. Harvesting occurs five or six months after the land preparation and around four months after the germination of the seeds. Therefore, some of the rice planted between September and November in year  $t$  will be harvested in year  $t+1$ ., potentially affecting the yield sensitivity to weather variation during this trimester<sup>11</sup>.

### 4.3 Future Rice Yields and Climate Change in Colombia

Recall that in Equation (2), we estimate the coefficients for temperature and precipitation at the department level (see again Table 3). We project future rice yields based on these coefficients and also use projected weather data from the Beijing Normal University Earth System Model (BNU-ESM) output prepared for the Coupled Model Intercomparison Project (CMIP5) (Ji et al., 2014). This project produced a dataset of long-term simulations of climatic variables for different locations around the earth, based on different CO<sub>2</sub> scenarios. Each scenario addresses a different possibility for population growth<sup>12</sup>, fossil fuel use, technological

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<sup>11</sup>Again, the full estimation results are available from the authors upon request.

<sup>12</sup> The population’s projections for the scenarios come from the United Nations projections (Wayne, 2013).

advancement, economics, and land use changes (van Vuuren et al., 2011; Core writing team, Pachauri, R.K., & Meyer, L.A., 2014; University Corporation for Atmospheric Research, 2022).

The experiments included in the CMIP5 are the work of the World Climate Research Programme's (WCRP) Working Group on Coupled Modelling (WGCM) (comprised of 20 climate modeling groups from around the world), with input from the International Geosphere-Biosphere Programme's (IGBP) Analysis, Integration, and Modeling of the Earth System (AIMES) project (Taylor, Stouffer, & Meehl, 2012)<sup>13</sup>. Since all the processes and relationships between different parts of the Earth system are not fully understood by the researchers, any model that projects weather variables, like CMIP5, embeds some uncertainties. However, as the University Corporation for Atmospheric Research (2022) explains, most of the uncertainty in these models comes from the fact that future human behavior (e.g., how much pollution humans will be adding to the atmosphere) is also unknown. Weather projections from the World Climate Research Programme were used in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). It is the best information available to project future rice yields in Colombia.

We analyze the CMIP5 dataset to obtain future values for temperature and precipitation at the department level for Colombia using three scenarios (RCP 2.6, RCP 4.5, and RCP 8.0) for both a mid-term (2046-2065) and a long-term (2081-2100) projection period. Specifically, we average future temperature and precipitation across the grid cells in each department. We then project future rice yields for the three scenarios and two periods.

We apply a bias correction to both the precipitation and temperature fields obtained from the future projection ensemble. To this end, we compare the historical period of these simulations (1987-2005) with the reliable reanalysis data (observations) obtained from the ERA5 dataset (e.g., CS3, 2017)<sup>14</sup>. Data contained in ERA5 are often considered to be the most representative of real meteorological and climatic conditions in retrospective analysis. We use the discrepancies between ERA5 and the data simulated (CMIP5) to correct values forecasted by the simulations. This bias correction is carried out to minimize potential overestimations or underestimations in the values for projected temperature and precipitation levels.

To estimate future rice yields, we assume that the population density and the per capita GDP in Colombia for the periods 2046-2065 and 2081-2100 will be constant and equal to the average of these variables in 1987-2016. Both variables are included in the estimations of Equation (2). There might be concern about this assumption since both population density and per capita GDP will change over time. Also, this method does not allow for the adaptation of farmers, or it assumes that they do not implement any changes in their practices to adapt to less favorable climatic conditions. However, keeping everything else constant (besides the weather

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<sup>13</sup> Taylor et al. (2012) explained how the experts in atmospheric sciences should deal with the specific limitations of the data included in the CMIP5.

<sup>14</sup> ERA5 is the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalyses of the global climate. See: <https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>

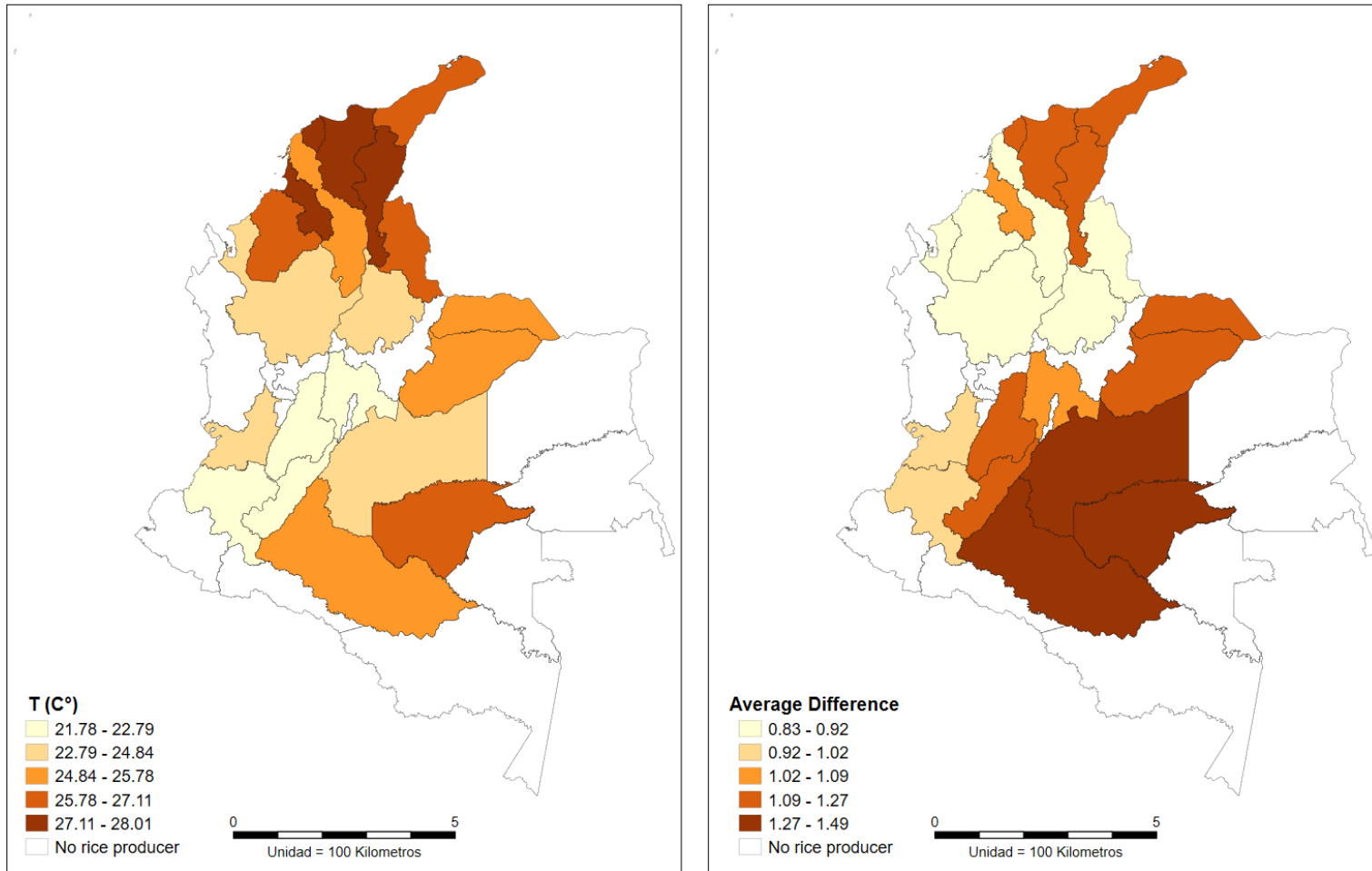
data), allows us to know the change in yields that is due exclusively to new weather. This setting is common in the literature where variables are projected using future weather data and coefficients estimated with a model on historical data (Bozzola et al., 2018). Also, it is important to recall that the projections used for temperature and precipitation are already considering different possibilities for many socioeconomic variables.

The RCP 2.6 scenario projects an incremental increase in global temperature of between 0.9 °C and 2.3 °C by 2100 relative to the pre-industrial era. In the case of the RCP 8.5, the projected increase in global temperature is expected to be between 3.2 °C and 5.4 °C. While the former is probably underestimating the future impacts of greenhouse gas emissions on temperature levels, the latter is likely overestimating the impacts. Therefore, we also consider the RCP 4.5 scenario, which projects that the incremental increase in global temperature will be between 1.3 °C and 3.2 °C by the end of this century. Among these three scenarios, there is a general consensus within the climate community that RCP 4.5 is likely to provide the most reliable projections of future conditions. For the purposes of this paper, we focus on presenting the results for the RCP 4.5 scenario. The results for the RCP 2.6 and RCP 8.5 scenarios are largely consistent and are available upon request.

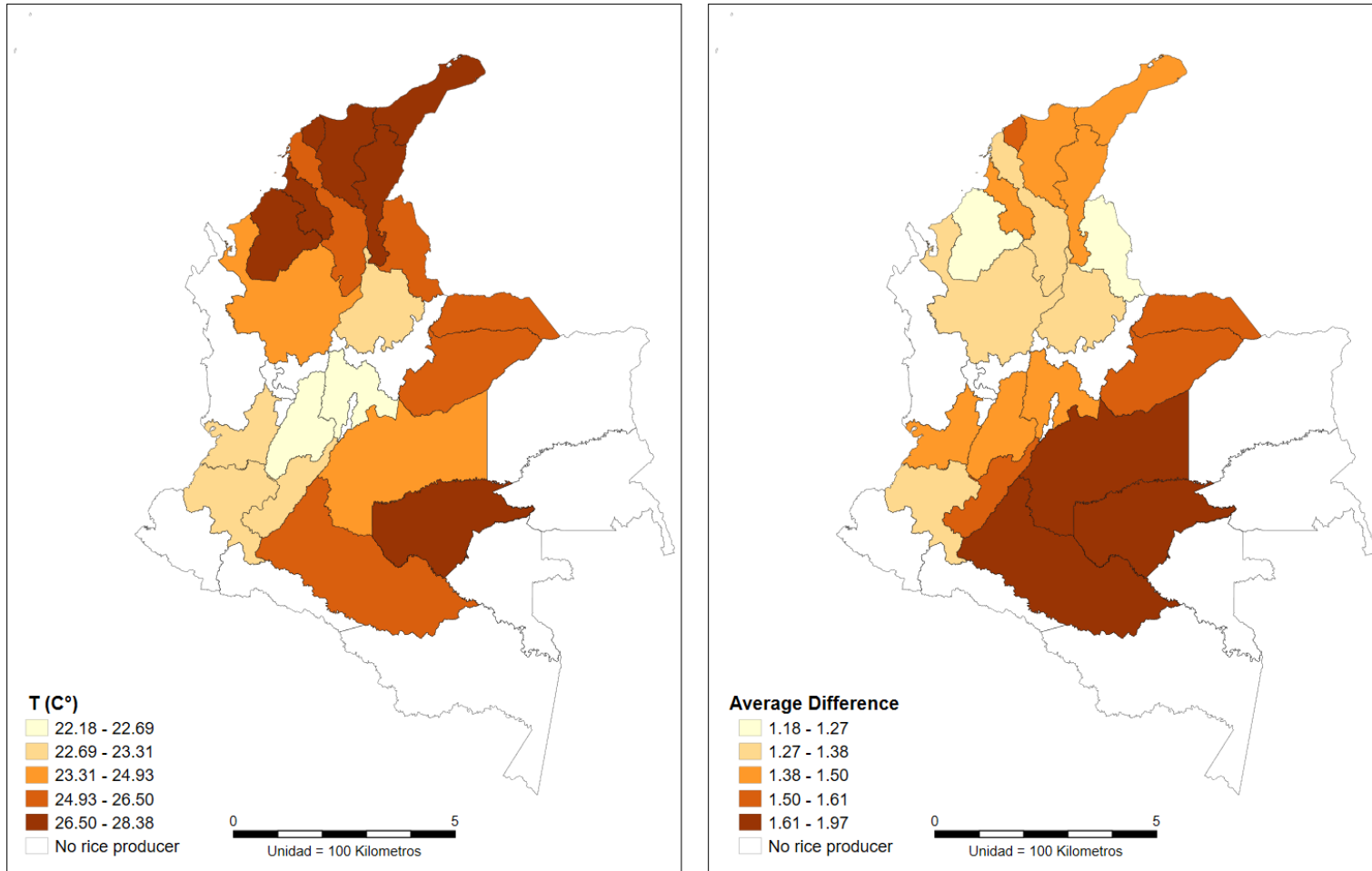
Figure 6 shows that for the period 2046-2065 the average annual temperature is expected to increase between 0.84 °C and 1.49 °C among the rice-producing departments with respect to the base period (1987-2005). The departments where temperatures are expected to increase the most would be Caqueta, Guaviare, and Meta, located in the Central region, and Llanos Orientales (see Appendix 1). The temperature would then continue to rise in all departments, with average annual temperatures expected to increase by 1.48 °C in 2081-2100 compared to the base period (Figure 7). Again, the rice-producing departments in the Central region and Llanos Orientales would be most impacted.

In 2046-2065, the RCP 4.5 scenario generates similar rainfall forecasts compared to those generated using the RCP 2.6 and 8.5 scenarios. According to the RCP 4.5 scenario, precipitation is projected to decrease in seven of the 20 producing departments (Figure 8). The greatest reductions will occur in rice-producing departments located in the Northern tip of Colombia, especially in Sucre (-57%), Magdalena (-51%), and La Guajira (-45%). The greatest increases in rainfall will occur in Valle del Cauca (+111%), Meta (70%), and Santander (64%) located in the Eastern and Central regions. In the future, these regions are expected to have the highest rainfall in the country. Additional projections using the RCP 4.5 scenario show that any changes in expected rainfall levels between 2046-2065 and 2081-2100 would not be significant (Figure 9).

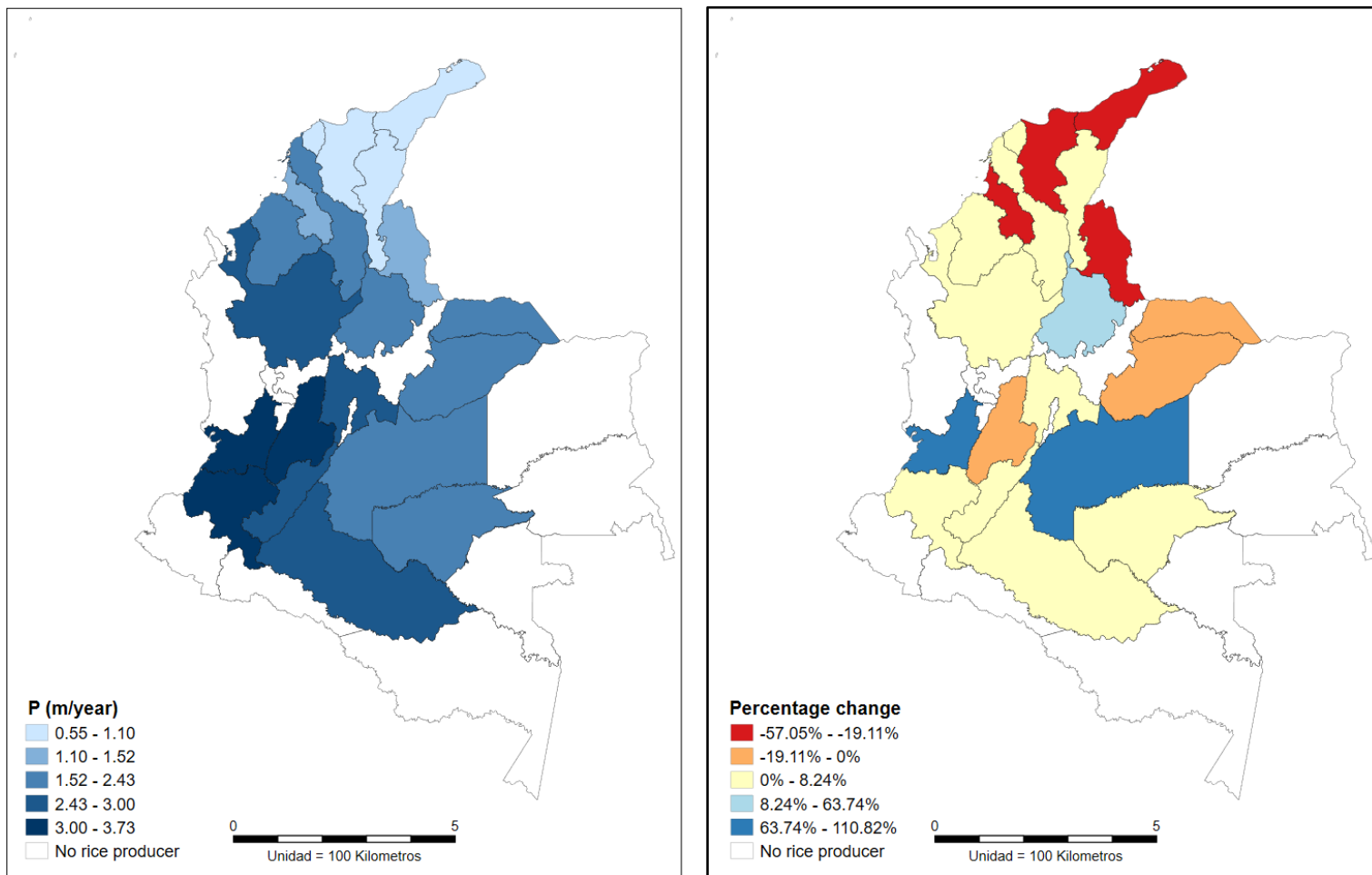
**Figure 6 Temperature for RCP 4.5 scenario 2046-2065 (Left). Difference in average annual temperature in 2046-2065 (RCP 4.5 scenario) with respect to the reference period 1987-2005 (Right)**



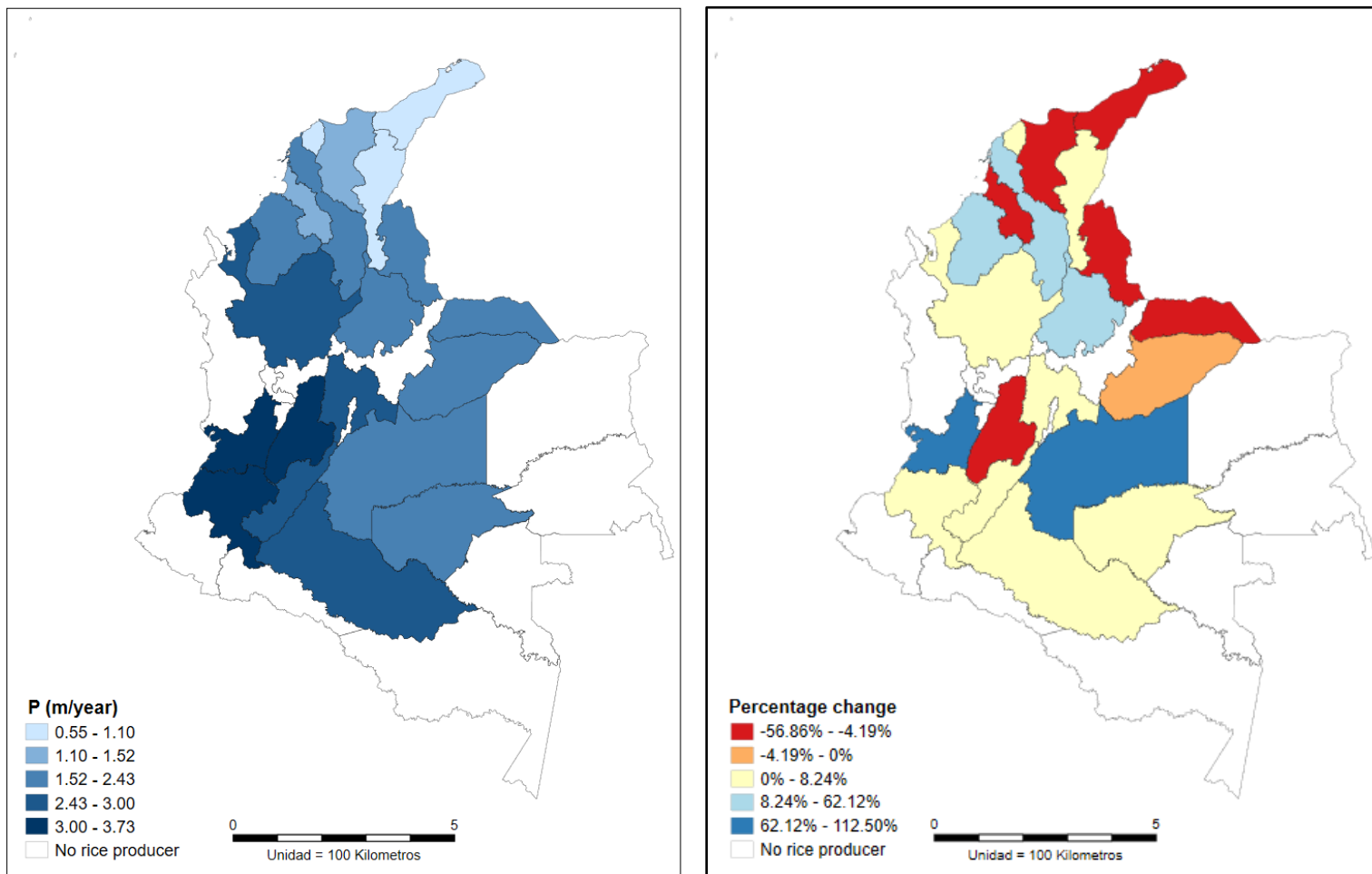
**Figure 7 Temperature for RCP 4.5 scenario 2081-2100 (Left). Difference in average annual temperature in 2081-2100 (RCP 4.5 scenario) with respect to the reference period 1987-2005 (Right)**



**Figure 8 Precipitation for the RCP 4.5 scenario 2046-2065 (Left). Percentage change in mean precipitation using RCP 4.5 scenario in 2046-2065 with respect to the period 1987-2005 (Right)**



**Figure 9 Precipitation for the RCP 4.5 scenario 2081-2100 (Left). Percentage change in mean precipitation using RCP 4.5 scenario in 2081-2100 with respect to the period 1987-2005 (Right)**



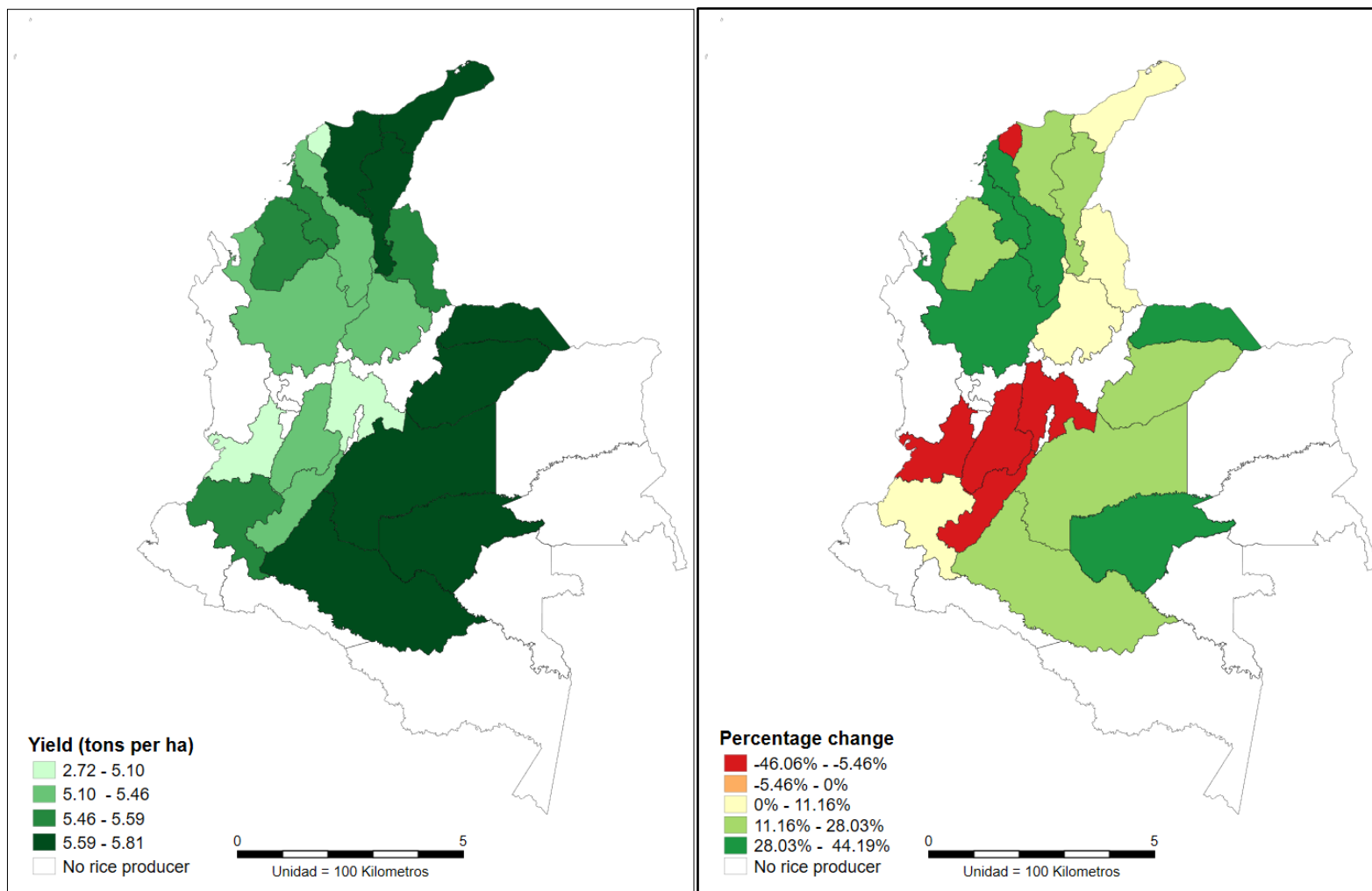
Our estimates using the projections generated by the RCP 4.5 scenario indicate that rice yields would increase in 15 of the 20 producing departments for the period 2046-2065. These estimates are similar across the three RCP scenarios<sup>15</sup>. According to RCP 4.5, average yields will increase by 10% at the national level compared to the average over 1987-2016. The departments with the highest rice yields will change. In 1987-2016 this group included departments in the Centro region, such as Tolima, Huila, Valle, and Cundinamarca. In 2046-2065 and 2081-2100, the departments with the highest rice yields (the “winners”) are expected to be mostly in the Llanos Orientales region (Arauca, Caquetá, Guaviare, Meta, and Casanare) (Figure 10). Notice that according to our projections, the potential “losers” departments cultivate rice with the irrigated system mainly, while “the winners” with the rainfed system. These results imply that the yields would increase the most in departments highly dependent on the rain to produce rice. In real life, rice producers in the “losers” departments could strengthen their irrigation system and implement other strategies to compensate for the potential adverse effects of climate change in those regions. However, the projections show that the yields would increase the most in departments highly dependent on the rain because these do not take into account the potential farmers' adaptation. As we mentioned, they relied only on the coefficients estimated and the future values of temperature and precipitation. In 2081-2100 the rice yield is expected to increase compared to the period 1987-2016, but it would not be very different from that forecasted for the period 2046-2065 (Figure 11).

In the first part of this paper, we showed that temperature and precipitation had a positive effect on rice yields in Colombia from 1987 to 2016. In this section, we relied on future weather data to project yields, which will increase on average from 4.88 in 1987-2016 to 5.36 tons per hectare in 2045-2065. A couple of papers have explored the impact of future weather conditions on rice yields in Colombia. Ramírez-Villegas et al. (2012) found that by 2050 the temperature will increase between 2 °C and 2.5 °C in 65% of the current rice-producing areas, and 61% of those areas could experience a 3% increase in precipitation. Hence, if this projection and ours are realized, given the positive relationship between these two variables and rice yields, production should increase in the coming decades. More recently, BID et al. (2014) made predictions for three periods (2011-2040, 2041-2070, and 2071-2100) using three IPCC SRES scenarios (A1B, B2, A2). The authors estimated how rice yields would change due to future climatic conditions in four producing departments. Their results coincide with ours in that the performance will be reduced in Tolima and Casanare. However, for Huila and Norte de Santander, the conclusions are reversed.

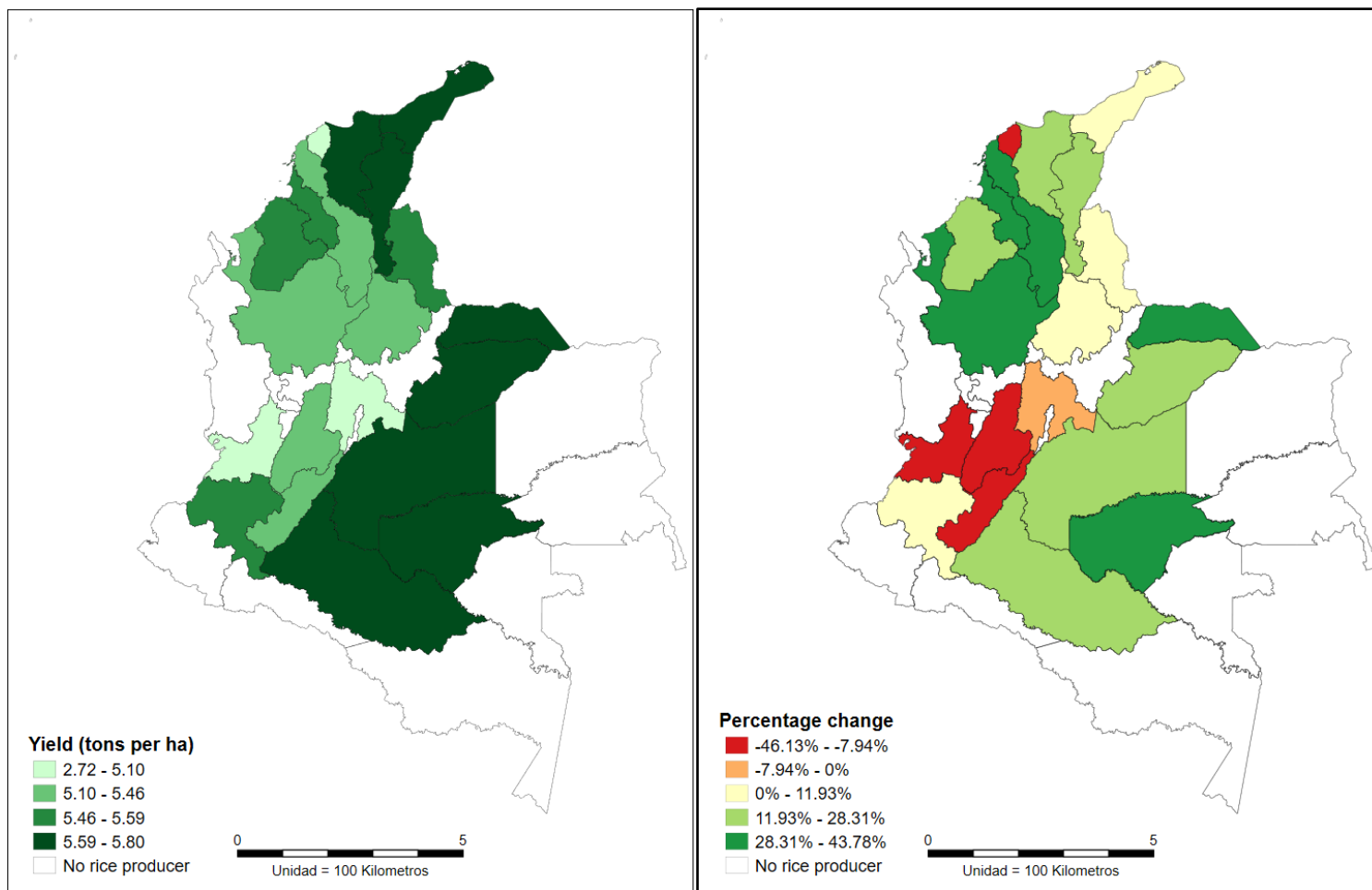
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<sup>15</sup> Confidence intervals for the projections are presented in Appendix 2.

**Figure 10 Average annual rice yields for RCP 4.5 scenario in 2046-2065 (Left). Percentage change in rice yields using RCP 4.5 scenario in 2046-2065 with respect to the period 1987-2016 (Right)**



**Figure 11 Average annual rice yields for RCP 4.5 scenario in 2081-2100 (Left). Percentage change in rice yields using RCP 4.5 scenario in 2081-2100 with respect to the period 1987-2016 (Right)**



## 5 Policy Implications and Conclusions

This paper examines the effects of weather variations on rice yields across Colombian departments. Rice is one of the fundamental products for the development of the agricultural sector in this country, due to its contribution to food security and rural employment. We found a significant effect of rainfall and temperature on rice yields in Colombia. Even though both effects are positive, one variable attenuates the effect of the other. Hence, the magnitude of their effects depends on the specific values they take. Our results indicate that, when  $T_{it}$  and  $P_{it}$  are at their mean values (25 °C, 2.12 m/year), an additional degree of Celsius increases yields by 0.04 tons per hectare, and an additional meter of rain per year increases yields by 0.09 tons per hectare.

The positive effects of temperature and precipitation are consistent with various forms of heterogeneity. Still, their magnitudes are different in areas with low and high altitudes. The attenuation effect is not present in lower altitudes, where other variables like solar radiation could play a more important role in determining rice yields. We also considered the effects of temperature and precipitation on rice yields during the key trimesters of rice planting in Colombia (March-May and September-November). We found that temperature is the main driver of yields in the first trimester, while it is precipitation in the second trimester. Also, the positive effect of precipitation is attenuated by temperature, to the point where the precipitation effect could become negative. These results might be analyzed in light of where the production is taking place, which production system is being used (irrigated or rainfed), and which stage of the rice growth cycle is taking place.

Finally, we predicted rice yields for two time periods (2046-2065, 2081-2100) using temperature and precipitation projected based on RCP scenarios 4.5, 6.5, and 8.0. If only temperature and precipitation change, rice yields will increase in 15 out of the 20 departments in our sample. At the national level, this increase would be an average of 10% between the base period and the two future periods considered (2046-2065, 2081-2100). Notice that we are not implying that extreme weather events would not harm rice yields. In those departments for which the yield would decrease according to our projections, rice is produced with the irrigated system mainly. Therefore, rice producers in those areas could strengthen their irrigation system from now on. Strategies such as investments in technology, and research would help to achieve higher yield growth and compensate for the potential adverse effects of climate change in those regions. Our results do imply that the geographical areas with the highest rice yields could change in the future, as a consequence of changes in temperature and precipitation. This could motivate policymakers to evaluate the likelihood and feasibility of relocating future rice production in Colombia.

Future development of this work could measure the sensitivity of rainfed versus irrigated departments to weather changes. Results along these lines could provide the government and the farmers with the incentives necessary to protect the rice sector against uncertain climate conditions and/or to relocate production.

An additional step would be to understand better the relationship between rice yields and poverty. This could be done based on monetary and non-monetary poverty measures. For the latter, one could rely on the

multidimensional poverty index available in Colombia. It covers fifteen factors that limit an individual's quality of life (illiteracy, unemployment, critical overcrowding, among others). Additionally, since rice production is mainly carried out in rural areas, it would also be worth analyzing whether higher rice yields are able to reduce socioeconomic inequalities (e.g., poverty, income inequality, food insecurity) between rural and urban areas of the country.

Finally, while we recognize that food security cannot be guaranteed only by increasing rice yields, our exercise has revealed how necessary it is to increase the productivity of Colombian agriculture. Many of the challenges that the rice sector faces are common to other types of crops. The limitations of predicting future weather conditions (especially precipitation) increase with the length of the time period being considered. However, this paper has used the best information available for Colombia. The results can help policymakers appreciate the regional differences embedded in our future yield forecasts. Questions such as where to produce rice, who will produce it, how to ensure water to sustain the irrigation districts, how to reduce inequalities in access to irrigation districts, and what type of public investments are necessary to produce enough food for everyone, will continue to be part of the food security debate in Colombia. To this end, this paper provides useful and necessary insights. Rice is the primary staple crop and food source in Colombia. Any discussion and public policy related to food security must start with an overall assessment of the current supply chain related to rice production. It will also need to include an evaluation of the anticipated future supply chain disruptions, which we have shown are likely to come from future changes in weather conditions.

## References

- AGRINET (Red de información y comunicación del sector agropecuario colombiano). (2017). *Rice production data at departmental scale. Colombia, 1987-2016*. Agricultural Ministry of Colombia [Data set]. <https://www.agronet.gov.co/estadistica/Paginas/home.aspx?cod=1>
- AGROPINOS (2021). *Cultivos de arroz en Colombia: papel económico en la industria del agro*. <https://www.agropinos.com/blog/cultivo-de-arroz-en-colombia#:~:text=Los%20climas%20tropicales%20son%20los,los%202.000%20m%20de%20altitud>
- Arias, P.A., Martínez, J. A., & Vieira, S. C. (2015). Moisture sources to the 2010–2012 anomalous wet season in northern South America. *Climate dynamics*, 45, 2861-2884. <https://doi.org/10.1007/s00382-015-2511-7>
- Berry S., & Schlenker W. (2011). *Technical Report for the ICCT: Empirical Evidence on Crop Yield Elasticities*. California Air Resources Board. Retrieved October 20, 2020, from <http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=C3EA696FC114594CD9A8058D521FBE25?doi=10.1.1.648.1920&rep=rep1&type=pdf>
- BID (Banco Interamericano de Desarrollo), CEPAL (Comisión Económica para América Latina y el Caribe), & DNP (Departamento Nacional de Planeación de Colombia). (2014). *Impactos Económicos del Cambio Climático en Colombia – Síntesis*. Nuevas Ediciones S.A.

- Blanc, E., & Reilly, J. (2017). Approaches to assessing climate change impacts on agriculture: An overview of the debate. *Review of Environmental Economics and Policy*, 11(2), 247-257. <https://doi.org/10.1093/reep/rex011>
- Bohorquez-Penuela, C., & Otero-Cortes, A. (2020). Blame it on the Rain: The Effects of Weather Shocks on Formal Rural Employment in Colombia. *Documentos de Trabajo sobre Economía Rural y Urbana*, 292, 1-73. <https://www.banrep.gov.co/en/blame-it-rain-effects-weather-shocks-formal-rural-employment-colombia>
- Bozzola, M., Massetti, E., Mendelsohn, R., & Capitanio, F. (2018). A Ricardian analysis of the impact of climate change on Italian agriculture. *European Review of Agricultural Economics*, 45(1), 57-79. <https://doi.org/10.1093/erae/jbx023>
- CEPAL (Comisión Económica para América Latina y el Caribe). (2012). *Valoración de daños y pérdidas. Ola invernal en Colombia, 2010-2011*. Naciones Unidas.
- Chica, J., Yeimy, T., & Barrerto, J. (2016). Indicadores de competitividad del cultivo del arroz en Colombia y Estados Unidos. *Revista de Ciencias Agrícolas*, 33(2), 16-31. <http://dx.doi.org/10.22267/rcia.163302.49>
- Core writing team, Pachauri, R.K., & Meyer, L.A. (Eds.). (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC. <https://www.ipcc.ch/report/ar5/wg1/>
- Cortés, Y., & Alarcón, J. (2016). Impacts of Climate change on best areas of nine crops in Cundinamarca – Colombia. *Revista Temas Agrarios*, 21(2), 51-64. <http://revistas.unicordoba.edu.co/index.php/temasagrarios/article/view/901>
- Copernicus Climate Change Service. (2017). *ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate*. Copernicus climate change service climate data store [Data set]. <https://cds.climate.copernicus.eu/cdsapp#!/home>
- Dall’erba S., Chen Z., & Nava N. (2021) Interstate Trade Will Mitigate the Negative Impact of Climate Change on Crop Profit. *American Journal of Agricultural Economics*, forthcoming.
- DANE (Departamento Administrativo Nacional de Estadística). (2018a). *Population projections* [Data set]. DANE. <http://www.dane.gov.co/index.php/estadisticas-por-tema/demografia-y-poblacion/proyecciones-de-poblacion>
- DANE (Departamento Administrativo Nacional de Estadística). (2018b). *Encuesta Nacional de Arroz Mecanizado. II Semestre de 2017. Boletín Técnico*. [http://www.dane.gov.co/files/investigaciones/boletines/arroz/bol\\_arroz\\_IIsem17.pdf](http://www.dane.gov.co/files/investigaciones/boletines/arroz/bol_arroz_IIsem17.pdf)
- DANE (Departamento Administrativo Nacional de Estadística). (2018c). *Departmental accounts. GDP information* [Data set]. DANE. <http://www.dane.gov.co/index.php/estadisticas-por-tema/cuentas-nacionales/cuentas-nacionales-departamentales>
- DANE (Departamento Administrativo Nacional de Estadística). (2017a). *Cuenta satélite de la industria del arroz 2012-2016p*. [http://www.dane.gov.co/files/investigaciones/pib/agroindustria/boletin\\_cta\\_sat\\_agroindustria\\_arroz\\_2012\\_2016.pdf](http://www.dane.gov.co/files/investigaciones/pib/agroindustria/boletin_cta_sat_agroindustria_arroz_2012_2016.pdf)
- DANE (Departamento Administrativo Nacional de Estadística). (2017b). Características que se destacan en el cultivo de arroz seco (Oryza Sativa L.) en Colombia. *Insumos y factores asociados a la producción agropecuaria*, 58, 1-5. [https://www.dane.gov.co/files/investigaciones/agropecuario/sipsa/Bol\\_Insumos\\_abr\\_2017.pdf](https://www.dane.gov.co/files/investigaciones/agropecuario/sipsa/Bol_Insumos_abr_2017.pdf)
- DANE (Departamento Administrativo Nacional de Estadística). (2016a). *4o Censo Nacional Arrocerero 2016*. <http://www.dane.gov.co/files/investigaciones/agropecuario/censo-nacional-arrocero/presentacion-4to-censo-nacional-arrocero-2016.pdf>

- DANE (Departamento Administrativo Nacional de Estadística). (2016b). *ENAM (National survey of mechanized rice)* [Data set]. DANE. <https://www.dane.gov.co/index.php/estadisticas-por-tema/agropecuario/encuesta-de-arroz-mecanizado>
- DANE (Departamento Administrativo Nacional de Estadística). (2016c). *Encuesta Nacional de Arroz Mecanizado. I Semestre de 2016. Boletín Técnico.*
- DANE (Departamento Administrativo Nacional de Estadística). (2015). *Encuesta Nacional de Arroz Mecanizado. II Semestre de 2014. Boletín Técnico.* [http://www.dane.gov.co/files/investigaciones/boletines/arroz/bol\\_arroz\\_IIsem14.pdf](http://www.dane.gov.co/files/investigaciones/boletines/arroz/bol_arroz_IIsem14.pdf)
- Dall'erba, S., & Domínguez, F. (2016). The Impact of climate change on agriculture in the Southwestern United States: The ricardian approach revisited. *Spatial Economic Analysis*, 11, 46-66. <https://doi.org/10.1080/17421772.2015.1076574>
- Delerce, S., Dorado, H., Grillon, A., Rebolledo, M.C., Prager, S.D., Patiño V.H., Garces, G., & Jimenez, D. (2016). Assessing weather-yield relationships in rice at local scale using data mining approaches. *Plos One*, 11(8). <https://doi.org/10.1371/journal.pone.0161620>
- Dell, M., Jones B.F., & Olken B. (2014). What do we learn from the weather? The new climate-economy literature. *Journal of Economic Literature*, 52(3), 740-98. <http://dx.doi.org/10.1257/jel.52.3.740>
- Deschenes, O., & Greenstone, M. (2011). Using panel data models to estimate the economic impacts of climate change on agriculture. In A. Dinar & R. Mendelsohn (Eds.), *Handbook on Climate Change and Agriculture* (pp. 544-573). Edward Elgar Publishing Limited.
- DNP (Departamento Nacional de Planeación). (n.d). *La economía del arroz en Colombia.* [https://colaboracion.dnp.gov.co/CDT/RevistaPD/1980/pd\\_vXII\\_n1\\_1980\\_art.2.pdf](https://colaboracion.dnp.gov.co/CDT/RevistaPD/1980/pd_vXII_n1_1980_art.2.pdf)
- FEDEARROZ (Federación nacional de arroceros). (2021). *Contexto mundial nacional del cultivo del arroz: 2000-2020.* [file:///C:/Users/katin/Documents/BlackBox/rice/Informaciion%20para%20Colombia/Colombia/Cartilla\\_Contexto\\_Mundial\\_y\\_Nacional\\_del\\_cultivo\\_de\\_arroz\\_2000-2020\\_dXUOLuO.pdf](file:///C:/Users/katin/Documents/BlackBox/rice/Informaciion%20para%20Colombia/Colombia/Cartilla_Contexto_Mundial_y_Nacional_del_cultivo_de_arroz_2000-2020_dXUOLuO.pdf)
- FEDEARROZ (Federación nacional de arroceros). (2018). *Production cost in rice sector* [Data set]. <http://www.fedearroz.com.co/new/costos.php>
- FEDEARROZ (Federación nacional de arroceros). (2017). *IV Censo nacional arrocero.* [http://www.fedearroz.com.co/doc\\_economia/Libro%20Censo%20General.pdf](http://www.fedearroz.com.co/doc_economia/Libro%20Censo%20General.pdf)
- FEDEARROZ (Federación nacional de arroceros). (2015). *Nutrición y fertilización en el cultivo de arroz rojo (oryza sativa l).* *Revista Arroz*, 63(518), 14-20. <http://www.fedearroz.com.co/revistanew/arroz518.pdf>
- FEDEARROZ (Federación nacional de arroceros). (2011). *Dinámica del sector arrocero de los llanos orientales en Colombia: 1999-2011.* [https://fedearroz.s3.amazonaws.com/media/documents/Dinamica\\_del\\_sector\\_arrocero\\_en\\_los\\_Llanos\\_orientales.pdf](https://fedearroz.s3.amazonaws.com/media/documents/Dinamica_del_sector_arrocero_en_los_Llanos_orientales.pdf)
- FEDESARROLLO (Fundación para la Educación Superior y el Desarrollo), & ANDI (Asociación Nacional de Empresarios de Colombia). (2013). *Política comercial para el arroz.*
- FINAGRO (Fondo para el Financiamiento del Sector Agropecuario). (2014). *Perspectiva del sector agropecuario colombiano.* [https://www.finagro.com.co/sites/default/files/2014\\_09\\_09\\_perspectivas\\_agropecuarias.pdf](https://www.finagro.com.co/sites/default/files/2014_09_09_perspectivas_agropecuarias.pdf)
- Fischer, R.A., Byerlee, D. & Edmeades, G.O. (2014). *Crop yields and global food security: will yield increase continue to feed the world?* Australian Centre for International Agricultural Research.

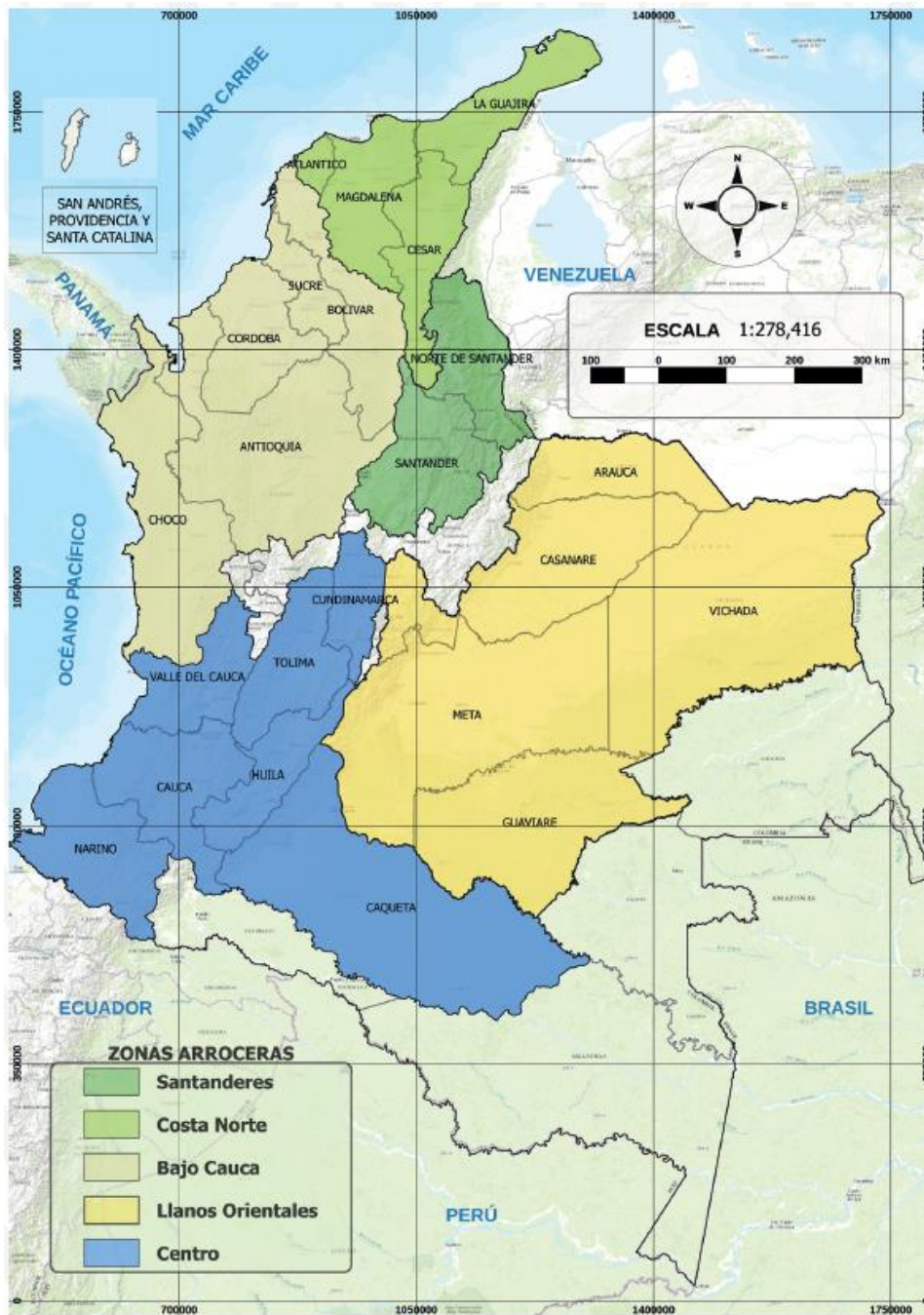
- FAO (Food and Agriculture Organization of the United Nations). (2002). World agriculture: toward 2015/2030. Summary report. <https://www.fao.org/global-perspectives-studies/resources/detail/en/c/411230/>
- ICBF (Instituto Colombiano de Bienestar Familiar). (2006). *Encuesta Nacional de la Situación Nutricional en Colombia*. (2005). Panamericana Firms e Impresos S.A.
- IDEAM (Instituto de hidrología, meteorología y estudios ambientales), PNUD (Programa de las Naciones Unidas para el desarrollo), MADS (Ministerio de ambiente y desarrollo sostenible), DNP (Departamento nacional de planeación), & Cancillería. (2015). *Nuevos escenarios de cambio climático para Colombia 2011-2100. Herramientas científicas para la toma de decisiones -Enfoque Nacional-Departamental: Tercera comunicación nacional de cambio climático.*
- IDEAM (Instituto de hidrología, meteorología y estudios ambientales). (2007). *Modelo institucional del IDEAM sobre el efecto climático de los fenómenos El Niño y La Niña en Colombia*. <http://www.ideam.gov.co/documents/21021/440517/Modelo+Institucional+El+Ni%C3%B1o+-+La+Ni%C3%B1a.pdf/232c8740-c6ec-4a73-a8f7-17e49c5edda0>
- Ji, D., Wang, L., Feng, J., Wu, Q., Cheng, H., Zhang, Q., Yang, J., Dong, W., Dai, Y., Gong, D., Zhang, R.H., Wang, X., Liu, J., Moore, J. C., Chen, D., & Zhou, M. (2014). Description and basic evaluation of BNU-ESM version 1. *Geoscientific Model Development*, 7(5), 1601-1647. <https://doi.org/10.5194/gmd-7-2039-2014>
- Liu, S., Pu, C., Ren Y., Zhao, X., Zhao X., Chen, F., Xiao, P., & Zhang H. (2016). Yield variation of double-rice in response to climate change in Southern China. *European Journal of Agronomy*, 81, 161-168. <https://doi.org/10.1016/j.eja.2016.09.014>
- Lomax., J. (2017, October 16). The link between rice sustainability and food security. *Rice Today*. <https://ricetoday.irri.org/the-link-between-rice-sustainability-and-food-security/>
- Lozano, I., & Restrepo, J.C. (2016). El papel de la infraestructura rural en el desarrollo agrícola en Colombia. *Coyuntura Económica: Investigación Económica y Social*, 46(1), 107-147. <http://hdl.handle.net/11445/3351>
- MINAGRICULTURA (Ministerio de Agricultura y Desarrollo Rural). (2018, May 19). *Colombia le apuesta a la competitividad del sector arrocero con investigación y desarrollo de nuevas variedades del grano*. <https://www.minagricultura.gov.co/noticias/Paginas/Colombia-le-apuesta-a-la-competitividad-del-sector-arrocero-con-investigación-y-desarrollo-de-nuevas-variedades-del-grano.aspx>
- Portafolio. (2019, August 12). El panorama que atraviesa el sector arrocero en Colombia. *Portafolio*. <https://www.portafolio.co/economia/el-panorama-que-atravesia-el-sector-arrocero-en-colombia-532502>
- Portafolio. (2018, February 18). Se busca integrar a toda la cadena del sector arrocero. *Portafolio*. <https://www.portafolio.co/negocios/se-busca-integrar-a-toda-la-cadena-del-sector-arrocero-514377>
- Ramírez-Villegas, J., Salazar, M., Jarvis, A., & Navarro, C. (2012). A way forward on adaptation to climate change in Colombian agriculture: perspectives towards 2050. *Climatic change*, 119, 565-574. <http://dx.doi.org/10.1007/s10584-013-0731-6>
- Rebolledo, M.C., Ramírez-Villegas, J., Graterol, E., Hernández-Varela, C.A., Rodríguez-Espinoza, J., Petro-Páez, E.E., Pinzón, S., Heinemann, A.B., Rodríguez-Baide, J.M., & van den Berg, M. (2018). *Modelación del arroz en Latinoamérica: Estado del arte y base de datos para parametrización*. Publications Office of the European Union.

- Schlenker, W., & Roberts, M. (2009). Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, 106(37), 15594-15598. <https://doi.org/10.1073/pnas.0906865106>
- Seck, P.A., Diagne, A., Mohanty, S., & Wopereis, M. (2012). Crops that feed the world 7: Rice. *Food Security*, 4, 7–24. <https://doi.org/10.1007/s12571-012-0168-1>
- Sheahan, M., & Barrett, C. (2017). Ten striking facts about agricultural input use in Sub-Saharan Africa. *Food Policy*, 67, 12-25. <https://doi.org/10.1016/j.foodpol.2016.09.010>
- Stephens, D.J., & Lyons, T. J. (1998). Rainfall-yield relationships across the Australian wheatbelt. *Australian Journal of Agricultural Research*, 49, 211-23. <https://doi.org/10.1071/A96139>
- Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, 93(4), 485-498. <https://doi.org/10.1175/BAMS-D-11-00094.1>
- UCAR (University Corporation for Atmospheric Research). (2022). *Climate Modeling*. <https://scied.ucar.edu/learning-zone/how-climate-works/climate-modeling#:~:text=Models%20use%20grids%20of%20%22cells,corners%20of%20the%20grid%20cells.&text=If%20the%20grid%20cells%20are,Earth's%20surface%2C%20increasing%20spatial%20resolution>
- UNIANDES (University of the Andes Foundation). (2018). *Microdata Catalog. Altitude per municipality* [Data set]. UNIANDES. <https://datoscede.uniandes.edu.co/es/catalogo-de-microdata>
- Van Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G., Kram, T., Volker, K., Lamarque, J.F., Toshihiko, M., Meinshausen, M., Nakicenovic, N., Smith, S., & Rose, S. (2011). The representative concentration pathways: an overview. *Climatic change*, 109, 5-31. <https://link.springer.com/article/10.1007/s10584-011-0148-z>
- Water Scarcity Clock. (2023, Agosto 31). *Average water availability per person 2020 (Map)*. <https://worldwater.io/>
- Wayne, G. (2013). *The beginner's guide to Representative Concentration Pathways*. Skeptical Science. [file:///C:/Users/katin/Documents/Dissertation%20Proposal%20Defense%20Presentations/Paper%201/bibliog%20future%20socioecn%20constant/RCP\\_Guide.pdf](file:///C:/Users/katin/Documents/Dissertation%20Proposal%20Defense%20Presentations/Paper%201/bibliog%20future%20socioecn%20constant/RCP_Guide.pdf)
- Yao, F., Xu, Y., Lin, E., Yokozawa, M., & Zhang, J. (2007). Assessing the impacts of climate change on rice yields in the main rice areas of China. *Climatic change*, 80, 395-409. <https://doi.org/10.1007/s10584-006-9122-6>
- Yu, Y., Zhang, W., & Huang, Y. (2014). Impact assessment of climate change, carbon dioxide fertilization and constant growing season on rice yield in China. *Climatic change*, 124, 763-775. <https://doi.org/10.1007/s10584-014-1129-9>
- Zhang, T., Zhu, J., & Wassmann R. (2010). Responses of rice yield to recent climate change in China: An empirical assessment based on long-term observations at different spatial scales (1981-2005). *Agricultural and Forest Meteorology*, 150, 1128-1137. <https://doi.org/10.1016/j.agrformet.2010.04.013>
- Zhou, Y., Li, N., Dong G., & Wenxiang W. (2013). Impact of recent climate change on rice yield in the Heilongjiang reclamation area of north-east China. *Journal of Science of Food and Agriculture*, 93, 2698-2706. <https://doi.org/10.1002/jsfa.6087>

# APPENDIX

## Appendix 1.

Rice regions in Colombia (2016).



Source: FEDEARROZ (2017)

## Appendix 2. Confidence intervals for the yield projections under the scenario RCP 4.5

### Period 2046- 2065

Department	Yield (2046-2065)	Standard Deviation	Confidence Interval	
			Lower bound	Upper bound
Antioquia	5.37	0.21	4.96	5.79
Atlántico	2.73	0.80	1.17	4.30
Bolívar	5.44	0.17	5.10	5.78
Caquetá	5.80	0.21	5.38	6.21
Cauca	5.53	0.26	5.02	6.04
Cesar	5.65	0.18	5.31	6.00
Córdoba	5.53	0.18	5.17	5.89
Cundinamarca	5.04	0.23	4.58	5.49
Huila	5.37	0.25	4.89	5.85
La Guajira	5.70	0.22	5.26	6.13
Magdalena	5.60	0.18	5.25	5.95
Meta	5.73	0.22	5.30	6.16
Norte de Santander	5.52	0.16	5.20	5.84
Santander	5.22	0.18	4.86	5.57
Sucre	5.48	0.19	5.10	5.86
Tolima	5.33	0.27	4.80	5.86
Valle del Cauca	4.88	0.26	4.37	5.40
Arauca	5.72	0.21	5.31	6.13
Casanare	5.72	0.24	5.26	6.19
Guaviare	5.80	0.20	5.40	6.20

### Period 2081- 2100

Department	Yield (2081-2100)	Standard Deviation	Confidence Interval	
			Lower bound	Upper bound
Antioquia	5.38	0.21	4.97	5.79
Atlántico	2.73	0.81	1.14	4.32
Bolívar	5.45	0.17	5.11	5.79
Caquetá	5.80	0.21	5.39	6.20
Cauca	5.57	0.26	5.06	6.07
Cesar	5.66	0.18	5.31	6.00
Córdoba	5.52	0.19	5.15	5.89
Cundinamarca	5.10	0.22	4.66	5.53
Huila	5.42	0.24	4.95	5.88
La Guajira	5.71	0.22	5.28	6.13
Magdalena	5.59	0.18	5.23	5.96
Meta	5.76	0.21	5.34	6.17
Norte de Santander	5.53	0.16	5.21	5.85
Santander	5.27	0.18	4.92	5.62
Sucre	5.46	0.21	5.06	5.87
Tolima	5.38	0.26	4.87	5.90
Valle del Cauca	4.91	0.26	4.40	5.42
Arauca	5.74	0.20	5.34	6.13
Casanare	5.74	0.23	5.28	6.19
Guaviare	5.80	0.20	5.41	6.19