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CIÊNCIAS AGRÁRIAS

Modeling of rice production areas in southern Brazil under extreme climate scenarios

Modelagem das áreas de produção de arroz no sul do Brasil sob cenários climáticos extremos

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RESUMO

O arroz é um importante produto agrícola brasileiro, sendo o estado do Rio Grande do Sul o maior produtor nacional da commodity. Como a agricultura é uma atividade extremamente dependente de condições climáticas, este estudo objetivou analisar os possíveis impactos de cenários de mudanças climáticas futuras na capacidade produtiva de arroz no sul do Brasil. Para isso, utilizou-se modelagem matemática de máxima entropia para a predição destes efeitos em dois cenários extremos, do ano de 2021 ao de 2100. Os dados demostram que em qualquer cenário há a projeção de redução das áreas produtivas no estado e a ocorrência de uma fragmentação dessas áreas, o que demandará diferentes estratégias de enfrentamento do efeito das mudanças climáticas sobre a produção de arroz no sul do Brasil.

Palavras-chave: Agricultura, Projeção, MaxEnt, Modelagem, SSP.

ABSTRACT

Rice is an important Brazilian agricultural product, with the Rio Grande do Sul State being the largest national producer of that commodity. Since agriculture is an activity that is extremely dependent on climate conditions, this study aimed to analyze the possible impacts of future climate change scenarios on rice production capacity in southern Brazil. To this end, maximum entropy mathematical modeling was used to predict these effects in two extreme scenarios, from 2021 to 2100. The data reveal that in any scenario there is a projection of a

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reduction in productive areas in the state and the occurrence of fragmentation of these areas, which will require different strategies to address the effect of climate change on rice production in southern Brazil.

***Keywords**: Agriculture, Projection, MaxEnt, Modeling, SSP.*

1. INTRODUÇÃO

Agriculture is a human activity that guarantees our survive, and it is totally dependent on environmental conditions (Conab, 2021).

Relative stability of weather conditions experienced by man in his history (Behling et al., 2009), since the discovery of possibility of growing food, allow development of cultivation techniques and new plant varieties. This historic moment allowed of obtaining not only food in a more stable way, but also fibers, drinks and medicines, allowing man explore and occupy better the potential of different environments and guarantee his subsistence.

Nowadays, however, climate change has started to attract global attention, since, undeniably, it began to respond to anthropic actions (IPCC, 2021) produced by the intense exploitation of the environment. These changes in the global climate are already being experienced all over the world, to a greater or lesser extent.

Climate change projections are only possible due to an increasingly robust set of data and analysis systems, which have come to justify the significant concern regarding issues of environmental conservation and the occurrence of extreme events. Above all, such changes and projections are worrying because they are associated with the global sustainability of food production, generating concerns in the socio-environmental and geopolitical scenario around the world for a still growing population (Mirzabaev et al., 2023).

Agriculture is an activity that is directly impacted by climate change, particularly the variables that allow populations of cultivated plants to express the maximum productive potential of each genotype (Gray and Brady, 2016; SOSBAI, 2018; ANA, 2021). Chhogyel at al., 2020, define which biophysical and environmental characteristics are determinant for the distribution and adaptability of living organisms. From this perspective, climatic conditions influence the potential agricultural productivity of a crop, as they are related to the limits of the physiological capacity of plants to support the climatic variables to which they are subjected, as well as influence phytosanitary or stress problems arising from environmental variations in limited areas of production.

According to the latest IPCC report, there is no doubt on the part of the scientific community regarding the human relationship with current climate change (IPCC, 2021).

It is a fact that this phenomenon of global scope must have consequences related to the safety of populations in sensitive areas, to biodiversity on Earth (guaranteeing the survival of other species) and, finally, it compromises our capacity to produce food of plant origin, being a trend that is practiced with increasing risk indices due to climate-related factors (Muluneh, 2021).

Rice is the second most cultivated and consumed cereal in the world (ANA, 2020), and the irrigated rice production system is responsible for 90% of Brazilian production. Irrigated rice is the most productive system, but clearly the most dependent on water availability.

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This production system accounts for approximately 25% of the total irrigated area in Brazil (considering all irrigated crops) and for 40% of the volume of water for agricultural use (ANA, 2021). According to the Grain Planting and Harvesting Calendar in Brazil (CONAB, 2021) rice is planted from September to November, with harvests from January to April.

In the 2015 to 2020 harvests, Brazil produced between 10.4 and 12.4 million tons of irrigated rice annually (CONAB, 2020; Embrapa, n.d.), with an average productivity of 7,000 kg/ha (SOSBAI, 2018). Rio Grande do Sul is, on the national scene, the largest Brazilian producer of irrigated rice, with 3 million hectares of floodplain cultivated with the grain. This planted area corresponds to 72.9% of the entire national irrigated rice production area, with Santa Catarina state accounting for 11.5% and Tocantins for another 8.4%. These three Brazilian states together are responsible for 92.8% of the area planted with rice in Brazil. However, rice cultivation has been suffering from a decrease in relation to the irrigated area in Rio Grande do Sul, a reduction of 255,000 hectares observed in the 2019/20 harvests, which represents 16% less cultivated area for the State (ANA, 2021).

These data show the climatic, soil and topographic potential of Rio Grande do Sul State for rice cultivation and the strategic importance of these production areas for national supply. The potential for expanding production activity in Rio Grande do Sul is also highlighted by the Agência Nacional de Águas e Saneamento Básico (ANA, 2021). The municipality of Uruguaiana, for example, with the largest planted area of irrigated rice in Brazil (79,727 ha), has a potential projection of 91,449 ha planted by 2030, reaching 102,105 ha in 2040, which reinforces the importance of irrigated rice for the gaucho agribusiness and the national supply of this, which is one of the most present food sources in the diet of Brazilians.

The projection made by the Agência Nacional de Águas (ANA, 2021) for the expansion of rice cultivation in Rio Grande do Sul, however, only considers the potential areas found in the State territory. However, future projections marked by climate change cannot be dissociated from climate projections that may or may not allow, in different scenarios and different classes of future time, the distribution of culture in potential areas in a given region.

Therefore, the objective of this research was to understand how "ideal areas" for irrigated rice are distributed in the State, the main producer, over time (from 2021 to 2100) and as a function of future climate scenarios SSP 1-2.6 (IPCC, 2021) and SSP5-5.8, using mathematical modeling based on a maximum entropy algorithm.

The SSP 1-2.6 scenario is characterized by being "moderate", considering that global CO2 emissions are completely suspended after 2050 (Zhao et al., 2021). The SSP 5-8.5 scenario is characterized by the "high emissions" scenario (Kriegler et al., 2017) in relation to the global future, thus defined by the high dependence on fossil fuels (IPCC, 2021).

This study aimed to analyze the possible impacts of future climate change scenarios on rice production capacity in southern Brazil, also aims to contribute to adoption of measures in relation to rice cultivation in southern Brazil, ranging from practices in the field to the adoption of economic policies in this sector.

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2. MATERIALS AND METHODS

2.1. Study Area

Rio Grande do Sul (RS) is the most southern Brazilian State in the national territory, establishing borders with Uruguay to the south and Argentina to the west and the Atlantic Ocean to the east. This study was based on the current area of irrigated rice production in the RS State, Brazil, specifically distributed over the southern half of the State where the municipalities that stand out in the production of this important national commodity are located.

2.2. Positioning of the production areas

The location of the points of this work were obtained from the list of the largest municipalities in the RS State that produced irrigated rice in the 2019/20 harvest.

Coordinates were used to select the points, specifically taken from the production areas, using images from the interactive system of the Irrigation Atlas of the National Water Resources Information System (ANA, 2021), confirmed through Google Earth. In the latter case, the most recent images available, from January 15th or as close as possible to it, were used in order to identify with greater certainty the subtle active areas of irrigated rice cultivation in each municipality.

Points of central coordinates (by the decimal degree system) obtained from functional cultivated areas of each of the eight municipalities with the largest areas of irrigated rice in the state of Rio Grande do Sul were used (Table 1), considering only the municipalities with areas planted over 30,000 ha and discarded areas of irrigated cultivation with the use of central pivot.

Table 1 - Municipal codes (see also map, Figure 1), irrigated cultivation area (except for central pivot) and percentage of land use for irrigated rice in relation to the total territorial area (IBGE, 2021), in the selected municipalities to obtain points in this work.

Municipality code	Municipality	Area of cultivation with irrigated rice (ha)	Territorial area total of the municipality (ha)	% of use of the municipal territory
(01)	Uruguaiana	79,726.9	570,209.8	13.98
(02)	Santa Vitória do Palmar	64,866.3	519,566.7	12.48
(03)	Itaqui	62,495.9	340,660.6	18.34
(04)	Alegrete	52,658.6	780,042.8	6.75
(05)	Dom Pedrito	37,748.5	519,405.1	7.27
(06)	São Borja	36,047.6	361,669.0	9.97
(07)	Mostardas	33,045.6	197,744.2	16.71
(08)	Arroio Grande	31,382.9	250,854.5	12.51

Source: the authors.

For the municipality of Uruguaiana, which has the largest area planted with irrigated rice in Brazil, 20 points distributed throughout its territory were taken. For the other municipalities, 10 points of the largest active planted areas in the territory were taken, which could be safely determined, according to the sources of images already mentioned.

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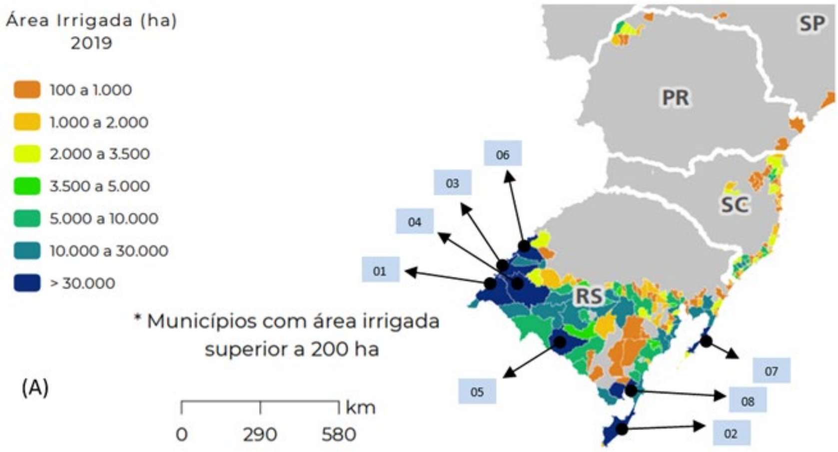
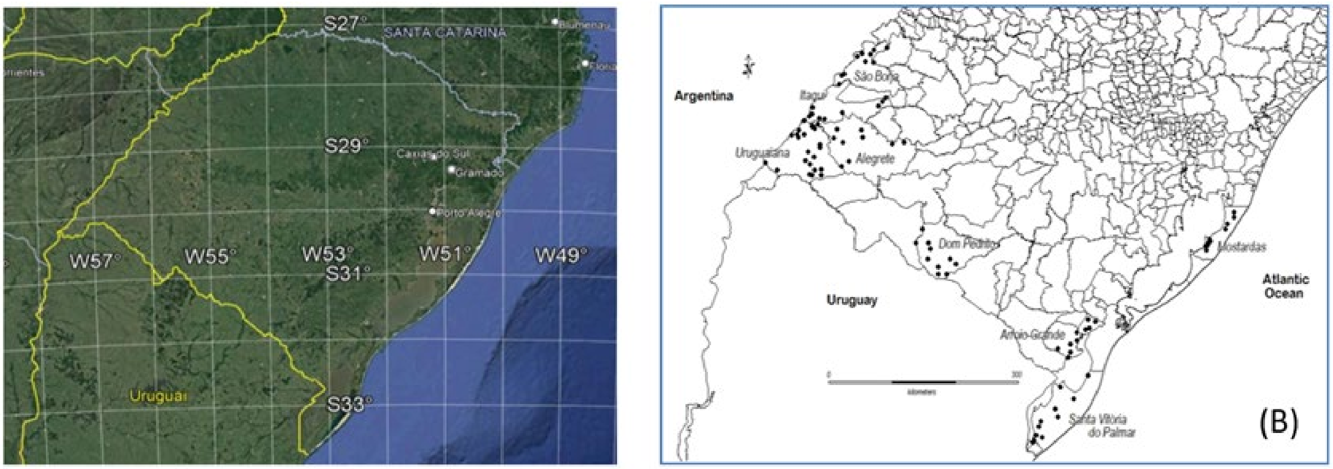
Figure 1 (A) - Map of the distribution of irrigated rice producing municipalities in southern Brazil, according to the size of the irrigated areas.



Source: adapted from ANA, 2021.

Figure 1 (B) - Maps of the territory of the Rio Grande do Sul State and of the sampling points for the mathematical modeling of the rice cultivation area in the state of Rio Grande do Sul.



Source: Google Earth and DivaGIS image, data from the authors.

2.3. Climate variables

For the forecast modeling, the Global Climate Model MIROC6 (Tatebe et al., 2019) was used, considering the SSPs (Shared Socio-economic Pathways): SSP 1-2.6 and SSP 5-8.5, in the four 20-year periods of the available future scenarios in the WorldClim database: 2021-2040, 2041-2060, 2061-2080, 2081-2100.

Nineteen bioclimatic variables (BioClim) were used, which constitute public domain data obtained from the website (https://worldclim.org/data/bioclim.html, version 2).

Altitude, an important variable for the analyses, was no longer used because it is not available in future models. These variables constitute average climate data for the years 1970-2000, with a spatial resolution of 2.5 minutes.

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The combined bioclimatic variables used were:

BIO1 = Annual Mean Temperature

BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp))

BIO3 = Isothermality (BIO2/BIO7) (×100)

BIO4 = Temperature Seasonality (standard deviation ×100)

BIO5 = Max Temperature of Warmest Month

BIO6 = Min Temperature of Coldest Month

BIO7 = Temperature Annual Range (BIO5-BIO6)

BIO8 = Mean Temperature of Wettest Quarter

BIO9 = Mean Temperature of Driest Quarter

BIO10 = Mean Temperature of Warmest Quarter

BIO11 = Mean Temperature of Coldest Quarter

BIO12 = Annual Precipitation

BIO13 = Precipitation of Wettest Month

BIO14 = Precipitation of Driest Month

BIO15 = Precipitation Seasonality (Coefficient of Variation)

BIO16 = Precipitation of Wettest Quarter

BIO17 = Precipitation of Driest Quarter

BIO18 = Precipitation of Warmest Quarter

BIO19 = Precipitation of Coldest Quarter

2.4. Modeling and presentation of data

The software used for the mathematical modeling for the prediction of rice growing areas was MaxEnt: Version 3.4.3, Nov 2020 (Phillips et al., 2020).

MaxEnt is an open software that uses maximum entropy modeling that has several applications, such as species niche modeling (Phillips et al., 2006). This resource is based on presence records, being a tool for studies in biological diversity, biogeography, ecology, biology, diseases caused by animals (Samy et al., 2016; Alcala-Canto et al., 2019; Abdalla, 2019), climate change, among many other applications (Elith et al., 2011; Zhang et al., 2018). Basically, the algorithm evaluates bioclimatic factors that occur in areas informed as presence (informed coordinates), and makes the prediction that other areas also present such environmental conditions, generating a model of probable distribution for the species (Phillips and Dudik, 2008; Merow et al., 2013). Although the case in this work is not specifically the ecological niche of a species, the distribution of areas made by the model addresses the same question: - which areas, in a given territory, present (currently) and will present the set of environmental conditions necessary for the establishment of the rice crop - in future scenarios?

During the preparation of future model data, the QGIS Desktop software, version 3.20.3, was used to convert the file in .TIFF format, obtained from the WorldClim database, to an .ASC format, entry in MaxEnt. As future climate files obtained from the database are presented in the form of multilayers, each layer (or band) represents one BioClim variable, so the bands were separated into independent files using QGIS. MaxEnt is powered with a coordinate plane (lat/long) of the occurrence points base (a .CSV file) in addition to the informed environmental variables to be able to perform combinatorial analyzes of points and environmental conditions.

The software was used with the following settings: auto features; create response curves, make pictures of predictions, the selected Output format was Logistic. After the data modeling by MaxEnt, the output file was converted to ASCII format, being processed in DIVAGis (Version 7.5.0.0), according to the classes of probability of occurrence of the modeled climatic conditions.

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The climatic suitability of rice indicated in the maps generated by the models was adapted from Chhogyel et al. (2020), having been categorized according to Table 2, according to the probability of occurrence of favorable climatic conditions for the crop.

Table 2 - Classification of the climate suitability of the models:

Category of suitability	Color	Probability of occurrence
Unsustable		<12.5%
Marginal		12.5-25%
Low		25-37.5%
Medium		37.5-50%
Hight		>50%
		No Data

Source: the authors.

Other authors, such as He and Zhou (2011), present different classes of percentages to compose the categorization, and these values depend on the objectives and the degree of specificity that each author seeks in their work. In this case, the planting regions that present more than 50% probability of occurrence of the cultivation conditions will be considered as highly suitable.

In order to evaluate the dynamics of these areas over future times, the areas, in km², and the perimeters, in km, were calculated, corresponding exclusively to the patches formed by the class defined as "high" probability. For this, the ImageJ software was used, taking exclusively the areas positioned within the Rio Grande do Sul State, although the images in this work present the continuity of the stains of the classes through the territories of other States, Uruguay and Argentina.

The receiver operating characteristic (ROC) curve is used to assess the accuracy of the model simulations and the "area below the ROC curve" is an indicator of this accuracy.

The output efficiency of the generated model was evaluated by the "Area Under the Curve" (AUC) indicator (Phillips et al., 2006). The AUC describes the relationship between the proportion of correctly predicted presences of species and the proportion of missing species incorrectly predicted in the model. In general, AUC values ranging between 0.9 and 1.0 show excellent prediction performance of the model, while AUC values ranging between 0.8–0.9 means good; 0.7-0.8 are mean values; 0.6-0.7 is bad and 0.5-0.6 is insufficient. (Thuiller et al., 2006; He and Zhou (2012), Galletti et al., 2013).

3. RESULTS AND ANALYSES

3.1. Applicability of the MaxEnt model

In order to validate the applicability of the model for the prediction of irrigated rice cultivation areas in Rio Grande do Sul, consolidated and current positions of the grain culture practice were used (Figure 2).

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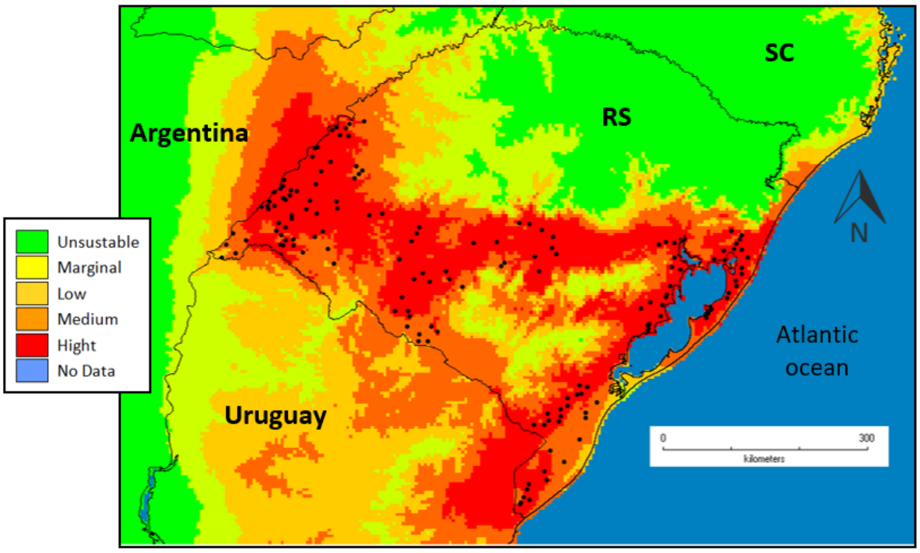
Figure 2 - Distribution of areas for rice cultivation in Rio Grande do Sul State, Brazil, under current climatic conditions (average conditions from 1970 to 2000). Points in the image represent verified areas of irrigated rice cultivation in the municipalities that constitute the largest producers in the State.



Source: DivaGIS image, authors data.

Table 3 shows the simulated effects of the SSP 1-2.6 and SSP 5-8.5 scenario, for each time interval (present and future), the variations of the total area with high potential for rice cultivation, the perimeter of the areas of this class, the AUC which represents the value of the algorithm's prediction quality for each modeled situation, as well as the participation of the four main bioclimatic variables in each simulated situation.

Table 3 – SSP 1-2.6 e SSP 5-8.5 - Total area with high availability of climatic conditions for irrigated rice, AUC and percentage participation of bioclimatic variables (PBV) in the models, in relation to the future time classes (from 2021 to 2100). In blue, the bioclimatic variables related to precipitation, highlighted and in orange, the variables related to temperature.

SSP 1-2.6										
	Currently (1970-2000)		2021-2040		2041-2060		2061-2080		2081-2100	
Total area (Hight)	81,655.6 km²		65,160.2 km²		66,300.3 km²		64,313.9 km²		56,839.5 km²	
Perimeter	8,022.4 km		6,733.8 km		6,916.6 km		7,236.5 km		7,246.1 km	
AUC	0.992		0.989		0.989		0.989		0.990	
Participation of bioclimatic variables (PBV)	PBV	%	PBV	%	PBV	%	PBV	%	PBV	%
	14	57.3	4	35.8	4	38	14	35.2	4	39.1
	4	14	14	30.3	14	26.3	4	33	17	22.9
	17	12.9	17	13.8	17	15.4	3	14.3	14	19
	3	12.1	3	12.8	3	10.3	17	7.9	3	7.4
	Sum	96.3%	Sum	92.7%	Sum	90%	Sum	90.4%	Sum	88.4%

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SSP 5-8.5										
	Currently (1970-2000)		2021-2040		2041-2060		2061-2080		2081-2100	
Total area (Hight)	81,655.6 km²		64,981.36km²		65,081.99km²		76,377.18km²		61,124.92km²	
Perimeter	8,022.4 km		7,214.36 km		7,301.11km		6,030.19km		6,473.93km	
AUC	0.992		0.989		0.989		0.990		0.989	
Participation of bioclimatic variables (PBV)	PBV	%	PBV	%	PBV	%	PBV	%	PBV	%
	14	57.3	4	34.3	4	34.1	4	29.7	17	38.1
	4	14	14	25.9	14	21.8	3	21.7	4	32.3
	17	12.9	17	19.1	17	19.4	17	20.6	3	15
	3	12.1	3	10.2	3	14.2	14	17.6	6	4
	Sum	96.3%	Sum	89.5%	Sum	89.5%	Sum	89.6%	Sum	89.4%

Colors and PBV description:

	BIO3 = Isothermality (BIO2/BIO7) (×100)
	BIO4 = Temperature Seasonality (standard deviation ×100)
	BIO6 = Min Temperature of Coldest Month
	BIO14 = Precipitation of Driest Month
	BIO17 = Precipitation of Driest Quarter

Source: the authors.

For the model based on current climate data, not only was MaxEnt able to well represent the general map of production zones according to the CONAB mapping (2020) (Figure 2), but also revealed an AUC value that can be classified as "excellent": 0.992. He and Zhou (2011), for example, used the MaxEnt algorithm to define corn growing areas in China based on 366 points and arrived at values considered "good", with an AUC of 0.818.

In this work, both for the simulation of the present and for the other periods of time and scenarios studied, MaxEnt was also able to make extremely reliable predictions, the lowest being AUC 0.989, classified as "excellent".

3.2. Major climatic factors affecting the geographic distribution of rice cultivation

The environmental variables that showed the greatest participation in the model results were: BIO3, BIO4, BIO14 and BIO17. These four variables contribute with different percentages in each simulation (present model and in future time intervals), but appear in all time classes with the highest percentage of contribution in relation to the other environmental variables tested. That is, 21% of the variables tested explain approximately 90% of the occurrence of favorable spots at all time intervals.

In addition to these, the variable BIO6 (dark orange in the Colorsand PBV description, Table 3) appears in one of the future projections, when the SSP5-8.5 scenario is simulated in the period 2081-2100, collaborating in the composition of the most significant variables of the models.

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Despite rice being a summer crop in southern Brazil, the variable BIO6 – Minimum Temperature of Coldest Month, appeared as a key predictor under the SSP5-8.5 scenario for the period 2080–2100. This may reflect the influence of winter temperatures on factors such as soil water availability, pest and disease cycles, and planting conditions. Additionally, warmer winters may expand the potential range for rice cultivation into areas currently limited by cold extremes. Thus, BIO6 likely captures indirect environmental constraints that become more relevant under future climate conditions.

The variable BIO3: "Isothermality", basically constitutes an index of temperature variability containing the relationship between the average range of the day and the average annual amplitude (Abdalla, 2019), corresponding to the expression

(BIO2 / BIO7) (×100),

that is, a ratio between the range of average, minimum and maximum diurnal temperatures (BIO2) and the annual temperature range (maximum temperatures of the warmest months and minimum temperatures of the coldest months).

The variable BIO4 corresponds to the seasonality of temperature, that is to say, it is a coefficient of variation that indicates the temperature value due to the four seasons of the year.

The variable BIO14 corresponds to the precipitation of driest month, while the variable BIO17 corresponds to the Precipitation of Driest Quarter, therefore, variables related to precipitation in months and in drier dry seasons.

Variable BIO6 represents the minimum temperatures in the coldest month.

Thus, three of the most important variables present in the models are related to temperature, and two others, to precipitation.

Environmental variables are able of influencing organisms of the same genus in different ways, and may cause two species to be distributed or behave differently as these environmental changes occur (Alcala-Canto, 2019). Therefore, a methodological difficulty in this analysis is to recognize cultivated rice as an organism with the same set of characteristics and environmental potential. Evidently, there is a set of different rice cultivars indicated for different regions (SOSBAI, 2018), and each of these cultivars is capable of responding differently than established by these models. However, data about cultivars were no found between public and private agencies consulted that would allow an independent evaluation by each cultivar.

However, an approach like this still makes it possible to understand, in a general way, the effects of climate change on crop areas, while a more specific analysis is not possible due to lack of data on the different cultivars practiced in these areas.

It can also be seen in Table 3 that the annual, diurnal and seasonal temperature is combined with the distribution of precipitation in the driest months and seasons for the qualification of an area and the selection of areas in which the model indicates how suitable for cultivation in the study region, as indicated by the participation of bioclimatic variables in the construction of the models.

The combination of these climatic elements was able to present categorized patches that generated predictive maps of suitable areas for irrigated rice cultivation in southern Brazil according to the selected climate change future scenarios, between the years 2021 to 2100 (A-H of Figure 3).

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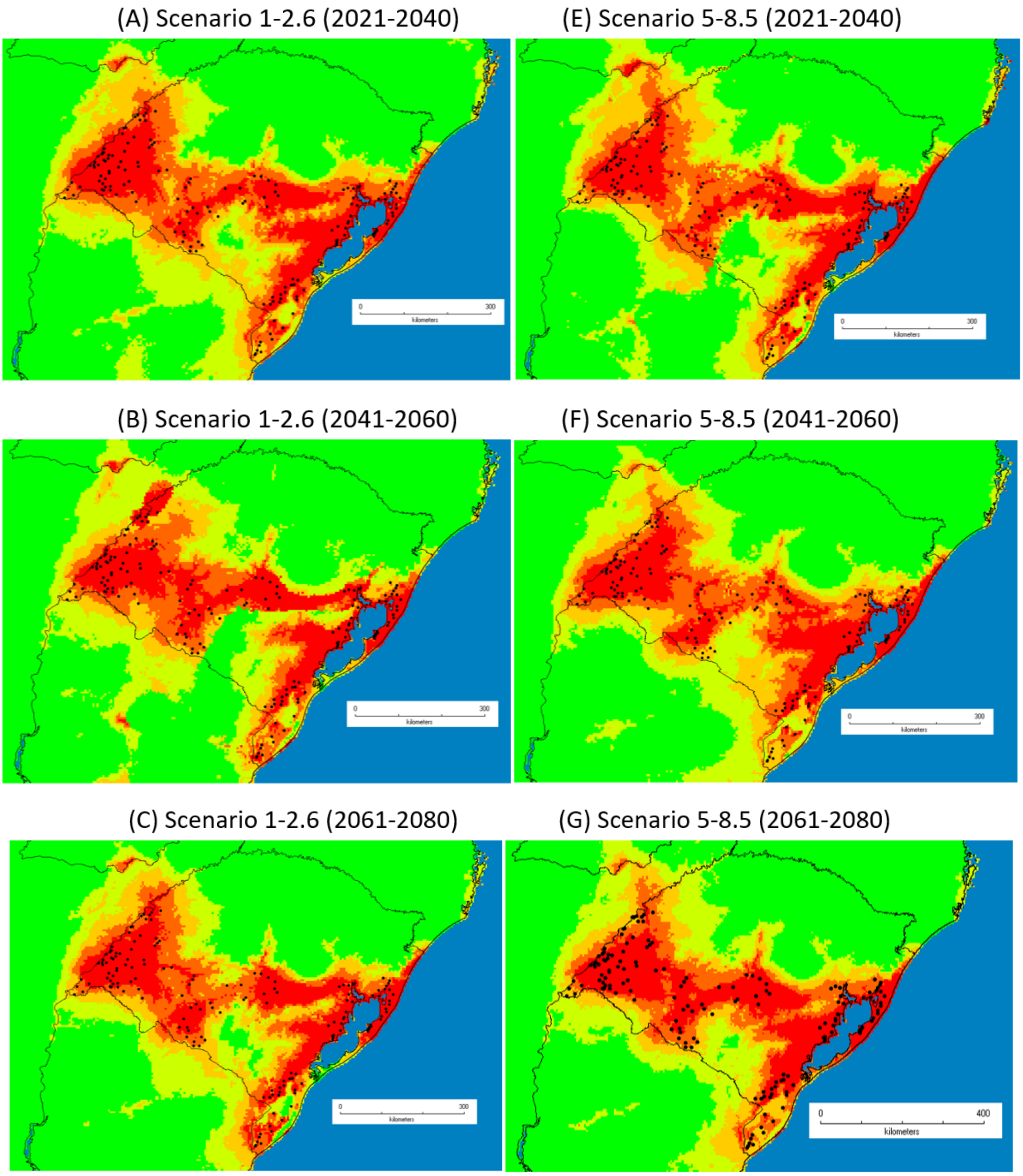
Figure 3 – Distribution of areas for irrigated rice cultivation in Rio Grande do Sul, under different future climatic conditions. (A to D): Scenario 1-2.6; (E to G); Scenario 5-8.5. Points in the images represent verified areas of irrigated rice cultivation in the municipalities that constitute the largest producers in the State.



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(D) Scenario 1-2.6 (2081-2180) (H) Scenario 5-8.5 (2081-2100)

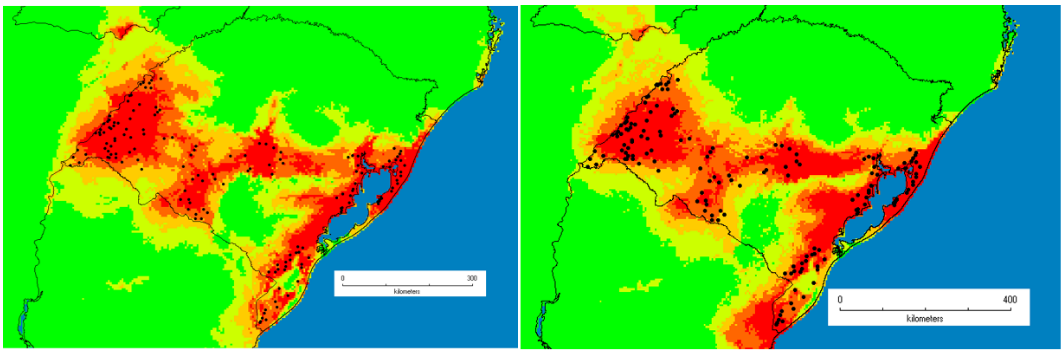


Image from DivaGIS, data from the authors.

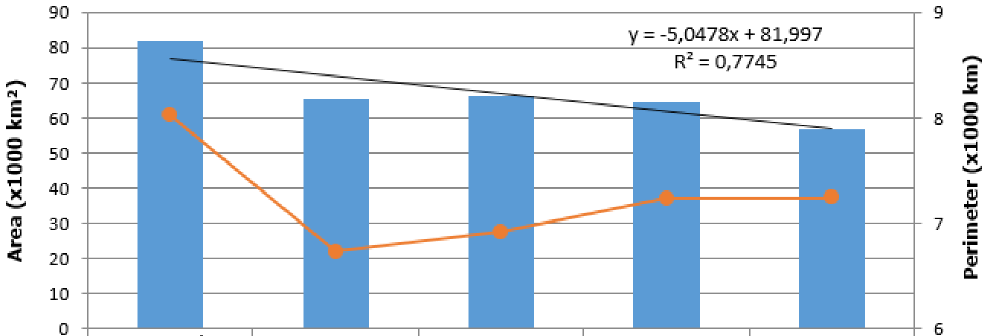
The colors presented in these maps are those already mentioned in Table 2 (Classification of the climate suitability of the models) and correspond to the adequacy of the areas (from high to a marginal adequacy), while inadequate areas are presented in light green and, in blue, the areas for which data do not apply.

The areas available for the cultivation of irrigated rice in Rio Grande do Sul State could be expressed in square kilometers (sq km or km²) by calculating the area and perimeter, in kilometers (km), of the patches of high climatic affinity, using the ImageJ software.

A more detailed analysis of the areas and perimeters of these spots are better represented by the graph, Figure 4.

Figure 4 - Temporal dynamics of areas favorable to irrigated rice cultivation in the Rio Grande do Sul State, Brazil, as a function of the SSP 1-2.6 [A] and SSP 5-8.5 [B] scenarios. Areas (and their trendline) and perimeters of ideal spots by time interval.

[A] Scenario SSP 1-2.6



	Currently	2021-2040	2041-2060	2061-2080	2081-2100
Total area (Hight)	81,656	65,160	66,300	64,314	56,840
Perimeter	8,022	6,734	6,917	7,237	7,246

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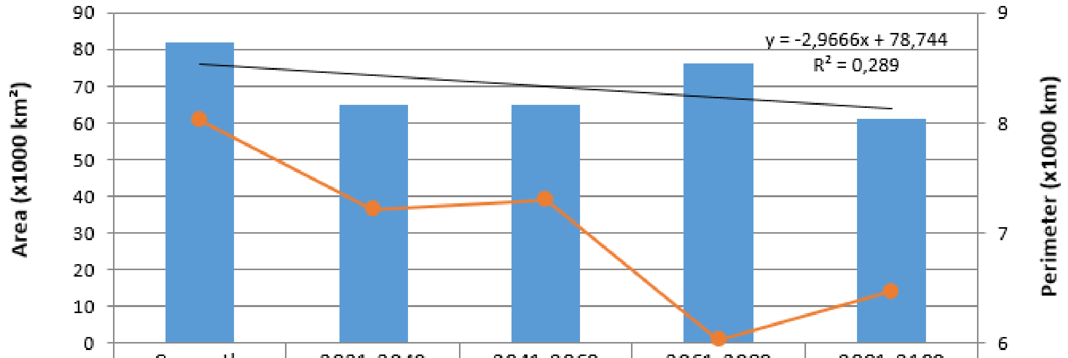
[B] Scenario SSP 5-8.5



	Currently	2021-2040	2041-2060	2061-2080	2081-2100
Total area (Hight)	81,656	64,981	65,082	76,377	61,125
Perimeter	8,022	7,214	7,301	6,030	6,474

Total area (Hight) — Perimeter — Linear (Total area (Hight))

Source: the authors.

For the SSP 1-2.6 scenario (Figure 3.A) there is a discontinuity in the result of areas currently available in relation to future projections. If we disregard the current distribution of the model (based on a dataset from 1970-2000), we observe in the future series a general reduction trend in areas until the year 2100, although it is also possible to perceive a slight tendency to increase the favorable areas until the year 2060, when this trend breaks, with a regression and later, in the following two decades, further reductions in area.

When we evaluated the perimeter line of the areas defined as "ideal" for future projections (2021 to 2100), on the other hand, we observed an increase in the total perimeter of these areas, indicating the possibility of a significant fragmentation of the large areas considered ideal for the future, as time progresses. "Dividing the whole, into parts", which could be one of the concepts of fragmentation, indicates for the scenario not only a future of reduction of areas of high suitability in the State, but also of increasingly fragmented areas, which, in any case, constitutes a problem for the maintenance of cultivation in the region.

The increase in areas favorable for rice cultivation, and consequently an increase in the potential of grain productivity until 2060, coincides with the description of SSP 1-2.6 since, in this future scenario, the use of fossil fuels should contribute to the increase in CO2 in the atmosphere by the year 2050, after which, other forms of energy and ecosystem management must be responsible for reducing these gases in the atmosphere. Such a prediction of the scenario may justify an increase in production, since rice is a plant that uses the C3-type carbon fixation method. Plants that use this system take advantage of an increasing amount to convert into productivity (Gray and Brady, 2016). Double the amount of CO2 in the environment, for example, can increase grain production about 30% in C3 species, such as rice, but less than 10% for C4 species (Hatfield et al., 2011). Therefore, the increasing availability of CO2 in the atmosphere, until 2050, can increase not only the areas but also the grain yields in the study region, although these areas are more fragmented, interspersing with areas of lower aptitude.

When analyzing the effect of a future scenario based on the exploitation of fossil fuels (SSP 5–8.5), what the graph shows us is that the most suitable areas will still be reduced, but a smoother

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reduction in each period of time. Here, the progressive increase in greenhouse gases must be related to other factors (linked to bioclimatic variables) that fail to compensate for the fact that the rice plant benefits from the C3 photosynthetic strategy, such as climatic disorders linked to changes in temperature or rainfall in cultivation season.

Regarding the perimeter of these patches, an initial trend of increase until 2060 is broken with a trend of unification of patches, which may explain the sharp reduction in the perimeter and the increase in the area observed in the 2061-2080 interval, following, later, the trend of loss and increasing fragmentation of areas of high suitability for rice cultivation.

4. CONCLUSION

This study assessed the influence of 19 bioclimatic variables on the distribution of potential areas for irrigated rice cultivation in southern Brazil, in relation to the current scenario and future climate change scenarios: optimistic and pessimistic (SSP 1-2.6 and SSP 5-8.5, respectively), in the period from 2021 to 2100.

The modeling performed demonstrated excellent prediction capacity in all present and future analyses, in both scenarios tested.

The areas with the greatest affinity for rice cultivation defined by the algorithm would currently correspond to 29% of the total area of the state: (281,707.149 km²). When the predictions for the most optimistic scenario are verified, this area would show a "real" loss of area of 8.8%, or the equivalent of 24,790.2 km² of area.

In a scenario of more pronounced climate change, the percentage losses of areas of high suitability compared to the present would be smaller, since rice could benefit from these future conditions. Losses, in this case, could be 7.3%, or 20,564.6 km² at the end of the period evaluated.

The loss of areas of high affinity for this crop is significant in any case. In the scenario of lower potential loss of areas of high suitability by the year 2100, the reduction would be greater than the entire territorial extension of the three largest municipalities in Rio Grande do Sul combined: Alegrete (with its 7,800.16 km²), Sant'Ana do Livramento (with 6,946.41 km²) and Uruguaiana (with 5,702.01 km²), which contradicts the estimate of an increase in areas for cultivation in Rio Grande do Sul, according to the National Water and Basic Sanitation Agency (ANA, 2021). The data presented can support decision-making regarding strategies for rice cultivation in the State of Rio Grande do Sul in a scenario of climate change and highlights the importance of measures that can reduce the effects of climate change, since it directly affects the capacity for food production and sustaining the regional and national economy.

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