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Climate Change Impacts on Agricultural Suitability in Rio Grande do Sul, Brazil

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Abstract

Changing climatic conditions are significant determinants of agricultural productivity. Rio Grande do Sul is the southernmost state and the second-largest agricultural producer in Brazil. The suitability of its land for farming can be used as a proxy for agricultural and economic success, making it a pertinent case for exploring the consequences of climate change on major crop production. The latest available climate and environmental data was used to develop an agricultural Suitability Index (SI) that quantifies the suitability of land for rice, tobacco, soybean, and corn production in 2020 (present), 2050 (near-future), and 2100 (far-future) under moderate (SSP245) and extreme (SSP585) climate scenarios. SI scores for each municipality of Rio Grande do Sul consider inputs from a three-layer framework (climatic, non-climatic, and current production) to provide critical insight into potential shifts in agricultural productivity. While terrestrial suitability for crop growth varies both spatially and temporally, widespread decreases in suitability for all four crops are expected across the state under both scenarios. Soybean is expected to be the least affected crop, and rice is the most affected crop, tied to shifting patterns in precipitation, which significantly determines suitability. Local and state governments, agribusinesses, and family producers will have to adapt to environmental challenges to ensure the provision of food, labor, and economic security.

Keywords: agriculture; climate change; suitability; agronomy; soybean; tobacco; corn; rice; Brazil; Rio Grande do Sul

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1. Introduction

Climate is considered to be the paramount determinant of agricultural productivity, and changing climatic conditions severely impact agricultural production patterns [1,2]. Brazil, a world leader in agriculture, has the potential to contribute significantly to meeting the rising demand for food and has already demonstrated incredible mass expansion of its agricultural production in recent decades, although at the expense of the natural environment [3,4]. Brazil is particularly vulnerable to changes in precipitation patterns under anthropogenic climate change, with the tropical coast of South America projected to face heavy endowments of pollutants from tributaries and key fluvial systems throughout the Rio de la Plata Basin [5].

Agricultural production capacity in Brazil is determined by changes in human capital, technology generation and diffusion, and natural resources and weather [6] (pp. 91–104). The southernmost state of Brazil, Rio Grande do Sul (RS) (shown in Figure 1), ranks consistently in the top three states for production of Brazil's most critical crops [7,8].

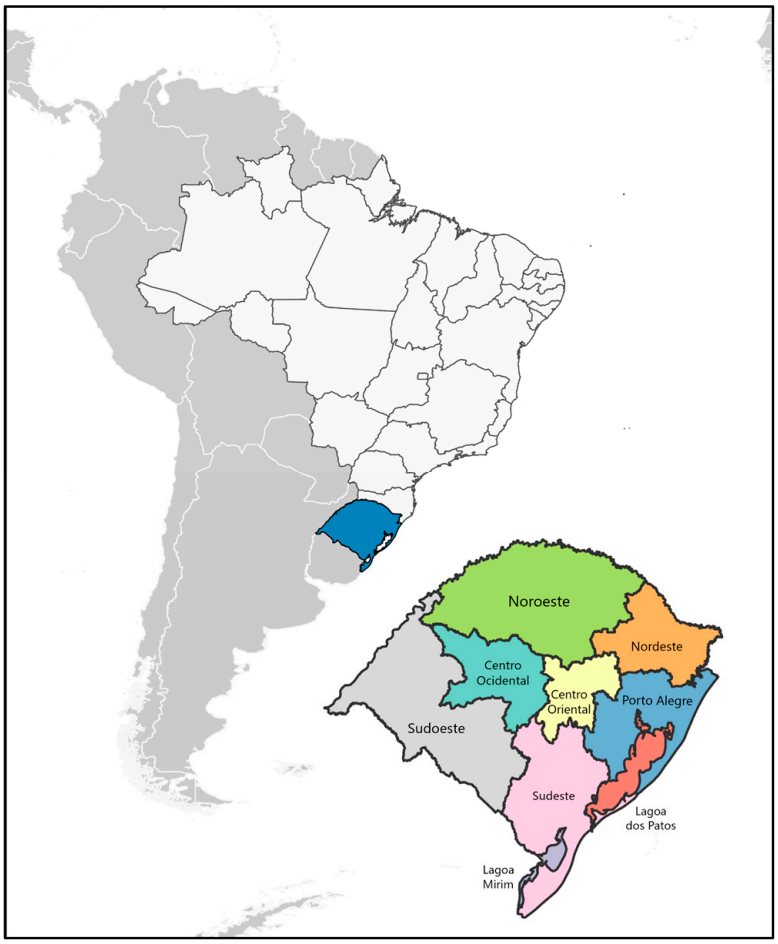

Figure 1. Rio Grande do Sul, the southernmost state of Brazil, and its nine mesoregions.

As a mostly humid subtropical region, RS has well-defined seasonal temperature and precipitation patterns that lend themselves well to agricultural production. The northern portion of the state is elevated along a plateau bordering the states of Santa Catarina and Paraná [9]. The western portion of the state encompasses grasslands ideal for pastoral work and livestock rearing, while the eastern coastal portion contains both the state's lagoons and the outlets of the river system drainage [9]. Despite coastal access, the region has experienced severe droughts in recent years. Along with increased hazardous environmental events like storms and floods, the maintenance of both life and agriculture has become increasingly at stake in RS. In April 2024, the worst Brazilian flood recorded in 80 years hit the state, killing 181 people, displacing 386,000, and affecting 2.3 million [10], with some estimates putting the displaced population above 600,000 [11]. Experts suggested this tragedy was strengthened by climate change [12,13]. The losses in the agricultural sector are estimated to be stark, including a Brazilian bank's estimate of a 3.5% recession in all of Brazil's agricultural Gross Domestic Product (GDP) from the previous year [12].

Agribusiness made up 40% of RS's GDP in 2021 and contributed to 73% of all state exports, which, in 2022, totaled USD 15.7 billion [14,15]. RS was responsible for 68% of Brazil's rice production, making it the largest producing state and generating USD 2.8 billion or 13% of the state's Gross Value of Agricultural Production (GVP, including livestock) in 2023 [16]. RS is also the leading exporter of tobacco in the country, generating USD 897 million in 2023 and 5% of the state's GVP [16]. Corn is one of the most evenly distributed crops across the state, being harvested in 98% municipalities (485 of 497) and making up 4% or USD 719 million of the state's GVP [16]. Soybean is by far the most profitable agricultural product in RS, making up 31% of the state's GVP and generating

USD 6.8 billion in 2023 [16]. Due to their economic importance, these four agricultural products are important determinants of both state livelihood and landscape sustainability. Demand for these crops will be threatened by changing climatic conditions, making the future adaptability of the land crucial. To meet these challenges head-on, producers may need to consider the implementation of alternative crops, upscale agroforestry techniques, and re-evaluate environmentally harmful farming practices.

Efforts to model Brazilian agriculture are ongoing but focus on global- and national-level analysis, lacking relevance for RS at the state level. Other agriculture, sustainability, and land use research has been conducted on specific regions or disciplinary focuses within RS [17–19], but at the intersection of climate change and agriculture, there is little scholarly work. Our research fills the gap in bringing attention to climate change impacts on the crops that matter most to RS's agribusiness sector and communities.

2. Methods

2.1. Modeling Agriculture Suitability

The agricultural Suitability Index (SI) was created based on three aggregated factors [20]. The first, the climatic factor, is based on crop-specific growth criteria for temperature and precipitation (Section 2.2). The second, the non-climatic factor, determines the land conditions to support the growth of each crop based on terrain and soil type (Section 2.3). The third factor is based on the spatial distribution of current agriculture as a proxy for modern growth suitability (Section 2.4). SI ranks the ability of the land to meet minimum or maximum standards for specific crop growth on a scale from zero to four—a range resulting from a final summation of factors in which the non-climatic and agricultural factors each have a maximum of one and the climatic factor has a maximum of two to account for its dynamic and predictive nature. The full dataset contains 11,928 data points encapsulating all modeled scenarios. Summary statistics and categories of low, medium, and high suitability, created based on frequency distributions, were used to capture the main patterns of this study.

Municipal SI was estimated by overlaying municipality boundaries and estimating mean zonal statistics based on the number of grids within each municipality. The lower the SI ranking for a municipality, the less suitable the area is for producing a specific crop in a certain year, and the closer the index is to four, the more suitable the land is for crop production. Mesoregions were used for some statistical and visual analysis to simplify references to regional areas (Figure 1). SI for these regions was calculated based on mean zonal statistics of SI rather than the averaging of municipal scores.

2.2. Climate Data

The National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM), part of the Coupled Model Intercomparison Project 6 (CMIP6), was used to obtain climate data through the Earth System Grid Federation data portal [21]. Daily surface air temperature and precipitation were both collected from NCAR-CESM for three periods—2015–2024 centered on 2020 (present), 2045–2054 centered on 2050 (near-term), and 2095–2104 centered on 2100 (long-term) for two shared socio-economic pathways (SSP). SSP245 is the 'middle-of-the-road' pathway, which projects a steady increase in greenhouse gas emissions through the end of the century, and SSP585 is the 'fossil-intensive' pathway, which projects the highest increase in greenhouse gas emissions in the atmosphere, intensifying spatial and temporal patterns of heat, drought, and overall climate impacts. Daily averages for each period were then used to produce decadal daily means to avoid biases associated with unusually hot or cold years within each period. By 2050, temperature over RS is projected to increase under SSP245 by more than 2 °C in the northern reaches of

the state and a much slighter 0.5 °C in the southwestern, with gradual variation in between. That increase remains steady through the end of the century, where some northern parts of RS are expected to warm by up to 3.3 °C. Under SSP585, those same spatial patterns intensify, with a maximum expected increase in northeastern RS of up to 2.8 °C by 2050 and up to 6.5 °C by the end of the century, particularly impacting the coastal region. Annual precipitation is similarly projected to increase across the state, though with contrasting spatial patterns. Under SSP245, an increase of several hundred mm/year is expected south of the Paranà Plateau by 2050 but only north of the plateau by 2100. Under SP585, the southern region would see a much smaller increase in precipitation, with some northeastern parts of the state experiencing a decline of up to 100 mm/year by 2050 and a slight increase only in the inland southwestern part of RS by 2100.

The daily decadal average temperature was then used to calculate annual growing degree days (GDDs), defined by the number of days within the ideal thermal growing window of a minimum and maximum daily average temperature for rice, tobacco, corn, and soybean (Table 1). An annual sum of precipitation was calculated based on each crop's minimum precipitation level for growth (Table 1) [22–24]. GDDs and annual precipitation were then normalized between zero and one using minimum-maximum normalization. The final climate factor layer was created for each crop by adding normalized GDD and total annual precipitation on a scale from zero to two.

Table 1. The criteria for model inputs are assumed ideal for crop growth.

Indicator	Rice	Tobacco	Corn	Soybean
Temperature/Thermal Growing Window (°C)	20–27	20–30	25–35	16–30
Precipitation (mm/year)	≥1200	≥600	≥550	≥500

2.3. Non-Climatic Data

Soil type was obtained from Brazilian soil type maps available through NASA's Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) [25]. The 19-class maps were chosen for this analysis in the interest of grid resolution and model processing time. Soil types were ranked in relative order based on ideal characteristics for crop growth, like soil pH and moisture content [26–28], and normalized to be between zero and one. Slope was calculated from a digital elevation model (DEM) at 30 arcseconds according to maximum percent slopes using NASA's Shuttle Radar Topography Mission (SRTM) outputs [29]. Previous studies found that slopes above 18 percent increase soil erosion and hinder crop growth [30], so only slopes below 18 percent were considered suitable for agriculture and were normalized. Normalized slope and soil types were merged into a non-climatic suitability factor ranging from zero to one.

2.4. Agriculture Data

The Brazilian Institute of Geography and Statistics (IBGE) produces municipal data on crop production and harvests, available through the Municipal Agricultural Production (PAM) portal. Current agriculture was obtained from counts of total produced tons per crop for all four crop foci in 2020 (Figure 2)—the most recent data available on PAM [31]. This data, arranged by municipality, was georeferenced and transformed into a grid at a resolution of 0.25 degrees. The normalized tons of agricultural inputs range from zero to one.

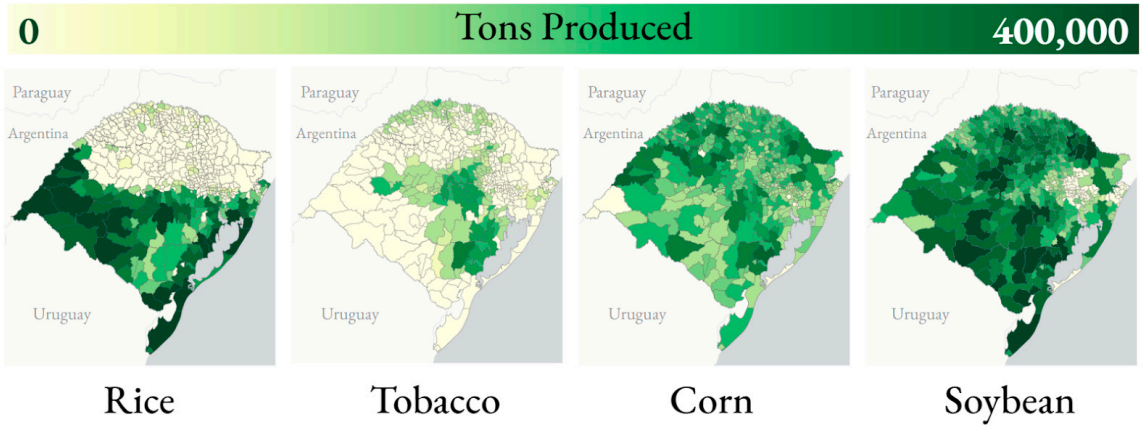

Figure 2. Tons of agriculture produced in Rio Grande do Sul in 2020, based on IBGE statistics [31].

3. Results

3.1. Agricultural Suitability Patterns and Change

At present, RS has a mean suitability value of 2.36, with a minimum index of 0.18 (least suitable) and a maximum of 3.44 (most suitable). Across all four crops, SI scores show a tendency to decrease with time (Figure 3). Under SSP245, the mean SI for each crop had a slight increase from 2020 to 2050 and a larger decrease from 2050 to 2100 (Table 2). Under SSP585, the mean SI for each crop decreased from 2020 through 2100. With a few exceptions, soybeans consistently had the highest mean SI compared to other studied crops, while rice had the lowest SI. SI can also be represented in categories, summarized in Table 3, as percentages of municipalities within low, medium, and high suitability categories, and as average mesoregion scores (Table 4).

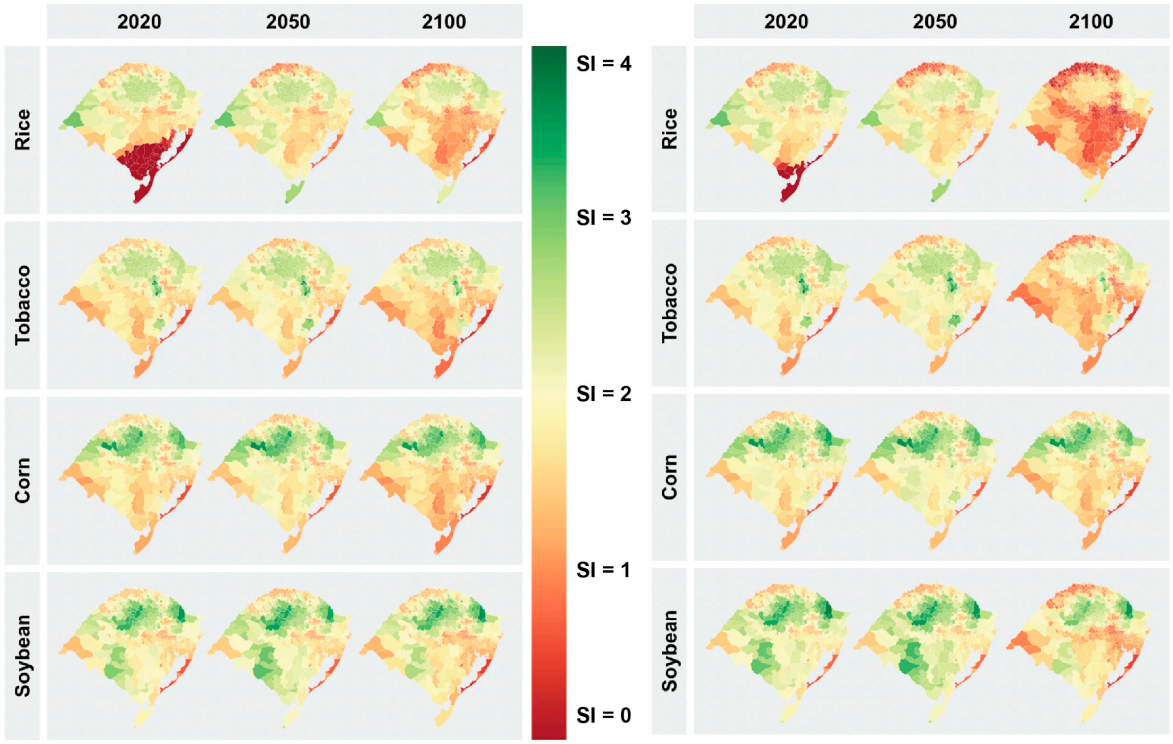

Figure 3. SI Scores for Rio Grande do Sul municipalities under SSP245 (**left**) and SSP585 (**right**). Despite being referenced as the "present" period, SI results for 2020 use forced data for two different climate scenarios, which are projections rather than historical records, causing the "present" period to have slightly different outcomes based on SSP.

Table 2. Summary statistics of the SI for four selected crops under SSP235 and SSP585 for present (2020), short (2050), and long-term (2100).

		Model Subset	Mean	ST.Dev	Median	Min	Max			Model Subset	Mean	ST.Dev	Median	Min	Max
		Full dataset	2.37	0.33	2.36	0.18	3.44			**Full dataset**	2.37	0.33	2.36	0.18	3.44
SSP 245	**Rice**	2020	2.28	0.43	2.33	0.18	3.02	**SSP 585**	**Rice**	2020	2.37	0.29	2.38	0.85	3.04
		2050	2.41	0.30	2.39	1.44	3.44			2050	2.28	0.29	2.29	1.66	3.12
		2100	2.22	0.30	2.18	1.44	2.89			2100	1.88	0.29	1.86	1.34	2.82
	Tobacco	2020	2.40	0.27	2.38	1.62	3.32		**Tobacco**	2020	2.45	0.27	2.44	1.65	3.44
		2050	2.41	0.27	2.39	1.66	3.34			2050	2.44	0.28	2.43	1.72	3.43
		2100	2.36	0.29	2.33	1.47	3.21			2100	2.22	0.30	2.20	1.53	3.16
	Corn	2020	2.43	0.29	2.38	1.63	3.25		**Corn**	2020	2.48	0.28	2.46	1.65	3.27
		2050	2.44	0.29	2.41	1.67	3.32			2050	2.48	0.28	2.46	1.74	3.33
		2100	2.40	0.32	2.35	1.47	3.24			2100	2.41	0.30	2.36	1.58	3.29
	Soybean	2020	2.44	0.30	2.41	1.63	3.29		**Soybean**	2020	2.49	0.30	2.47	1.65	3.38
		2050	2.44	0.31	2.42	1.71	3.22			2050	2.48	0.31	2.45	1.76	3.30
		2100	2.40	0.32	2.35	1.47	3.31			2100	2.26	0.33	2.23	1.56	3.27

Table 3. Percentage of municipalities with SI scores ranking low, medium, or high Suitability.

		Model Subset	% Low	% Medium	% High			Model Subset	% Low	% Medium	% High
SSP 245	Rice	2020	16	68	16	SSP 585	Rice	2020	12	71	17
		2050	20	65	15			2050	22	69	8
		2100	32	57	11			2100	70	30	0
	Tobacco	2020	7	73	20		Tobacco	2020	2	76	22
		2050	9	71	20			2050	7	70	23
		2100	12	71	18			2100	29	66	5
	Corn	2020	7	72	21		Corn	2020	1	76	23
		2050	6	72	22			2050	0	77	23
		2100	11	68	21			2100	9	70	21
	Soybean	2020	7	71	23		Soybean	2020	1	74	25
		2050	7	69	24			2050	4	69	27
		2100	11	68	21			2100	30	57	13

Table 4. Mean SI Scores of Rio Grande do Sul mesoregions under SSP245 and SSP585 for all subsets. The region with the highest net decrease in mean SI for each crop from 2020 to 2100 is highlighted in red, and the second highest is in orange. Any regions with net increases in SI scores are highlighted in green.

	Rice				Tobacco				Corn				Soy			
SSP245																
Mesoregion	**2020**	**2050**	**2100**	**Net Change**	**2020**	**2050**	**2100**	**Net Change**	**2020**	**2050**	**2100**	**Net Change**	**2020**	**2050**	**2100**	**Net Change**
Sudoeste Rio-Grandense	2.37	2.56	2.35	−1.1%	2.28	2.38	2.20	−3.2%	2.36	2.47	2.30	−2.8%	2.6	2.7	2.5	−2.8%
Sudeste Rio-Grandense	1.17	2.32	2.05	74.8%	2.15	2.25	2.00	−7.1%	2.15	2.24	2.00	−7.1%	2.4	2.5	2.2	−6.4%
Noroeste Rio-Grandense	2.54	2.48	2.42	−4.7%	2.58	2.57	2.57	−0.1%	2.71	2.71	2.72	0.1%	2.7	2.7	2.7	−0.1%
Nordeste Rio-Grandense	2.54	2.48	2.50	−1.6%	2.54	2.49	2.53	−0.6%	2.67	2.61	2.65	−0.6%	2.7	2.6	2.6	−0.6%
Metropolitana De Porto Alegre	1.85	2.20	2.02	9.0%	2.22	2.24	2.11	−5.0%	2.19	2.21	2.08	−4.8%	2.2	2.2	2.1	−5.0%
Centro Oriental Rio-Grandense	2.24	2.25	2.04	−8.8%	2.44	2.49	2.35	−3.6%	2.33	2.38	2.25	−3.5%	2.4	2.4	2.3	−3.7%
Centro Ocidental Rio-Grandense	2.42	2.48	2.27	−6.1%	2.39	2.48	2.34	−2.0%	2.50	2.60	2.46	−1.8%	2.6	2.7	2.6	−1.8%
SSP585																
Mesoregion	**2020**	**2050**	**2100**	**Net Change**	**2020**	**2050**	**2100**	**Net Change**	**2020**	**2050**	**2100**	**Net Change**	**2020**	**2050**	**2100**	**Net Change**
Sudoeste Rio-Grandense	2.56	2.52	2.06	−19.6%	2.36	2.42	2.09	−11.5%	2.452	2.527	2.355	−4.0%	2.65	2.71	2.38	−10.3%
Sudeste Rio-Grandense	1.79	2.36	1.89	5.8%	2.20	2.32	2.05	−6.5%	2.194	2.32	2.111	−3.8%	2.44	2.56	2.29	−5.8%
Noroeste Rio-Grandense	2.52	2.38	2.02	−19.9%	2.57	2.57	2.38	−7.3%	2.716	2.723	2.721	0.2%	2.68	2.68	2.49	−7.0%
Nordeste Rio-Grandense	2.63	2.53	2.25	−14.4%	2.64	2.56	2.47	−6.5%	2.76	2.686	2.626	−4.9%	2.76	2.69	2.59	−6.2%
Metropolitana De Porto Alegre	2.31	2.23	1.79	−22.3%	2.33	2.33	2.06	−11.3%	2.295	2.297	2.141	−6.7%	2.32	2.32	2.05	−11.4%
Centro Oriental Rio-Grandense	2.33	2.25	1.73	−25.6%	2.54	2.58	2.24	−11.9%	2.433	2.471	2.306	−5.2%	2.49	2.52	2.19	−12.1%
Centro Ocidental Rio-Grandense	2.49	2.42	1.94	−22.0%	2.47	2.54	2.20	−11.1%	2.59	2.665	2.518	−2.8%	2.684	2.748	2.41	−10.2%

3.1.1. Rice

Under the moderate climate change scenario, SSP245, the suitability of all RS municipalities for rice growth increased by 5.6% from 2.28 in 2020 to 2.41 in 2050, followed by a 7.7% decrease to 2.23 in 2100 (Table 2). By 2100, there is a 31.3% decrease in municipalities ranking in the high suitability category, with only 11% of all municipalities in RS expected to have highly suitable land (Table 3). Conversely, the low suitability category sees a 100% increase, reaching 161 municipalities by 2100 that will have little to no rice suitability. Under SSP585, a 20.7% decrease in mean SI occurred from 2020 to 2100 in RS (Table 2). Almost none of the municipalities will be highly suitable compared to the nearly 70% in the low suitability category, a substantial shift toward low SI scores (Table 3).

Centro Oriental Rio-Grandense exhibits the largest drop in mean SI scores under both SSP245 (−8.8%) and SSP585 (−25.6%) from present to end-of-century, followed by Centro Ocidental Rio-Grandense at −6.1% for SSP245 and Metropolitana De Porto Alegre at −22.3% for SSP585 (Table 4). Sudeste Rio-Grandense, however, despite starting with the lowest mean suitability score in 2020, saw an increase in suitability under both scenarios, with a 74.8% increase in SSP245 and a 5.5% increase in SSP585. This increase in suitability, however, is likely only due to the comparatively low starting suitability for Sudeste Rio-Grandense in 2020, elicited by a significant drought period. The dramatic difference in modern suitability between this region and others positions it as a unique outlier. The increase in projected precipitation above the threshold for rice growth effectively improves the land suitability score.

3.1.2. Tobacco

Behind rice, tobacco has the subsequent highest decline in land suitability. Under SSP245, the mean SI value of all municipalities for tobacco growth saw only a 0.4% increase from 2020 to 2050, followed by a 2.1% decrease from 2050 to 2100 (Table 2). The percentage of municipalities in the low, medium, and high suitability categories is much more consistent across the three time periods than for rice. Under SSP585, the decline from present to the end of the century was significant at a −9.4% change in mean SI, though at a much smaller rate of change than for rice (Table 2). The only significant change is a shift of municipalities from high suitability to low from 2050 to 2100 for both SSP245 and SSP585 (Table 3).

Regional patterns for tobacco suitability are less distinct than those of rice, however. The mesoregion with the largest decrease in suitability in the moderate scenario from 2020 to 2100 is Sudeste Rio-Grandense at −7.1%, followed by Metropolitana De Porto Alegre at −5.0%. These decreases are more pronounced in SSP585, though for different regions, with Centro Oriental Rio-Grandense having the largest decrease (−11.9%), followed by Sudoeste Rio-Grandense (−11.5%). No tobacco subsets project net increases in the mean SI scores across either scenario.

3.1.3. Corn

Corn shows similar trends in moderate decline in land suitability to tobacco (Figure 3). While both show significant change, they both fall within the spectrum between rice and soybeans. Corn exhibits less fluctuation than tobacco; however, there is a slight change in SI scores from the present to the end of the century. The mean SI score increased from 2.43 to 2.44 from 2020 to 2050, a 0.4% increase in the index (Table 2). From 2050 to 2100, that increase was followed by a 1.6% decrease in mean SI scores across the state. The pattern of consistent decline in SSP585 remains true here, with a 2.8% net decrease overall by 2100.

Compared to tobacco and rice, corn is a more consistent crop when it comes to the distribution of land suitability scores, possibly because of its more even spatial distribution of farmlands (see corn production in Figure 2). Throughout the 21st century, suitability categories remain fairly consistent, hovering around 10% of municipalities with low suitability, 70% with medium, and 20% with high. Despite a much larger percentage increase in low-ranking municipalities by 2100 for the fossil-intensive scenario, the overall consistency of land suitability across Rio Grande do Sul points toward corn's position as a crop with more climatically reliable criteria.

Corn production change across mesoregions shows some strong patterns. Metropolitana De Porto Alegre, the mesoregion dedicated to the greater Porto Alegre metropolitan region, shows the second-highest decrease in net SI from 2020 to 2100 in SSP245 at 4.8% and the highest in SSP585 at 6.7%. The largest net loss came from Sudeste Rio-Grandense, which saw a 7.1% decrease. Noroeste Rio-Grandense, however, was the only mesoregion to have predicted net increases in SI by the end of the century under both scenarios, with 0.1% for SSP245 and 0.2% for SSP585.

3.1.4. Soybean

While predicted changes for croplands suitable for soybean growth show a significant decline, soybean remains the most resilient crop by 2100. Soybean croplands are expected to see a plateau in suitability from 2020 to 2050 under the moderate scenario before a 1.6% decrease from 2050 to 2100. Under the fossil-intensive scenario, there is a slight decline from 2020 to 2050: a −0.4% change in SI, which is followed by a much larger 8.9% decrease in suitability from 2050 to 2100 for a net decrease of −9.2%, overall. However, while this is a relatively large net change in SI, soybean remains widely successful compared to other crops (as seen in the results maps of Figure 3) because of the higher SI scores for soybean croplands prior to suitability degradation. Soybean is the most widely grown crop of the four studied here and is the highest produced (visualized in Figure 2), which allows it to remain steady throughout the century compared to other crops whose spatial growth patterns create more vulnerabilities for loss.

The percentage of municipalities scoring in the high suitability category reflects this strength. In moderate and extreme scenarios, the greatest number of municipalities indicate higher suitability for soybeans than for any other crop. With a change from just four municipalities to almost 150, there is a significant increase in municipalities in the low suitability category. This decline points toward an evenly distributed decline in suitability with little spatial variability in impacts.

Regional means for soybean suitability reflect key patterns seen in other croplands. Sudeste Rio-Grandense will have the largest net change in SI (−6.4%), followed by Metropolitana De Porto Alegre (−5.0%) in SSP245. Centro Oriental Rio-Grandense will have the largest net change in SSP585 at −12.1%, followed by Metropolitana De Porto Alegre at −11.4% (Table 3).

4. Discussion

4.1. Agricultural Suitability Under a Changing Climate

The breakdown of SI scores, scaled either to municipalities or to mesoregions, across the four crops reveals some interesting patterns. While all four crops fall in a similar range of SI scores, a definitive rank emerges with soybean scoring the highest and rice the lowest for both SSP245 and SSP585 (Table 2). Overall, the mean scores for SSP585 project higher decreases by 2050 and 2100 compared to SSP245, under which SI does not change significantly by 2050 but shows a strong decline by 2100, driven by the steady decrease in available precipitation and growing degree days.

The Sudeste Rio-Grandense region has the highest net decreases in SI under SSP245 for tobacco, corn, and soybean, but it exhibits a large net increase in land suitable for rice growth under the moderate scenario and a much smaller increase in the extreme scenario. Under SSP585, Centro Oriental Rio-Grandense has the highest net decreases for rice, tobacco, and soybean, and the second-highest for corn. Under both scenarios, the Metropolitana De Porto Alegre region ranks among the highest net decreases. Noroeste Rio-Grandense shows a slight, consistent increase in agricultural suitability for corn under both scenarios. All of these comparisons reveal strong spatial patterns of agricultural suitability loss across RS, with very few locations showing suitability increases.

4.2. Policy Implications

4.2.1. Rice

Rice is currently grown primarily in the southern region (Figure 2). There are only two municipalities in which rice production remains relatively suitable under both 2100 scenarios: Chuí and Santa Vitória do Palmar, both in the far south of RS. Irrigation is a critical variable in rice production around the world, but farmers are relying increasingly on continuous flood irrigation, which has decreased water efficiency [32].

Recent record-breaking rainfall and the floods that ensued in RS have caused drastic measures to be enforced in Brazil. With a death toll in the hundreds and an estimated 620,000 citizens displaced [33], the federal government has signed a measure allowing the import of one million metric tons of rice to make up for agricultural losses, and additionally implemented relief spending in tandem with private bank debt relief for affected farmers [11]. While other crops in RS have suffered similarly from these floods, the government has prioritized a response to impacts on rice stores because of RS's national importance in supplying 70% of Brazilian rice production [15]. Extreme events like these call for a more overarching assessment of agricultural suitability in RS, but also serve as examples of what government actions may become more necessary as suitability decreases. With rice in particular, Brazilian dependency may be expected to shift away from RS, as is apparent through this tragedy.

4.2.2. Tobacco

Tobacco production will also face severe challenges by 2100 under both scenarios, especially in the Central-South region, where it is currently grown, but less so compared to rice. If the state of RS were a country, it would be the 4th largest tobacco-producing country in the world [34]. The many countries that rely on Brazilian tobacco should expect changes from the predicted decreases in land suitable for growth. Since the tobacco industry cares significantly about the quality of yields, RS tobacco farmers need to be prepared for decreasing profits as their tobacco becomes less desirable under worse growing conditions.

However, there are strong ongoing campaigns to decrease tobacco consumption and production. Global tobacco use rates have decreased in the last 20 years [35]. Given the relatively higher 2100 suitability of corn and soybean in many of the regions where tobacco is currently grown in RS (Figures 1 and 2), farmers might benefit from the WHO campaign to "grow food, not tobacco" [36].

4.2.3. Corn

Corn is spread out widely across Rio Grande do Sul [37]. Corn has three growth seasons in Brazil [38], though RS only partakes in the first season due to climate limitations [39] (pp. 4–8). First-season corn is primarily used for animal feed, a significant use, as livestock is another massive industry in both RS and all of Brazil [40]. Corn has also been a staple food for Brazilians, but rising incomes are beginning to shift this tradition [40].

Our results estimate that land suitable for corn growth will be less impacted compared to tobacco and rice. There is also a slight increase in suitability along the southwestern edge of RS when comparing the present (2020) to the near-future (2050, see Figure 3). Both 2100 scenarios, however, highlight noticeably worse suitability compared to the 2050 scenarios. Farmers, especially in the Southern region, should expect more long-term challenges to growing corn, which may affect the input costs of livestock production and local food supplies.

4.2.4. Soybean

Soybean is the most profitable crop for RS [14], with its primary uses being animal feed and the second largest source of vegetable oil [41]. Being the most-grown crop in RS, it is set to suffer from the recent flooding in the state [42], just like rice (see Section 4.2.1). Again, this kind of disruption and its negative impacts on communities can and should be expected to become a more frequent occurrence as climate disasters worsen [43].

Soybean will be the least negatively affected of the four study crops. Multiple municipalities in the lower southwest show an increase in suitability from 2020 to 2050. In the case of soybeans, such a noticeable increase can perhaps be attributed to the higher production rates of the crop over the landscape—a spatial consistency (shown in Figure 2) that points toward the crop's versatility in required landscape characteristics. All the municipalities around this region, including the rest of the Sudoeste Rio-Grandense, show decreases in suitability throughout both scenarios. All the increases in suitability in this region are lost, however, by 2100, when the suitability reverts to its 2020 levels. Still, given the profitability, scale, and popularity of soybeans in RS, not much can be expected to change until the late 21st century. By 2100, a few municipalities where soybean is currently produced in great quantities will become particularly unsuitable. In these places, soybeans will be under significant threat by 2100.

4.3. Further Implications for Rio Grande do Sul

Brazil and RS specifically already have a few sustainability and climate change-related agriculture policies and programs in place [44,45]. On the national level, the Agricultural Activity Assurance Program (or PROAGRO) provides an exemption of certain financial obligations for farmers hurt by environmental problems [45] and specifically targets rural farmers, with heavy coverage in the south of Brazil [46]. ZARC (Zoneamento Agrícola de Risko Climático or Agricultural Zoning of Climate Risk) is another program that serves as a decision-making helper for farmers and insurers [47]. The benefits of zoning programs like these include reduced costs of insurance, risk reductions, and productivity increases [45]. The state-owned research corporation that runs ZARC has reported the program to be a success, with ZARC services increasing overall crop production by at least 20% [48].

The State of Rio Grande do Sul similarly embraces multiple sustainability approaches to reduce carbon emissions and improve the resiliency of the system, such as no-tillage and integrated crop-livestock-forest systems (ICLFS) [49]. Their adherence to these practices, along with the rest of Brazil, is confirmed by independent research [50] and has successfully begun to reduce RS's agricultural greenhouse emissions [51]. However, aside from insurance programs, there is little talk of resiliency for RS agriculture in the face of a changing climate. Three approaches to improving the density, efficiency, and livelihood of the agribusiness sector in RS in the wake of climatically driven changes in agricultural suitability may include second-season Carinata growing, greenhouse farming, and addressing pesticide use.

Rio Grande do Sul could benefit from helping pioneer the rising popularity of a winter crop called Brassica carinata, commonly named Carinata [51] (pp. 25–27). In RS, Carinata

could be used as a productive cover crop following soy harvests. Success with this method has been proven in neighboring Uruguay and may have even better-growing potential in certain regions of RS [51] (pp. 25–27). Carinata also has massive potential to become a low-carbon-intensity biofuel and chemical product, so its ability to be grown as an unobtrusive cover crop is enticing [52].

A second approach that could help with the suitability challenges RS may face is greenhouse farming, which could ensure ideal growing temperatures year-round [53]. This could be especially important to the regions identified to be entirely unsuitable in all scenarios: Osório and the Metropolitano de Porto Alegre microregions and the entire northern ridge of the Noroeste Rio-Grandense. Greenhouses also provide higher yields from year-round operations and have demonstrated a positive correlation with employment and labor demand in South America [54]. While greenhouse farming may not be a scalable solution to replace the magnitude of agricultural suitability loss, it can be used in tandem or as inspiration for newer, more scalable solutions.

Another major issue to ensure the future agricultural productivity of RS cropland for its people and communities is addressing pesticide use. Brazil is consistently ranked among the top five highest pesticide-using countries [55]. The effects of pesticides on human and animal health alone are damning and extensively understood [56,57]. Alternative crop protection measures to pesticides can include crop rotation and other agroforestry techniques (like Carinata intercropping), an expansion of biopesticides, and reductive (also known as biological or anaerobic) soil disinfestation.

These implications may offset an expected decline in growth capabilities as a result of precipitation decline and changes in growing degree days. However, inadequate farming practices, soil loss, or the increasing frequency of climate disasters may accelerate the model-estimated losses of agricultural suitability for many regions. Future research is needed to further integrate climate modeling frameworks, explore potential shifts in agricultural productivity, and improve farming practices. In the meantime, the outcomes of models like this should be considered baselines for the future agricultural production, technology, and expenditure inputs necessary for preserving agribusiness livelihoods in RS.

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Abbreviations

The following abbreviations are used in this manuscript:

RS	Rio Grande do Sul
SI	Suitability Index

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