atmosphere

Article

Revisiting Climate-Related Agricultural Losses across South America and Their Future Perspectives

Célia M. Gouveia [1,2,*], Flávio Justino [3], Carlos Gurjao [3], Lormido Zita [3] and Catarina Alonso [1,4]

1 Instituto Português do Mar e Atmosfera (IPMA), 1749-077 Lisboa, Portugal; catarina.alonso@ipma.pt
2 Instituto Dom Luiz (IDL), Faculdade de Ciências da Universidade de Lisboa, 1747-077 Lisboa, Portugal
3 Department of Agriculture Engineering, Universidade Federal de Vicosa, Viçosa 36570-000, Brazil
4 Departmento de Engenharia Geográfica, Geofísica e Energia, Universidade de Lisboa, 1600-548 Lisboa, Portugal
* Correspondence: celia.gouveia@ipma.pt

Abstract: Climate plays a major role in the spatiotemporal distribution of most agricultural systems, and the economic losses related to climate and weather extremes have escalated significantly in the last decades. South America is one of the most productive agricultural areas of the globe. In recent years, remote sensing data and geographic information systems have been used to improve geo-environmental hazard assessment. However, food security is still highly dependent on small farmer practices that are frequently the most vulnerable to climate extremes. This work reviews climate and weather extremes' impacts on crop production for South American countries, focusing on the projected ones considering different climate scenarios and countries. A positive trend in the productivity of maize, mainly related to agricultural improvements, was recently observed in Colombia, Ecuador, and Uruguay by up to 200%, as well as in the case of soybean in Bolivia and Uruguay by about 125%. Despite the generalized adverse impacts of climate extremes, results from agrometeorological models generally indicate an increase in crop production in southern regions of Chile (and highlands) and Brazil mainly related to increased temperature. Positive impacts in response to CO_2 fertilization are also foreseen in Peru and Brazil (southeast, south, and Minas Gerais); in particular, in Brazil, increases in productivity can be raised by about 40%. The use of double-cropping systems, although with very good results in recent years, may also be at risk in a few decades, mainly due to forecasted precipitation decrease, delay in rainy season onset, and temperature increase. The development of timely early warning systems is imperative to produce technically accurate alerts and the interpretation of the risk assessment based on the link between producers and consumers. Promoting climate index insurance is crucial to build resilient food production, but its implementation should rely on regional or international support systems. Moreover, the implementation of adaptation and mitigation also requires climate-resilient technologies that involve an interdisciplinary approach.

Keywords: crops losses; climate extremes; climate change; adaptation

Citation: Gouveia, C.M.; Justino, F.; Gurjao, C.; Zita, L.; Alonso, C. Revisiting Climate-Related Agricultural Losses across South America and Their Future Perspectives. *Atmosphere* **2023**, *14*, 1303. https://doi.org/10.3390/atmos14081303

Academic Editor: Gianni Bellocchi

Received: 12 July 2023
Revised: 9 August 2023
Accepted: 10 August 2023
Published: 17 August 2023

1. Introduction

The climate is one of the major factors influencing the spatiotemporal distribution of most agricultural systems. Crop and livestock are vulnerable to interannual climate variability, extreme events, and changes in typical regional climate patterns [1]. In the last decades, weather and climate extremes and their relationship with climate variability and change triggered significant crop losses. The long-lasting socio-economic costs of floods, heatwaves, wildfires, and hailstorms, among other extremes, affect severely farmers and the local communities [2,3]. Unlike the economic losses associated with other natural disasters that have remained relatively stable, the financial loss related to climate and weather-related events (such as droughts, floods, and storms, among others) has risen significantly during the 21st century [2]. The global surface temperature in the previous two decades was 1 °C higher than in the period 1850–1900 (1.1 °C higher in the last decade), with a larger increase over land (around 1.6 °C) than over the ocean [4]. The continuous increase in the global average surface temperature has been associated with an increase in disaster frequency and severity. Definitely, the last decade has been characterized by record-breaking high temperatures, ice melting, glacier retreat, and sea level rise [3]. Climate-related extremes are responsible for 26% of the damage and losses in agriculture in the least developed and lower-middle-income countries [2].

The continuous growth of the world population requires a rise in overall food production by 70% between 2005 and 2050 and double the output in developing countries [5]. Intensive agriculture and livestock practices are also particularly vulnerable to pests and diseases, and the link between natural hazard-related disasters with intensified animal and plant pest and disease outbreaks is also growing [6]. Drought and floods are firmly impacting agricultural and livestock systems. At the same time, they show a complex relationship between pest and disease outbreaks, as both can catalyze disease-spreading conditions, foster vector-breeding sites, and intensify disease transmission [4].

Modern agriculture faces many weather and climate hazards that pose a risk to crops and livestock. The agricultural sector is already exerting extreme pressure on the environment, being responsible for 30% of greenhouse gas emissions and the consumption of 70% of Earth's water resources [7]. To guarantee the sustainability of production and secure wealth and livelihoods, the agricultural sector must identify climate and weather-related risks and provide mechanisms to cope with them. Developing effective and reliable climate services is crucial to achieving those goals. The 2030 Agenda for Sustainable Development and the Paris Agreement asked for a food system transformation, with the implication that food and natural resources will no longer be managed separately. The conventional risk assessment approaches only contemplate single hazards, but nowadays, there is strong evidence that natural hazards are synergistic and that their combined occurrence may aggravate impacts. In line with the Sendai Framework for Disaster Risk Reduction, it is urgent to assess compound disasters and their associated risks, rather than focusing on single hazards [8]. Better understanding how climate-related disasters impact the sector is crucial to allowing predominantly agro-intensive countries to pursue a development trajectory in a manageable, renewable, and sustainable way [4]. Statistical tools offer great potential for assessing collaborative synergies within a complex data system that uses complex, reliable, and timely data to evaluate the impact of climate extremes on agriculture.

Recently, Remote Sensing (RS) techniques and Geographic Information Systems (GISs) have been included to improve the geo-environmental hazard assessment. Satellite data contain information that can be used to estimate aboveground biomass and crop production [9]. Interpolations using satellite data of temperature and precipitation from weather stations can also be used to assess environmental stress during the growing season. Weather data may help to understand crop health that remote sensing data cannot detect. Satellite-derived indices can also be used to distinguish the growth stages of crops, helping to better interpret weather variables. Combining different sources of remote sensing data can improve yield forecasts, frequently providing better prediction variables to capture changes during sensitive growth stages. Nowadays, the increased volume and accessibility of remote sensing data has opened a window of opportunity to new machine learning techniques to model crop production and losses.

2. General Overview of Climate Extremes and the Agricultural Sector

The role played by temperature and precipitation in the agricultural sector on a global scale, and in South America, in particular, is unquestionable. Figure 1 shows the trends of annual accumulated precipitation and annual mean temperature, as obtained from monthly means from the CRU v4.03 dataset, for three periods: a large period from 1961 to 2019 and two sub-periods, 1961–1990 and 1991–2019. A strong pattern of significant and positive trend values of temperature are spread over South America, with the exception of the Bolivian region, in the most recent period. Strong values are observed in northwest and inland regions of Brazil and in southern regions of Chile and Argentina. The same pattern is observed for the longer period, and a pattern showing negative trends of temperature in the first sub-period is observed over eastern Brazil. On the other hand, the patterns of precipitation trend values are not so clear (Figure 1, bottom panel). Small patterns of negative trend values are found over southern Chile and Argentina and over the eastern and western sectors of Brazil. Very small spots of significant and positive trend values are found in northwestern and northeastern Brazil. A quite similar spatial pattern is observed for the longer period, but in the first sub-period, spots of a positive and significant trend are found over eastern Brazil, Bolivia, and northern Argentina. A strong and small spot of a negative and significant precipitation trend is found over the northeastern sector of Brazil (Figure 1, bottom panel).

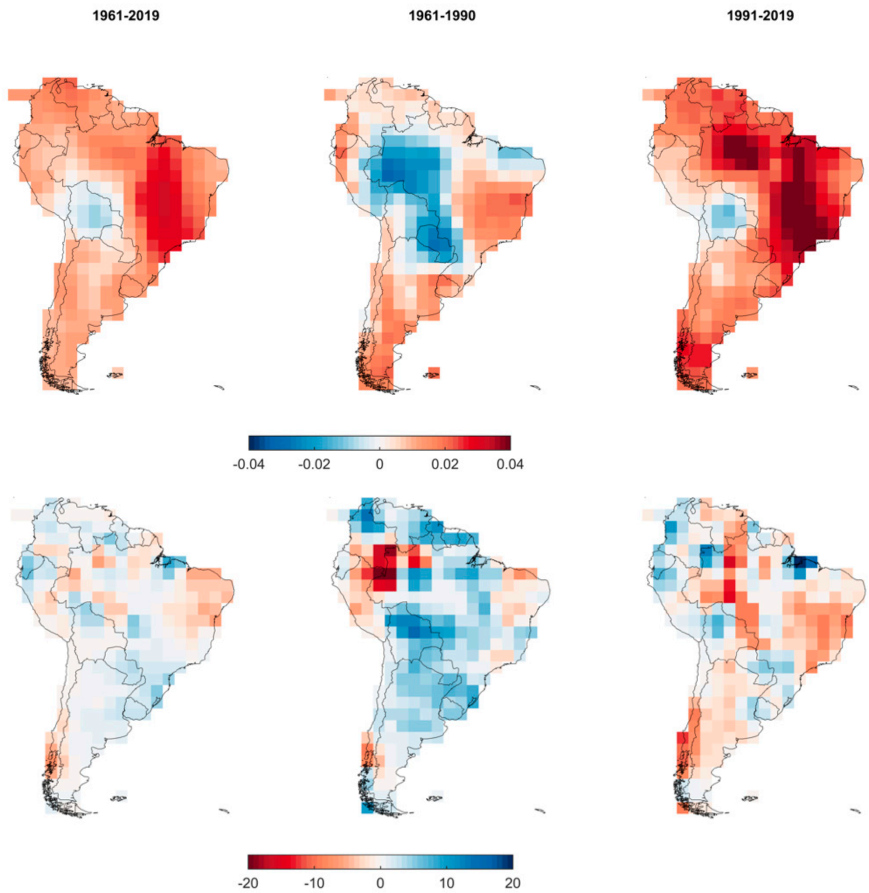

Figure 1. Trends of annual mean temperature (**top panel**) and accumulated precipitation (**bottom panel**) for the periods from 1961 to 2019 (**left panel**), 1961 to 1990 (**central panel**), and 1991 to 2019 (**right panel**), as obtained from monthly means from the CRU v4.03 dataset.

The negative impact of climate and weather extremes on crop production and yield was highlighted by the recent Intergovernmental Panel on Climate Change (IPCC) report on climate extremes [3]. Precipitation variability plays a major role in explaining variability in crop production and yield in semi-arid and tropical regions of the globe. Agricultural ecosystems have been critically affected by extreme weather and climate events. Farmers have faced significant challenges, mainly due to changes in the intensity, frequency, and timing of precipitation, and a deeper knowledge of the link between the historical precipitation extremes and crop production is crucial to assess the sustainability of the agricultural system [10]. Hence, regions dedicated to agricultural practices and recurrently affected by extreme events require an enhanced assessment of climate-related crop failures considering the different spatial and temporal scales of weather extremes.

Drought is considered the single most significant cause of agricultural production loss and is responsible for over 34% of agricultural production loss across the least developed and lower-middle-income countries [4]. Floods are the second leading cause of crop losses and agricultural infrastructure damage in those countries, responsible for 19% of the agricultural losses. Recently, storms are playing an important role, accounting for over 18% of overall loss. The frequency of heatwaves over the summer in northern South America has doubled in the last decades, and a tendency to increase is also found in southern South America [11]. From September to November 2020, record-breaking maximum temperature values were reported over Brazil, Argentina, Peru, Paraguay, and Bolivia. In some places were recorded temperature values 10 °C higher than normal, and maximum temperatures were above 40 °C for several days. This heatwave exacerbated the drought over Pantanal, increasing fire occurrence and severity [12]. Wildfires seem to have a low impact on the agricultural sector, accounting for 1% of the losses. However, if the effect of wildfires on the forest sector is included, the loss of timber and other systems is much higher [4].

The tendency to increase precipitation variability has been documented in many regions worldwide [3,12]. The damages produced by floods doubled over the past decades, with a very rapid increase worldwide, and continuous growth is expected under climate change scenarios, namely, in flood-prone regions, such as Southeast Asia, Peninsular India, eastern Africa, and the northern half of the Andes [13]. The impact of floods on food security presents two effects: one direct effect related to the reduction of crops productions and damages to pastures and livestock, and one indirect effect associated with factors such as erosion of agricultural soils, loss of nutrients, and development of microbial and fungal activities, which could derail the future crops. The direct and indirect effects of floods depend on if they occur in the non-growing, fallow periods or the growing season. Moreover, environmental degradation, deforestation, intensified land use, changes in land cover, and the increasing population cause or increase the flood risk, particularly in regions with high vulnerability [14].

Recent extreme heat events challenged agricultural production, raising the risk of food insecurity. Excessive heat exposure stresses plants, restricts development, and causes plant mortality, frequently decreasing the quality and yield of crops. Recent heatwaves, such as 2003 and 2018 in Europe, 2010 in Russia, and 2012 in the central United States, have reduced yields for cereal crops [15–20]. In Mexico/Central America and the Caribbean, the year 2020 was one of the three warmest years on record and the second warmest for South America [21].

For crops well adapted to summer heat, damage usually happens when anomalously warm temperatures occur during the cool season, while crops are in the dormancy stage or the bloom phase. During the warm season, irrigation may provide a buffer for heat stress. However, the projected decrease in precipitation and water availability for some regions may exacerbate the expected increase in heat extremes. The combination of heat and water stress may affect significantly crop yield, size, and quality. Some adaptive strategies to mitigate damages from extreme heat exposure have been pointed out: irrigation, site management (cover crops, shade slopes, the planting of rows in northeast–southwest orientation for the northern hemisphere, among others), and cultivars selection [22]. The increase in maximum temperature can lead to severe yield reduction and reproductive failure in many essential annual crops. Rice production and yield decrease when the temperature surpasses heat thresholds, as the full-blossom stage is very sensitive to high temperatures. Warm night temperatures may be difficult for apple, peach, and nectarine vernalization. Higher temperatures are also associated with higher ozone concentrations harmful to all plants.

Tropical cyclones impact the agricultural systems in different ways. Strong damages to crop structure may occur due to strong winds, and/or complete crop destruction may happen from floods and landslides in sloped areas due to heavy precipitation. The storm surges may be responsible for severe salt contamination of the soils. It is estimated that salt contamination due to Hurricane Katrina has reduced crop production by around 20% in Louisiana and Mississippi, lasting up to two years [23]. The adverse effects of hurricanes on agriculture range from slight and temporary to profound and long-lasting, depending on the condition and status of the crop type, i.e., the damages on seasonal crops are short-term, and on fruit trees may be permanent.

Fire is a natural disturbance of the ecosystems, a necessary element for the ongoing survival of ecological communities. Negative impacts arise when fire cannot be controlled in time and space. The length of the fire season and burned area have increased in many parts of the world, mainly associated with historical wildfire suppression, deforestation increase, and climate extremes related to climatic change, like drought and heatwaves. These trends are projected to continue under a range of global climate models, namely, in the mid-to-high latitudes. Globally, it has been reported an increase in extreme wildfires in North America, Australia, Brazil, and other locations [24]. Frequently, wildfires may result in widespread destruction and damage to many environmental, social, and economic sectors. Wildfires are responsible for heavy losses in the agriculture and livestock sectors that are strongly dependent on the crops affected and the crops unharvested during the fire season.

With likely increased wildfire activity and frequency, and intensity of climate extremes due to global warming, surface ozone will be further enhanced [25,26]. Ozone is a secondary pollutant, as it is formed from other pollutants that are increasing quickly in several regions. The surface ozone associated with wildfire activity poses adverse effects on vegetation because stomatal uptake of ozone by plants decreases chlorophyll contents and increases chloroplast deformities, reducing gross primary productivity [26]. The reduction of agricultural yields associated with ozone has been considered an indirect impact of fires on crop production. The decrease in yields associated with ozone may be related to the market value that depends on the appearance of the horticultural crop, which can be strongly affected by a decrease in yield due to ozone. Ozone impacts on crops, for instance, have been reported in North America and Europe [27–29], Mexico, Egypt, India, and Taiwan [30–35].

3. Climate-Related Agricultural Losses in South America in Recent Decades

Agricultural production plays a key role in the process of industrialization and economic development. Agricultural sectors in South America have been boosted and benefited by several factors, such as the favorable climate for the cultivation of various crops; the availability of fertile land; the use of modern technologies, such as irrigation and agricultural machinery; in addition to production incentive policies.

Small farmers are key to ensuring food security in South America, although they are often the most vulnerable to climate variability and change. This makes family farming in the region dependent on favorable climate conditions, making it vulnerable to extreme weather events, and several studies show that agricultural productivity around the world is facing serious challenges as a result of climate change [36,37]. In this work, some aspects of how South American countries have been individually affected by climate and weather extremes will be discussed.

Figure 2 shows the evolution of maize, potato, and soybean annual productivity from 1961 to 2021 for some South American countries based on the FAOSTAT dataset (https://www.fao.org/faostat/en/#data/QV accessed on 17 June 2023). It is evident the positive trend of maize productivity, most accentuated from 2005, in Colombia, Ecuador, and Uruguay, despite changes in climate conditions. This increase is related to improvements in agricultural management. Turning to soybean productivity, trends are less sharp than noticed in maize, but Bolivia and Uruguay show a remarkable increase (Figure 2 bottom), although with very high interannual variability. Differently than noted for maize and soybeans, the evolution of potato production has not experienced substantial trends, and in Peru, the production is going down (Figure 2, bottom panel). Steady growth is clear for Chile and Bolivia.

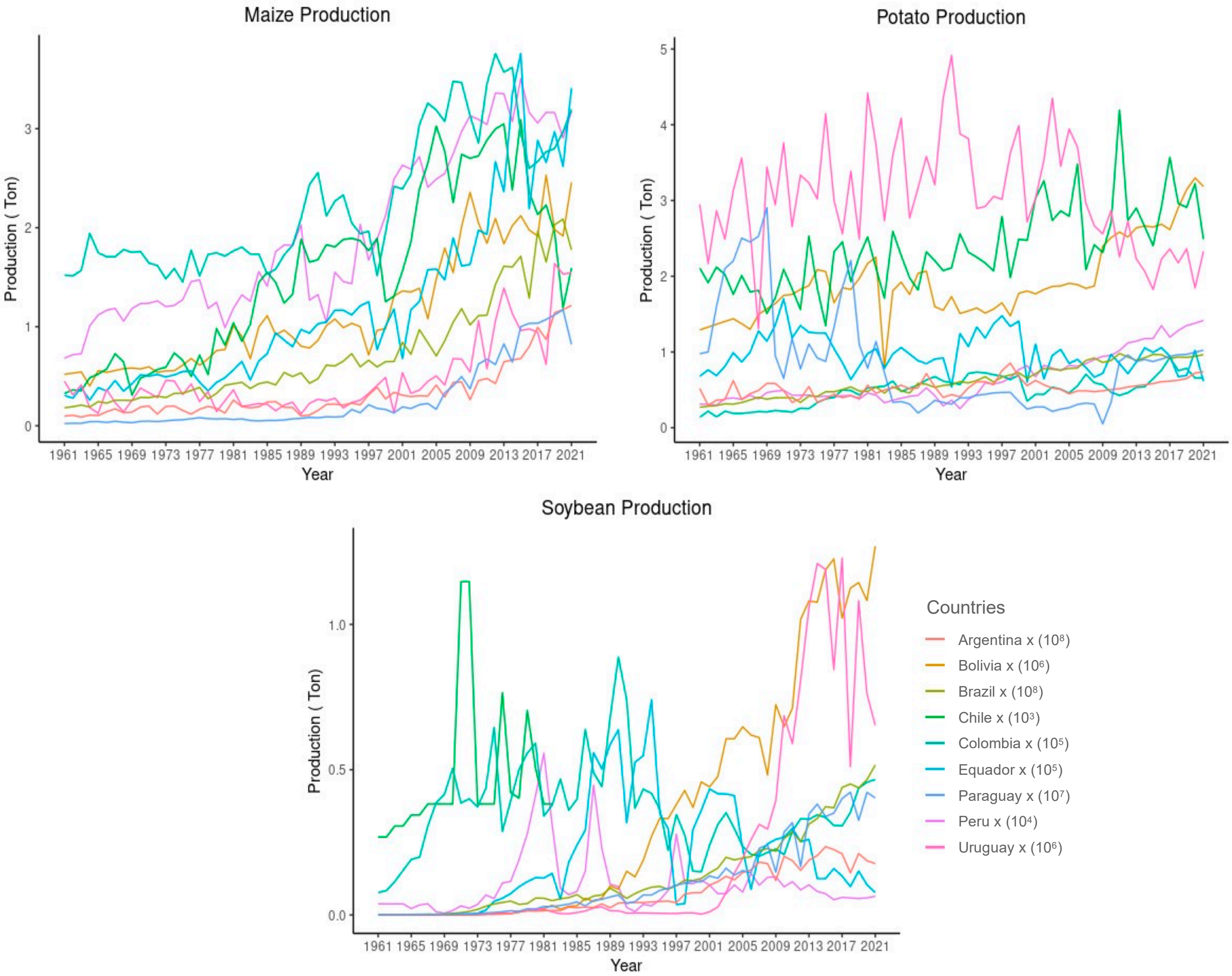

Figure 2. Productivity of maize, soybean, and potato for some South American countries from 1961 to 2021 based on the FAOSTAT dataset. Please note that productivity varies in magnitude from 10^3 to 10^8.

Figure 3 shows the yield trend values for 10 main crops for the last 60-year period (from 1961 to 2021) in South American countries. A generalized pattern of significant and positive trends is observed for the majority of the countries. Exceptions are observed for sorghum in Bolivia and Ecuador and for sugarcane in Peru, Venezuela, Guiana, and Suriname. Stronger positive trends are observed for barley in Chile and rice in Brazil, Bolivia, and Peru. However, as observed in Figure 2, the crop yield trend is stronger in the last 30 years for some crops and countries. Therefore, the trend values of crop yields for the two sub-periods are shown in Figure 4. Considering the first sub-period of 30 years, significant and strong negative trend values are observed for Brazil, Ecuador, and Bolivia for sorghum and for Ecuador, Peru, Guiana, and Suriname for sugarcane. Strong and significant trend values are found for sugarcane in Brazil and Colombia and for rice in Colombia, Chile, Venezuela, Guiana, and French Guiana. Significant, although less strong, positive and negative trends are found in South American countries for beans, coffee, and maize. On the other hand, a generalized significant positive trend is found for all considered crops and countries, with the strongest trend values observed for rice, barley, and sugarcane for the majority of the South American counties. Exceptions are observed in Peru, Venezuela, and Guiana for sugarcane and in Bolivia and Ecuador for sorghum.

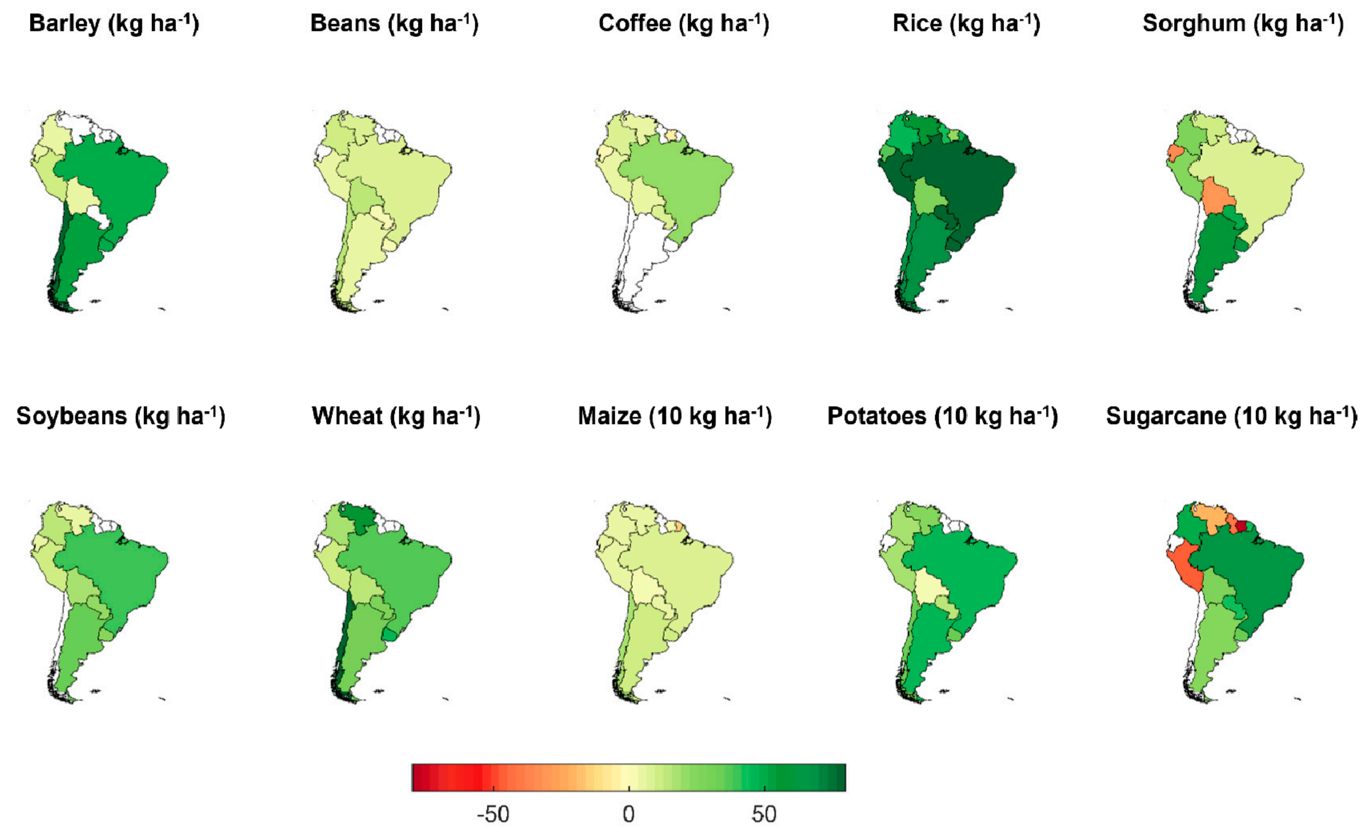

Figure 3. Annual trend of crop yield at national scale over South America considering the period from 1961 to 2021, as obtained from the FAOSTAT dataset. Only significant trends (p-value < 0.05) are shown. White regions show countries do not discussed in the study.

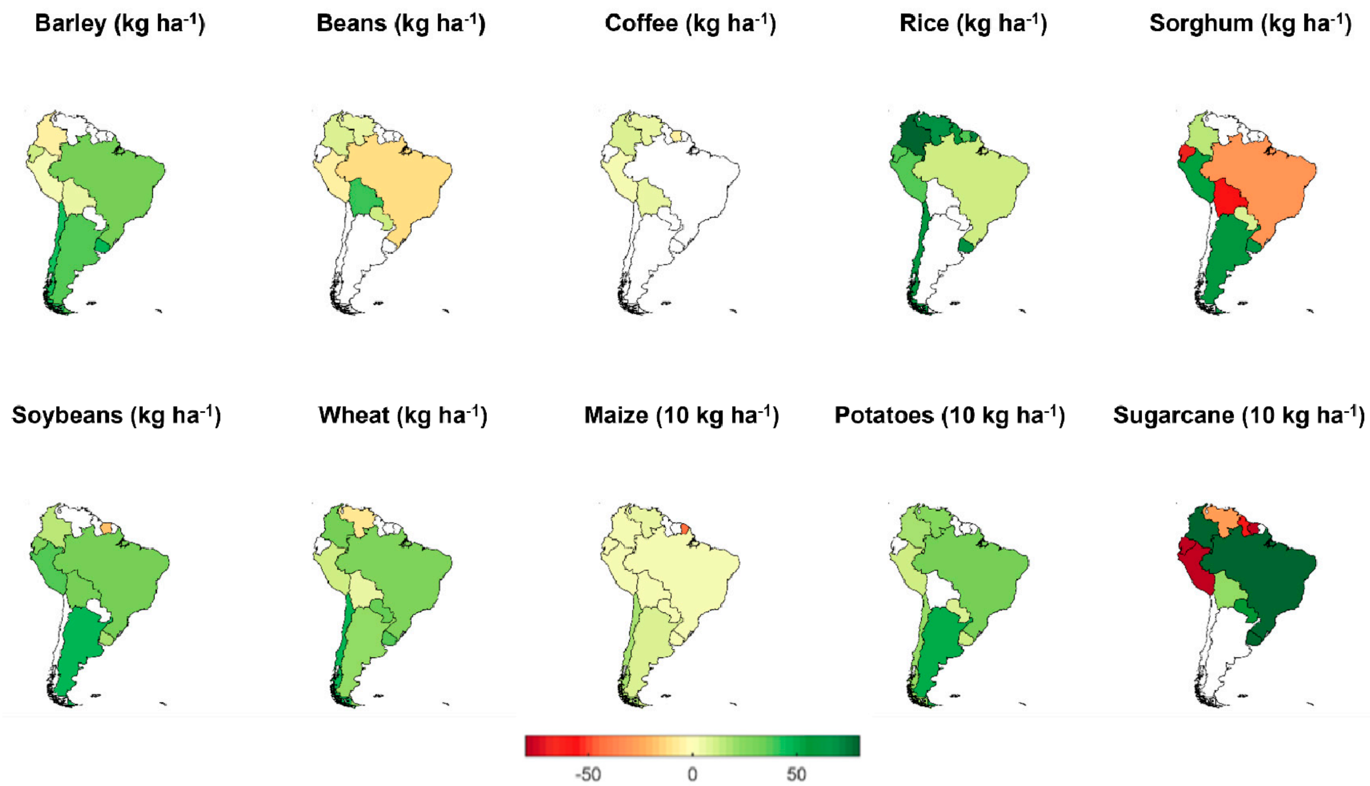

Figure 4. As in Figure 3 for the period from 1991 to 2021.

Table 1 presents a summary of the observed trends of temperature, precipitation, barley, rice, sorghum, wheat, maize, potatoes, and sugarcane for the periods 1961–2021 (yields) and 1961–2019 (climate variables). The trend signal is represented by + and − for positive and negative trends, respectively. The magnitude of the trend is represented by the number of symbols used (+++, ++, + represent high, moderate, and small positive trends, respectively). The symbol ± is used when positive and negative trends are observed in different regions of a specific country.

Table 1. Summary of the observed trends of temperature, precipitation, Barley, Rice, Sorghum, Wheat, Maize, Potatoes, and Sugarcane for the periods 1961–2021 (yields) and 1961–2019 (climate variables). The trend signal is represented by + and − for positive and negative trends, respectively. The magnitude of the trend is represented by the number of symbols used (e.g., +++, ++, + represent high, moderate, and small positive trends, respectively). The symbol ± is used when positive and negative trends are observed in different regions of a specific country.

		Precipitation	Barley	Rice	Sorghum	Wheat	Maize	Potatoes	Sugarcane
Venezuela	+			++	+	+++	+	+	−
Argentina	+	±	++	++	++	++	+	++	+
Bolivia	−	−	+	++	−	+			+
Brazil	++	±	++	+++	+	++	+	++	++
Chile	+	+	++	++		+++	+	+	
Colombia	+	±	+	++	+	+	+	+	++
Ecuador	+	−	+	++	−		+		
Paraguay	+	−		+++	++	++	+	+	+
Peru	+	±	+	+++	+	+	+	+	−−
Uruguay	+	−	++	+++	++	++	+	+	+

The generalized positive trends of temperature may be associated with the generalized increase in crop yields, namely, when the latter is coincident with a positive trend of precipitation, as observed in the case of rice in Brazil and wheat in Chile. On the other hand, the coincident negative trend in temperature and precipitation over Bolivia may be related to the decrease in sorghum production.

However, it should be stressed that the simple comparison between the signal of the observed trends may lead to misleading interpretations, as the impacts of temperature and precipitation are different when they occur together or separately. Moreover, the effect is also strongly dependent on the season and moment of the crop's vegetative cycle. Additionally, the analysis performed does not take into consideration the location of the regions within a country where the crops are planted and neither if the farm's location is coincident with the regions affected by positive and negative trends of climate variables, in particular, when a consistent pattern affecting the entire country was not identified.

4. End-of-Century Climate-Related Agricultural Losses in South America

4.1. Peru, Bolivia, Ecuador, and Venezuela

Precipitation and temperature affect the levels of agricultural productivity in a given region [38]. A precipitation deficit has been observed in southern Peru and western Central America, in addition to a 1 °C increase in temperature over Mesoamerica and South America [39]. Countries like Bolivia and Peru are based on subsistence agricultural production, that is, through rudimentary techniques and little technology. According to a study carried out for the Madre de Dios region of Peru, [40] found that, in recent decades, climate variability has affected many local subsistence activities, where the greatest impacts have occurred due to increased temperatures and fires, followed by strong winds and torrential rains. Furthermore, for these countries, the direct effects of CO_2 can lead to changes in productivity, as well [41].

According to some future scenarios, crop yields are projected to increase by up to 20% in response to rising CO_2 concentration [42]. Changes in CO_2 concentration may be enough to offset negative impacts on agricultural productivity. Agricultural productivity modulated by the El Niño–Southern Oscillation (ENSO) has been previously documented, and a decreased phenological cycle of cotton and mango across northern Peru, due to increased temperature in El Niño years, has been found [43]. According to [44], the drop in agricultural productivity in Bolivia is much greater during La Niña events than in El Niño. Although half of Venezuela is covered by forests, only one-quarter of the land is used for agriculture. According to the Ministry of Agriculture of Venezuela, the impacts caused by floods associated with extreme weather events resulted in 60% of crops lost and were responsible for leaving approximately 4000 rural families in a vulnerable situation. Deforestation activities are also commonplace. It is estimated that within the period 2000–2004, around 246,000 hectares were affected due to forest fires, legal agricultural activities, and illegal logging. According to the projections of future scenarios, the reduction in precipitation by up to 20% and an increase of 2 °C for 2060 should impact negatively agricultural productivity [39] (Figure 5).

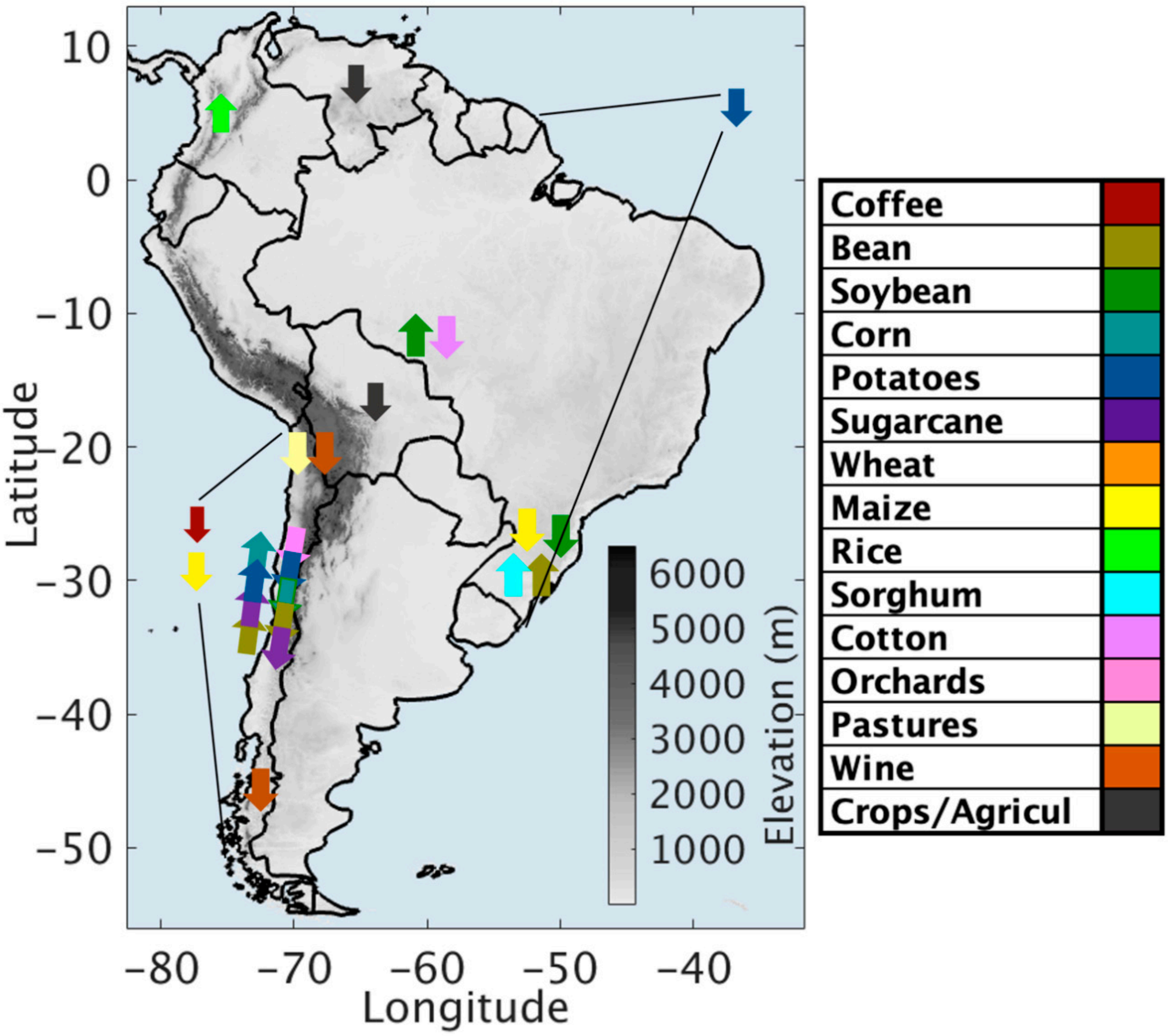

Figure 5. End-of-century projected changes in crop production for some South American countries, considering different climate scenarios without adaptation measures.

Agriculture plays an important role in Ecuador's economic system, with the main source of employment in the country, representing 25% of the population, involving about 1.6 million people [45]. In Ecuador, its agricultural productivity has also been impacted by changes in rainfall due to climate variability, including floods and droughts. In the last decades, occurrences of extreme events associated with ENSO have been registered, since the Ecuadorian region is closely related to the ocean–atmosphere interaction. This causes an increase in torrential rains that generate floods in the western Andes region, as well as extreme droughts in the north and east areas [46]. Floods are becoming more common, harming agricultural production, mainly during El Nino events. However, during the 2012 La Niña, the rainfall was above the average of the prior decade, affecting more than 195,000 hectares and expenses of more than USD 237 million [47]. Between 2010 and 2011, floods associated with La Niña also generated high costs, reducing the harvests of main products, such as rice, maize, and vegetables [48]. In the last 50 years, Ecuador has registered increases in maximum and minimum temperatures, which exceed the thresholds of 1.0 °C. Moreover, the number of warm nights increased, while the number of cold nights decreased [49].

4.2. Chile

Since 1990, the agricultural sector has been vital in Chile, contributing approximately 5% of GDP and 10% of employment generation, but climate change has threatened the sector's development. The changes in precipitation patterns, temperatures, and winds, together with the increase in the intensity and frequency of extreme weather events, have led to the risk of disasters that significantly affect agriculture, crops, and the livelihoods of people. Chile has been affected by a long-lasting drought situation (12 years) and registered historically high temperature records in the last five years [50,51]. Changes in food yields and quality; the growing season; physicochemical and biological soil conditions; water availability; displacement of suitable crop areas; the presence of new or more pathogenic diseases and pests; the loss of pollinators; and living conditions, migration, and poverty are the most common impacts related to weather and climate extremes and variability. It is urgent, therefore, to develop and implement strategies for adaptation to cope with these changes.

One adverse impact of climate change is the decreased quality of products due to more frequent heat or cold waves, frost, heavy rain, or drought. Positive impacts could be achieved with summer warming and dryness, with adequate temperatures, winters less extreme, springs less cold, and more humid air. These conditions may improve the quality of the products, leading to a specific type of agriculture that is better adapted to new climatic conditions. A statistically significant decrease in rainfall for the central–southern zone of Chile has been observed since 2012, and it is projected that the Central Valley will be much hotter and drier by 2050. Precipitation reduction (5% to 15%) from 2031 to 2050 is foreseen in the area between the basins of the Copiapó and Aysén rivers. Between the basins of the Mataquito and Aysén rivers is expected a decrease in rainfall, but a slight increase is expected in the south Magallanes. Positive impacts are expected in the southern zones, and adverse production and net income losses are expected in the central zone due to lower water availability for irrigation. Negative effects are foreseeable not only in the quantity, but also in the quality of the products (Figure 5). The most vulnerable would be the farmers in the dry interior and the arid coast, between the regions of Valparaíso and Biobío, the transverse valleys, and the dry lands ranchers [52].

Climate change projections in Chile have indicated that rainfed wheat yields would decrease between 5% and 10% in northern and central Chile, associated with the expected droughts [51]. From the Biobío region to the south, the wheat yield could increase by more than 30% due to higher temperatures in winter. The outcomes of beans, corn, potatoes, and sugar beets would also decrease from the north to the Biobío region, although they would increase along the coast and the Andean foothills, and from Araucanía to the south. The annual productivity of pastures is projected to decrease in the Atacama and from Coquimbo to Los Lagos due to the lower water availability in the soils, increasing in the central region of Chile and the Altiplano. Due to increased solar radiation, pasture yields would also be reduced in the coastal mountain range and from Biobío to Los Lagos in response to prolonged dry periods. Cereal yields may increase by 10% from Valparaíso to the Maule River due to higher winter temperatures. On the other hand, table and wine grape yields would be reduced in the north of Chile due to the early crop development associated with high temperatures expected for winter and spring, and the advance in the harvest detected in the areas of Coquimbo and Maipu. Lower yields would also be recorded from the metropolitan area to the south due to lower solar radiation, high temperatures and precipitation, and late spring frosts. In contrast, crop productivity could increase in the Maule and Biobío regions and from Araucanía to the south [50,51] (Figure 5).

The Valparaíso region appears to be the most vulnerable region to climate change linked with the projected increases in the minimum, average, and maximum temperature and a decrease in rainfall. The latter added to the change in winds, and air, soil, and dry vegetation conditions will increase the probability of forest fires. It is also expected to reduce snow accumulation in the mountain range, with the consequent decrease in river flows. A general abandonment of orchards has been observed due to drought. Peach productivity could increase, whereas apple yields will decrease throughout the country up to Araucanía due to excessive heat that reduces the fruiting period [52].

4.3. Argentina

The Pampas is one of the major agricultural regions globally and contributes to a large proportion of crop production in Argentina. More than 40% of the total exports in Argentina rely on grain and oil crops [53]. The impact of climate change on wheat, maize, and soybean yields was evaluated in the Pampas region, and seasonal maximum and minimum temperatures are projected to increase in the near (2025–2039) and far (2075–2099) future, accompanied by an increment of annual seasonal precipitation in the near future and a significant increase in the distant future. The CO_2 fertilization effect is projected to cause a slight decrease in wheat yield, a moderate increment in maize, and a substantial rise in soybean yield for both the near and far future. On average, Pampa and the area southwest of Buenos Aires would profit from climate change. The projected increase in yield may be associated with the summer precipitation, mainly in the case of maize and soybean. The changes in wheat yield in the central area of Argentina (Córdoba, Santa Fe, and north of Buenos Aires provinces) are linked with the reduced winter–spring precipitation and the lengthening of the winter dry season (Figure 5). Measures for the adaptation of wheat and maize in the near and far future were proposed, and it is expected to increase by up to 45% of yield [53].

4.4. Colombia

Agriculture in the Colombian Andes is vulnerable to climate change, namely, in the case of small farmers in the highlands (e.g., Bochalema). The assessment of the climate change impacts on national rice production identified suitable areas for farming irrigated rice in Colombia, in mid-latitudes for 2050 in the case of RCP8.5, despite the projected decrease by 60% of the productive area, mainly in low land regions [54]. The farmers in areas projected to be less suitable for rice production face the challenge of shifting to other crops (Figure 5). Land-use changes in areas projected to increase rice yield should be environmentally sustainable and ensure long-term food security [54].

4.5. Brazil

Sugarcane grows in tropical and subtropical climates with a long growing season, lasting in the soil during all seasons. Brazil is the largest world producer of sugarcane and sugar and the second largest producer of ethanol. Sugarcane is an essential national crop, playing a vital role in economic development and generating employment and income. Central–south regions account for about 90% of the sugarcane and sugar production and

92% of the ethanol production. Climate factors are crucial for sugarcane development. Low temperature values and water scarcity are responsible for losses in production and quality [12]. Positive relations with precipitation and negative with temperature were identified in Paraiba state. Under climate change, sugarcane productivity levels may be reduced. The Mata Paraibana region shows a greater likelihood of producing sugarcane than other regions, and irrigation could encourage sugarcane production in drier areas [55]. The climate impact on irrigation water was analyzed in the northeastern Jaguaribe River basin [56]. The water resource demand for irrigated agriculture was assessed. It is projected that the rise in temperature will increase water demand from vegetation (increase reference evapotranspiration) and, therefore, crops and irrigation water needs for the RCP8.5 and RCP4.5 scenarios, whereas positive and negative impacts of precipitation are predicted (Figure 5).

A reduction of 30% in the productivity of beans and maize is expected from 2050 to 2080 in southeast Brazil, mainly linked to the shortening of the phenological stage. The CO_2 fertilization effect is expected to increment bean productivity, hampering the thermal effect. In the case of maize, the CO_2 fertilization was weaker and did not cancel the thermal impact, suggesting that climate change will not favor the maize yield [57]. The modeling experiments conducted for an experimental area of Janaúba and Sete Lagoas located in Minas Gerais State, Brazil, also showed the mitigation of the temperature effect on sorghum development and growth, in particular, due to CO_2 fertilization through the reduction of water stress. Increasing CO_2 atmospheric concentration will reduce the impact of water stress during critical sorghum phases, modifying the crop cycle duration and sowing window. The yields are estimated to decrease for sowing dates from August to November. Increases in grain yield may compensate for the reduction of other sowing dates [58]. However, a sensitivity analysis of the dependence of sorghum on climate variables showed a clear dependence on water availability in Minas Gerais. The increase of atmospheric CO_2 concentration has a slightly positive effect on water stress years, but accumulated radiation during the vegetative cycle, below 1900 MJm^{-2}, will reduce the yield. Sorghum seems to be less sensitive to relative humidity and wind speed changes [59]. Climate variability and change will affect the success of soybean production in southern Brazil, namely, the states of Paraná, Santa Catarina, and Rio Grande do Sul. Lower soybean yields are expected to be linked to temperature increments. Reduction of plant branches and racemes, changes in the crop structure to take advantage of increased CO_2 [60], and changes in planting dates [61] may reduce the temperature impacts (Figure 5).

Southern Amazon is envisaged to be very vulnerable to climate change, mainly due to the high deforestation rate observed for cattle ranching and the expansion of soybean fields in regions such as Mato Grosso (MT) and Pará (PA), main hotspots of deforestation [62]. MT and PA states are the largest producers of soybean and maize in Brazil. These crops are crucial for the national economy, as Brazil is responsible for, respectively, 27% and 7% of the world's production [63]. The viability of these crops for future climate change scenarios (2070–2100, GHG) was evaluated using regional climate simulations from HadRM3 (B2 and A2 scenarios). Despite soil management with optimum fertilization, a clear decrease in maize yield was foreseen for 2100. An increase of up to 60% in soybean is possible in the case of optimum soil management and no water stress. It has to be mentioned that future climate conditions increase the interannual variability leading to large fluctuations in the productivity of both crops [63].

Additional deforestation can lead to increased productivity loss due to further reductions in September and October rainfall. Due to climate change, urgent adaptation strategies are needed to maintain highly productive double-cropping systems in Brazil. However, the projected positive effect of CO_2 fertilization may not be strong enough to compensate for the expected adverse impact of dry conditions on the early planted soybean cycle [64].

The employment of double-cropping systems (two crops in the same year on the same land) in places with a long enough wet season has been proven to dramatically increase the total production of these two crops [65]. The evaluation of soybean productivity in Brazil after climate change demonstrates an increase in productivity when only one crop grows in the agricultural calendar, with sowing occurring around November–December. When farmers opt for sowing two crops and planting short-cycle cultivars in late September, productivity may be strongly reduced.

The delay of the planting date may compensate for productivity losses, but jeopardizes the option of a second crop. However, rainfed double-cropping systems are projected to be at risk in 2040 due to the high summer temperature, precipitation decline, and delay of the rainy season onset dates [62]. Future crop yields were simulated [63], and soybean yields are projected to remain relatively similar, whereas maize and cotton productivities are forecasted to decrease by 28% and 17%, respectively. The sustainability of double-cropping systems requires adopting effective and urgent adaptation measures.

It should be noted that a possible expansion of agriculture to the north may lead to irreversible damage. The solution for sustainable agriculture in this region should combine several approaches, ranging from more climate-friendly production (livestock–forest systems, effective control mechanisms to prevent deforestation) to adaptation measures to minimize yield losses (drought tolerance) [62]. Among others, technological solutions center on the beginning of the soybean cycle in the case of short-cycle cultivars in places with an expected water deficit increase (new drought-tolerant species), improvements in yield for short-cycle soybean and maize, and incorporation of recent and updated climate predictions in the Climate Risk Agricultural Zoning. A lousy option could be to shift the farms to areas with more favorable precipitation regimes, promoting higher deforestation, and further decreasing the wet season duration and precipitation in September and October, adversely affecting the yields once again. It is urgent to reinforce the measures to halt deforestation in Amazonia and Cerrado to preserve tropical biomes and simultaneously maintain highly productive and global agricultural systems in Brazil [64].

5. Discussion

Until the 1980s, agricultural research aimed to increase productivity in order to cope with population growth. In many developing countries, the success of the green revolution was based on the increased use of improved seeds, fertilizers, irrigation, pesticides, and fungicides, among others. With the beginning of the 21st century, the agricultural research community faces a new challenge that intends to balance the continuous need to increase productivity with the new concerns associated with the positive trend in the frequency of extreme weather and climatic events.

Table 1 aims to synthesize the major impacts projected for the end of the 21st century over South American countries, considering different adaptation measures. Crop yields are projected to increase in response to CO_2 fertilization in Peru, despite the negative impact projected in Venezuela due to foreseen precipitation reduction. Climate change scenarios in Chile pointed to a positive impact in the southern regions and hills and an adverse effect in central regions, mainly associated with lower water availability for irrigation (Figure 5). The most vulnerable regions are located in the dry interior and arid coast, between Valparaíso and Biobío, the transverse valleys, and the dry lands ranchers. The beans, corn, potatoes, and sugarcane yields will increase along the coast and hills and in the south.

The production of orchards will decrease in the Valparaíso region associated with heat extremes. Negative effects are foreseeable not only in the quantity, but also in the quality of the products. The small farmers in the highlands of the Colombian Andes will face significant challenges due to the foreseen reduction of suitable regions for rice production. A significative reduction of beans and maize productivity is projected in southeast Brazil, mainly related to a shortening of the phenological stages, as well as a decrease in soybean production in southern Brazil, linked to temperature increase. CO_2 fertilization is expected to increase bean productivity in the southeast, sorghum in Minas Gerais, and soybean in southern Brazil. Despite the expected increase in soybean production in the southern Amazonia region in the case of soil fertilization, a decrease in maize production is projected.

In places where the wet season is long enough, the employment of double-cropping systems will allow a significant increase in these crops. However, these systems are projected to be at risk in 2040 due to precipitation decrease, delay in the onset date of the rainy season, and temperature increase, which is projected to adversely affect maize and cotton productivity (Figure 5).

Currently, the central question is whether agricultural and food systems will be able to meet the needs of the growing global population [65]. The overall impact of extreme weather events on the agricultural sector is a very complex problem, requiring an urgent effort to establish efficient and sustainable management systems [66]. The great heterogeneity and the difficulty in predicting the global and regional effects of climate change highlight the continuing need to monitor and predict extreme weather events to facilitate adaptation. Measures to minimize the adverse impacts of climate change have been analyzed, namely, the resilient agricultural systems resulting from increases in biodiversity; the improvement of biotechnologies and genomic tools; the selection of new varieties; the modification of the distribution of current varieties; the use of species more tolerant to conditions triggered by climate change; the incremented production of new cultivars; improved irrigation; and more effective use of fertilizers, selecting the sowing time and zoning paddock. An important component of this analysis focused on tools and technologies for early detection or risk maps [66]. Table 2 aims to synthesize the major impacts projected for the end of the 21st century over South American countries, considering different adaptation measures.

Table 2. End-of-century projected changes in crop production for some South American countries, considering different climate scenarios and the application of different adaptation measures. ↓ and ↑ indicate the role of irrigation, CO_2 fertilization, rainfed, rainfed 2 crops and fertilizers to decrease or increased productivity.

Adaptation Measures	Irrigation	CO_2 Fertilization	Rainfed	Rainfed 2 Crops	Fertilizers
Wheat		Argentina ↓	Chile ↓ Chile ↑ *		
Maize		Argentina ↑		Brazil ↓	Brazil ↓
Wine	Chile ↑				
Soybean	Brazil ↑	Argentina ↑			
Potatoes	Brazil ↑				
North Chile					

Even for the case of a projected increase in precipitation in Brazil, the magnitude of raised precipitation, which occurred mainly in the rainy season, is not enough to compensate for the water demand increase linked to evapotranspiration increments. Irrigation will be predominant in the adaptation measures proposed to cope with climate change. The projected water availability would not meet future irrigation needs in the current situation. Therefore, the sustainability of irrigated agriculture is at high risk in the Jaguaribe River basin, foreseeing a negative impact of climate change on agricultural practices and being a driver of production losses [57].

Farmers' strategies against weather extremes should be limited to preventive and/or corrective activities. Agricultural insurance based on weather indexes is a novel financial instrument for farmers. Unlike traditional insurance, it can mitigate moral hazard and adverse selection, allowing lower premiums, making this type of insurance an attractive mechanism for developing economies with a large part of the rural population submerged in severely precarious conditions. In Bolivia, where the agricultural sector exceeds 30% of the employment and generates more than 12% of the GDP, agricultural insurance can become an instrument capable of improving farmers' conditions and quality of life.

A pilot case was carried out at the municipality of Anzaldo, Bolivia. Results highlighted the relevance of using quantitative techniques and methodological processes to design agricultural insurance based on climatic indices, even when historical information on yields is deficient and there is missing climatic data. The recent increase in the popularity of climate-based insurance at the national level is strongly linked to the availability of high-quality information on climate factors in the various microclimates, and the dispersal of information on crop production and its characteristics in Bolivia [67].

In the climate change context, climate-smart agriculture constitutes an ongoing proposal to adapt agricultural systems to the new climate change risks, following three main objectives: sustainable increase in agricultural productivity and incomes; adaptation and creation of resilience to climate change; and reduction and absorption of greenhouse gases, taking care of ecological, carbon, water, and energy footprints [68]. At the Chilean national level, the strategy relies on working jointly, bringing together the public sector, civil society, and the private sector with a comprehensive approach to achieve strategic information in the three axes: economic, social, and environmental.

Various methodologies provide information on the degree of fulfilment of the bioclimatic requirements of the different fruit species. The risk index can be calculated based on variables that affect development and productivity during the different phenological phases. The model developed in AGRIMED [69] incorporates risk components, such as sensitivity to frost, sensitivity to high temperatures, and sensitivity to thermal stress at temperatures of 28, 30, 32, 34, and 36 °C. At the same time, the phenological simulation considers the accumulation temperature in growing degree days. For example, the projected productivity of the cherry tree for 2050 to 2070 increases towards the south of Biobío, Chile, due to the improvement associated with temperature increase, allowing planting in sectors bordering the mountain range. In contrast, the projected production in the north begins to decline, mainly due to the water deficit. In the case of the walnut trees, the current prospects can be maintained through adaptive technologies in the south. In the central zone, the conditions deteriorate due to the lack of cold, but improve considerably towards the south of Biobío.

The requirements for avocado plantations, on the other hand, improve throughout the national geography since they are not affected mainly by climate change, except for a slight loss in oil content. For the case of grapevine, conditions improve to the south of Biobío and deteriorate in the central valley due to thermal stress, which will affect the transfer to the south of Biobío, being possible adaptation measures to maintain the levels of current potentials. In the case of grapes for vinification, the quality of the final wine depends on a set of factors that form the “terroir”, which strongly affects the wine’s typicity, finesse, and quality. However, if the water problem in the northern zone is solved and adequate technical management is implemented, a productive advantage could be obtained for these species due to climate change [69].

Recent studies show that small farmers are sensitive to current climate extremes. In the case of cropland, the small farmer’s perceptions are different, depending on several conditions: the extreme event (flood or drought), the year of occurrence, the time passed since the last event, and the type of environment (dryland or rural). In the case of floods, the adopted measures depend on the level of data refinement, and there is no clear response in terms of risk behavior, as floods could be beneficial in certain conditions. The level of damage depends on sowing time and mechanisms to cope [70]. In Chile, farmers seem to be adapted to the environment; they prefer legumes, tubers, and vineyards in arid environments, whereas cereals, industrial crops, and vegetables in a wet environment. Decisions from policymakers should be oriented to help small farmers in drylands due to water scarcity and difficulties coping with the effects of droughts. Erosion problems should also be considered in regions frequently stricken by floods [70].

6. Final Remarks and Recommendation

Enormous pressure has been put on agriculture to ensure food and nutrition security due to population growth in a warming world. Even considering the uncertainties associated with future climate scenarios and likely impacts, the forecasted decrease in agriculture productivity shows considerable consensus. Changes in temperature, precipitation regime and quantity, and greenhouse gases significantly affect soil fertility, plant physiology, irrigation, and water availability and quality. Several mitigation and adaptation strategies have been developed to minimize the adverse impact of climate change and extremes on agricultural sustainability. However, the implementation of such measures is not always easy, namely, considering that the associated impacts are highly unpredictable, and require climate-resilient technologies that involve an interdisciplinary approach according to the region [71].

The Banco Interamericano de Desarrollo (BID) has stated that the main challenges for agriculture in the 21st century will be improving access to food, increasing its supply and distribution, and increasing the food system's resilience. At the same time, GHG emissions will be reduced, and air and water pollution produced by agricultural activity and land use should be eliminated, thus avoiding damaging the habitat and biodiversity and gradually stopping unsustainable water extraction [72,73].

Recently, many recommendations and suggestions to mitigate climate extremes and impacts on the agriculture system have been proposed. Assessing climate extreme risk and impacts on different agroecosystems is crucial to consolidate and/or rehabilitate the agrometeorological observation networks, to support data collection and analyses. Databases including meteorological, agricultural, hydrological, land use, soil types, and economic data are essential for assessing and mitigating natural disasters [65]. Recently, satellite-derived products, such as soil moisture, evapotranspiration, and precipitation, have been used in many agrometeorological applications for disaster risk management and early warning in agriculture. The satellite-derived Climate Data Records (CDRs), recently made available, complement the traditional in situ observations, making data available in regions not covered by surface observations. A set of new products, such as microwave-derived products, allow global coverage, even in the overcast sky. Nowadays, data from atmospheric models and from the new gridded reanalysis are providing a complete set of variables with global coverage. Weather and climate services (CSs) were developed to increase the ability of the agricultural system to manage the risks and the coping capacity in case of climate extremes in the most vulnerable countries.

In the Sendai Framework for Disaster Risk Reduction (SFDRR), several priorities were established, namely, "Enhancing disaster preparedness for effective response and to 'Build Back Better' in recovery, rehabilitation and reconstruction". These priorities highlight the need for multi-hazard early warning systems. The development of a timely early warning system should produce technically accurate alerts, requiring interpretation of the risk assessment based on the link between producers and consumers of information on impacts on agriculture.

The efficiency of these early warning systems is largely dependent on the availability of reliable short- and medium-term forecasts (3 to 10 days in advance), as well as seasonal weather forecasts. The SFDRR further calls for building effective partnerships on regional and sub-regional platforms that allow knowledge sharing, and promotes the integration of disaster risk management in other relevant sectors. Building resilient food production and livelihood systems is imperative to promoting climate index insurance. However, as mentioned above, individual recourse to these insurance systems is very difficult, and for its implementation, it is imperative to resort to cooperatives or other regional or international support systems [65].

Author Contributions: Conceptualization, C.M.G. and F.J.; writing—original draft preparation, C.M.G.; writing—review and editing, F.J.; visualization, C.G., C.A. and L.Z.; supervision, C.M.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: All authors included in this study have consented to the acknowledgement.

Data Availability Statement: Not applicable.

Acknowledgments: The current publication was funded by the World Meteorological Organization Expert Team on Agromet Risk Management (ET-ARM) as part of the report "Estimation of crop and livestock losses per extreme weather events".

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ribeiro, A.F.S.; Russo, A.; Gouveia, C.M.; Páscoa, P.; Zscheischler, J. Risk of crop failure due to compound dry and hot extremes estimated with nested copulas. *Biogeosciences* **2020**, *17*, 4815–4830. [CrossRef]
2. FAO. *Global Outlook on Climate Services in Agriculture—Investment Opportunities to Reach the Last Mile*; FAO: Rome, Italy, 2021. [CrossRef]
3. FAO. *The Impact of Disasters and Crises on Agriculture and Food Security*; FAO: Rome, Italy, 2021. [CrossRef]
4. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter 11—Weather and Climate Extreme Events in a Changing Climate*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Pe, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Eds.; Cambridge University Press: Cambridge, UK, 2021, *in press*.
5. FAO. Global Agriculture towards 2050. High Expert Forum. Rome. 2009. Available online: www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf (accessed on 17 June 2023).
6. Praveen, B.; Sharma, P. A review of literature on climate change and its impacts on agriculture productivity. *J. Public Aff.* **2019**, *19*, e1960. [CrossRef]
7. Crippa, M.; Solazzo, E.; Guizzardi, D.; Monforti-Ferrario, F.; Tubiello, F.N.; Leip, A. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food* **2021**, *2*, 198–209. [CrossRef]
8. Sutanto, S.J.; Vitolo, C.; Di Napoli, C.; D'Andrea, M.; Van Lanen, H.Á.J. Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale. *Environ. Int.* **2020**, *134*, 105276. [CrossRef]
9. Gouveia, C.; Liberato, M.L.R.; DaCamara, C.C.; Trigo, R.M.; Ramos, A.M. Modelling past and future wine production in the Portuguese Douro Valley. *Clim. Res.* **2011**, *48*, 349–362. [CrossRef]
10. FFeng, P.; Wang, B.; Liu, D.L.; Xing, H.; Ji, F.; Macadam, I.; Ruan, H.; Yu, Q. Impacts of rainfall extremes on wheat yield in semi-arid cropping systems in eastern Australia. *Clim. Chang.* **2018**, *147*, 555–569. [CrossRef]
11. Feron, S.; Cordero, R.R.; Damiani, A.; Llanillo, P.J.; Jorquera, J.; Sepulveda, E.; Asencio, V.; Laroze, D.; Labbe, F.; Carrasco, J.; et al. Observations and Projections of Heat Waves in South America. *Sci. Rep.* **2019**, *9*, 8173. [CrossRef] [PubMed]
12. Marengo, J.A.; Ambrizzi, T.; Barreto, N.; Cunha, A.P.; Ramos, A.M.; Skansi, M.; Carpio, J.M.; Salinas, R. The heat wave of October 2020 in central South America. *Int. J. Climatol.* **2022**, *42*, 2281–2298. [CrossRef]
13. IPCC. *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*; Core Writing Team, Pachauri, R.K., Meyer, L.A., Eds.; IPCC: Geneva, Switzerland, 2014; 151p.
14. Yamazaki, D.; Watanabe, S.; Hirabayashi, Y. Global Flood Risk Modeling and Projections of Climate Change Impacts. *Geophys. Monogr. Ser.* **2018**, 185–203. [CrossRef]
15. Mind'je, R.; Li, L.; Amanambu, A.C.; Nahayo, L.; Nsengiyumva, J.B.; Gasirabo, A.; Mindje, M. Flood susceptibility modelling and hazard perception in Rwanda. *Int. J. Disaster Risk Reduct.* **2019**, *38*, 101211. [CrossRef]
16. Russo, A.; Gouveia, C.; Dutra, E.; Soares, P.M.M.; Trigo, R.M. The synergy between drought and extremely hot summers in the Mediterranean. *Environ. Res. Lett.* **2018**, *14*, 014011. [CrossRef]
17. Gouveia, C.M.; Martins, J.P.; Russo, A.; Durão, R.; Trigo, I.F. Monitoring heat extremes across central Europe using land surface temperature data records from SEVIRI/MSG. *Remote Sens.* **2022**, *14*, 3470. [CrossRef]
18. Barriopedro, D.; Fischer, E.M.; Luterbacher, J.; Trigo, R.M.; García-Herrera, R. The hot summer of 2010: Redrawing the temperature record map of Europe. *Science* **2011**, *332*, 220–224. [CrossRef]
19. Barriopedro Cepero, D.; Sousa, P.M.; Trigo, R.M.; García Herrera, R.; Ramos, A.M. The exceptional Iberian heatwave of summer 2018. *Bull. Am. Meteorol. Soc.* **2020**, *101*, S29–S33. [CrossRef]
20. Bastos, A.; Gouveia, C.M.; Trigo, R.M.; Running, S.W. Analysing the spatio-temporal impacts of the 2003 and 2010 extreme heatwaves on plant productivity in Europe. *Biogeosciences* **2014**, *11*, 3421–3435. [CrossRef]

21. Duine, G.J.; Carvalho, L.M.; Jones, C. Mesoscale patterns associated with two distinct heatwave events in coastal Santa Barbara, California, and their impact on local fire risk conditions. *Weather Clim. Extrem.* **2022**, *37*, 100482. [CrossRef]
22. WMO. *2019 State of Climate Services: Agriculture and Food Security*; World Meteorological Organization: Geneva, Switzerland, 2021; ISBN 978-92-63-11242-2.
23. Parker, L.E.; McElrone, A.J.; Ostoja, S.M.; Forrestel, E.J. Extreme heat effects on perennial crops and strategies for sustaining future production. *Plant Sci.* **2020**, *295*, 110397. [CrossRef]
24. Williams, V. Identifying the economic effects of salt water intrusion after Hurricane Katrina. *J. Sustain. Dev.* **2010**, *3*, 29–37. [CrossRef]
25. Ebi, K.L.; Vanos, J.; Baldwin, J.W.; Bell, J.E.; Hondula, D.M.; Errett, N.A.; Hayes, K.; Reid, C.E.; Saha, S.; Spector, J.; et al. Extreme weather and climate change: Population health and health system implications. *Annu. Rev. Public Health* **2021**, *42*, 293–315. [CrossRef]
26. Liu, J.C.; Wilson, A.; Mickley, L.J.; Dominici, F.; Ebisu, K.; Wang, Y.; Sulprizio, M.P.; Peng, R.D.; Yue, X.; Son, J.-Y.; et al. Wildfire-specific fine particulate matter and risk of hospital admissions in urban and rural counties. *Epidemiology* **2017**, *28*, 77–85. [CrossRef]
27. Lei, Y.; Yue, X.; Liao, H.; Zhang, L.; Yang, Y.; Zhou, H.; Tian, C.; Gong, C.; Ma, Y.; Gao, L.; et al. Indirect contributions of global fires to surface ozone through ozone–vegetation feedback. *Atmos. Chem. Phys.* **2021**, *21*, 11531–11543. [CrossRef]
28. Ashmore, M.R. Assessing the future global impacts of ozone on vegetation. *Plant Cell Environ.* **2005**, *28*, 949–964. [CrossRef]
29. Fumigalli, I.; Gimeno, B.; Velissariou, D.; de Temmerman, L.; Mills, G. Evidence of ozone-induced adverse effects on crops in the Mediterranean region. *Atmos. Environ.* **2001**, *35*, 2583–2587. [CrossRef]
30. Velissariou, D. Toxic effects and losses of commercial value of lettuce and other vegetables due to photochemical air pollution in agricultural areas of Attica, Greece. In *Critical Levels for Ozone—Level II*; Fuhrer, J., Achermann, B., Eds.; Swiss Agency for Environment, Forest and Landscape: Bern, Switzerland, 1999; pp. 253–256.
31. Emberson, L.D.; Ashmore, M.R.; Murray, F. *Air Pollution Impacts on Crops and Forests—A Global Assessment*; Imperial College Press: London, UK, 2003.
32. Emberson, L.; Ashmore, M.; Murray, F.; Kuylenstierna, J.; Percy, K.; Izuta, T.; Zheng, Y.; Shimizu, H.; Sheu, B.; Liu, C.; et al. Impacts of air pollutants on vegetation in developing countries. *Water Air Soil Pollut.* **2001**, *130*, 107–118. [CrossRef]
33. de Bauer, M.L. Air pollution impacts on vegetation in Mexico. In *Air Pollution Impacts on Crops and Forests—A Global Assessment*; Emberson, L.D., Ashmore, M.R., Murray, F., Eds.; Imperial College Press: London, UK, 2003; pp. 263–286.
34. Mills, G.; Pleijel, H.; Malley, C.S.; Sinha, B.; Cooper, O.R.; Schultz, M.G.; Neufeld, H.S.; Simpson, D.; Sharps, K.; Feng, Z.; et al. Tropospheric Ozone Assessment Report: Present-Day Tropospheric Ozone Distribution and Trends Relevant to Vegetation; Elementa: Science of the Anthropocene 6; 2018. Available online: https://online.ucpress.edu/elementa/article/doi/10.1525/elementa.302/112843/Tropospheric-Ozone-Assessment-Report-Present-day (accessed on 17 June 2023).
35. Sheu, B.H.; Liu, C.P. Air pollution impacts on vegetation in Taiwan. In *Air Pollution Impacts on Crops and Forests—A Global Assessment*; Emberson, L.D., Ashmore, M.R., Murray, F., Eds.; Imperial College Press: London, UK, 2003; pp. 145–163.
36. Lal, S.; Venkataramani, S.; Naja, M.; Kuniyal, J.C.; Mandal, T.K.; Bhuyan, P.K.; Kumari, K.M.; Tripathi, S.N.; Sarkar, U.; Das, T.; et al. Loss of crop yields in India due to surface ozone: An estimation based on a network of observations. *Environ. Sci. Pollut. Res. Int.* **2017**, *24*, 20972–20981. [CrossRef]
37. Huffman, W.E.; Jin, Y.; Xu, Z. The economic impacts of technology and climate change: New evidence from US corn yields. *Agric. Econ.* **2018**, *49*, 463–479. [CrossRef]
38. Tol, R.S. The economic impacts of climate change. *Rev. Environ. Econ. Policy* **2018**, *12*, 4–25. [CrossRef]
39. Rosenzweig, C.; Elliott, J.; Deryng, D.; Ruane, A.C.; Müller, C.; Arneth, A.; Boote, K.J.; Folberth, C.; Glotter, M.; Khabarov, N.; et al. Assessing Agricultural Risks of Climate Change in the 21st Century in a Global Gridded Crop Model Intercomparison. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 3268–3273. [CrossRef] [PubMed]
40. Masson-Delmotte, V.; Zhai, P.; Pörtner, H.O.; Roberts, D.; Skea, J.; Shukla, P.R. *Global Warming of 1.5 °C: An IPCC Special Report on the Impacts of Global Warming of 1.5 °C*; Cambridge University Press: Cambridge, UK, 2018; pp. 43–50.
41. Chavez Michaelsen, A.; Huamani Briceño, L.; Vilchez Baldeon, H.; Perz, S.G.; Quaedvlieg, J.; Rojas, R.O.; Brown, I.F.; Pinedo Mora, R. The effects of climate change variability on rural livelihoods in Madre de Dios, Peru. *Reg. Environ. Chang.* **2020**, *20*, 70. [CrossRef]
42. Parry, M.L.; Rosenzweig, C.; Iglesias, A.; Livermore, M.; Fischer, G. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Glob. Environ. Chang.* **2004**, *14*, 53–67. [CrossRef]
43. Andersen, L.; Mamani, R. Cambio climático en Bolivia hasta 2100: Síntesis de costos y oportunidades. *Estud. Reg. Econ. Cambio Climático Sudamérica*. 2009. Available online: https://www.researchgate.net/publication/242477920_Cambio_Climatico_en_Bolivia_hasta_2100_Sintesis_de_Costos_y_Oportunidades (accessed on 17 June 2023).
44. Torres, F.; Peña, F.; Cruz, R.; Gómez, E. Impacto de El Niño sobre los cultivos vegetales y la productividad primaria en la sierra central de Piura. In *El Niño en América Latina, Impactos Biológicos y Sociales*; Tarazona, J., Arntz, W., Castillo, E., Eds.; Editorial Omega S.A.: Barcelona, Spain, 2001.
45. Arenas, J.C. *La Economía del Cambio Climático en Bolivia: Impactos de Eventos Extremos Sobre Infraestructura y Producción Agropecuaria*; Banco Interamericano para el Desarrollo: La Paz, Bolivia, 2014. Available online: https://repositorio.cepal.org/bitstream/handle/11362/39833/1/2014-290_CCBol_eventos_extremos.pdf (accessed on 17 June 2023).

46. Ecuador. Third National Communication to the UNFCCC. 2017. Available online: https://unfccc.int/documents/77568 (accessed on 17 June 2023).
47. UNDP. National Adaptation Plans in Focus: Lessons from Ecuador. 2018. Available online: https://www.adaptation-undp.org/sites/default/files/resources/nap_in_focus_lessons_from_ecuador_english.pdf (accessed on 17 June 2023).
48. Ecuador. National Climate Change Plan 2015–2018. 2015. Available online: https://info.undp.org/docs/pdc/Documents/ECU/PLAN%20NACIONAL%20DE%20CAMBIO%20CLIMÁTICO.pdf (accessed on 17 June 2023).
49. FAO. Subregional Strategy to Prevent the Introduction of Foot-and-Mouth Disease, and Plan of Action to Improve the Management and Attention of Health Emergencies. Family Farming Knowledge Platform. 2019. Available online: http://www.fao.org/3/ca5163es/CA5163ES.pdf (accessed on 17 June 2023).
50. Wehner, M.; Seneviratne, S.; Zhang, X.; Adnan, M.; Badi, W.; Dereczynski, C.; Di Luca, A.; Ghosh, S.; Iskandar, I.; Kossin, J.; et al. Weather and climate extreme events in a changing climate. In Proceedings of the AGU Fall Meeting 2021, New Orleans, LA, USA, 13–17 December 2021.
51. Academia Chilena de Ciencias Agronómicas. Cambio Climático: Efectos Sobre la Producción Hortofrutícola y Estrategias de Adaptación en Chile. 74p. Juan Izquierdo, J., Ed.; 2020. Available online: www.academiaagronomica.cl (accessed on 17 June 2023).
52. Ortiz, R. El Cambio Climático y la Producción Agrícola. s.l., BID, 2012. 41p. Available online: https://keneamazon.net/Documents/Publications/Virtual-Library/Economia-Desarrollo/99.pdf (accessed on 17 June 2023).
53. Ministerio del Medio Ambiente. Elaboración de una Base Digital del Clima Comunal de Chile: Línea Base (1980–2010) y Proyección al año 2050. 2016. Available online: http://portal.mma.gob.cl/wp-content/doc/Clima-Comu-nal_Informe_Final_29_08_2016-web.pdf (accessed on 17 June 2023).
54. Rolla, A.L.; Nuñez, M.N.; Guevara, E.R.; Meira, S.G.; Rodriguez, G.R.; de Zárate, M.I.O. Climate impacts on crop yields in Central Argentina. Adaptation strategies. *Agric. Syst.* **2018**, *160*, 44–59. [CrossRef]
55. Castro-Llanos, F.; Hyman, G.; Rubiano, J.; Ramirez-Villegas, J.; Achicanoy, H. Climate change favors rice production at higher elevations in Colombia. *Mitig. Adapt. Strat. Glob. Chang.* **2019**, *24*, 1401–1430. [CrossRef]
56. Medeiros Silva, W.K.; de Freitas, G.P.; Junior, L.M.C.; de Almeida Pinto, P.A.L.; Abrahão, R. Effects of climate change on sugarcane production in the state of Paraíba (Brazil): A panel data approach (1990–2015). *Clim. Chang.* **2019**, *154*, 195–209. [CrossRef]
57. Gondim, R.; Silveira, C.; de Souza Filho, F.; Vasconcelos, F.; Cid, D. Climate change impacts on water demand and availability using CMIP5 models in the Jaguaribe basin, semi-arid Brazil. *Environ. Earth Sci.* **2018**, *77*, 550. [CrossRef]
58. Costa, L.C.; Justino, F.; Oliveira, L.J.C.; Sediyama, G.C.; Ferreira, W.P.M.; Lemos, C.F. Potential forcing of CO_2, technology and climate changes in maize (*Zea mays*) and bean (*Phaseolus vulgaris*) yield in southeast Brazil. *Environ. Res. Lett.* **2009**, *4*, 014013. [CrossRef]
59. Grossi, M.C.; Justino, F.; Andrade, C.D.L.T.; Santos, E.A.; Rodrigues, R.A.; Costa, L.C. Modeling the impact of global warming on the sorghum sowing window in distinct climates in Brazil. *Eur. J. Agron.* **2013**, *51*, 53–64. [CrossRef]
60. Grossi, M.C.; Justino, F.; Rodrigues, R.D.Á.; Andrade, C.L.T. Sensitivity of the sorghum yield to individual changes in climate parameters: Modelling based approach. *Bragantia* **2015**, *74*, 341–349. [CrossRef]
61. Pereira-Flores, M.E.; Justino, F.; Ruiz-Ver, U.M.; Stordal, F.; Melo, A.A.M.; de Avila Rodrigues, R. Response of soybean yield components and allocation of dry matter to increased temperature and CO_2 concentration. *Aust. J. Crop Sci.* **2016**, *10*, 808–818. Available online: https://search.informit.org/doi/10.3316/informit.323038266929010 (accessed on 17 June 2023). [CrossRef]
62. do Rio, A.; Sentelha, P.C.; Farias, J.R.B.; Sibaldell, R.N.; Ferreir, R.C. Alternative sowing dates as a mitigation measure to reduce climate change impacts on soybean yields in southern Brazil. *Int. J. Climatol.* **2016**, *36*, 3664–3672. [CrossRef]
63. Hampf, A.C.; Stella, T.; Berg-Mohnicke, M.; Kawohl, T.; Kilian, M.; Nendel, C. Future yields of double-cropping systems in the Southern Amazon, Brazil, under climate change and technological development. *Agric. Syst.* **2020**, *177*, 102707. [CrossRef]
64. Justino, F.; Oliveira, E.C.; Rodrigues, R.D.A.; Gonçalves, P.H.L.; Souza, P.J.O.P.; Stordal, F.; Marengo, J.; da Silva, T.G.; Delgado, R.C.; da Silva Lindemann, D.; et al. Mean and interannual variability of maize and soybean in Brazil under global warming conditions. *Am. J. Clim. Chang.* **2013**, *2013*, 40455. [CrossRef]
65. Pires, G.F.; Abrahão, G.M.; Brumatti, L.M.; Oliveira, L.J.; Costa, M.H.; Liddicoat, S.; Kato, E.; Ladle, R.J. Increased climate risk in Brazilian double cropping agriculture systems: Implications for land use in Northern Brazil. *Agric. For. Meteorol.* **2016**, *228*, 286–298. [CrossRef]
66. Sivakumar, M.V.K.; Das, H.P.; Brunini, O. Impacts of present and future climate variability and change on agriculture and forestry in the arid and semi-arid tropics. In *Increasing Climate Variability and Change*; Springer: Dordrecht, The Netherlands, 2005; pp. 31–72.
67. Cogato, A.; Meggio, F.; De Antoni Migliorati, M.; Marinello, F. Extreme weather events in agriculture: A systematic review. *Sustainability* **2019**, *11*, 2547. [CrossRef]
68. Nogales, R.; Córdova, P. *Gestión de Riesgos Climáticos en Bolivia: Condiciones y Mecanismos para la Creación de un Seguro agrícola Basado en Índices Climáticos*; Centro de Investigaciones Económicas y Empresariales (CIEE)-Universidad Privada Boliviana: La Paz, Bolivia, 2013.
69. Lipper, L.; Thornton, P.; Campbell, B.M.; Baedeker, T.; Braimoh, A.; Bwalya, M.; Caron, P.; Cattaneo, A.; Garrity, D.; Henry, K.; et al. Climate-smart agriculture for food security. *Nat. Clim. Chang.* **2014**, *4*, 1068–1072. Available online: https://www.nature.com/articles/nclimate2437 (accessed on 17 June 2023). [CrossRef]

70. AGRIMED. Sistema de Gestión de Riesgos Agroclimáti-cos para la Adaptación a Nuevos Escenarios Climáticos. 2019. Available online: http://www.fondefriesgos.agrimed.cl/contenido.asp?Id=10 (accessed on 17 June 2023).
71. Rubilar, F.I.Z. Riesgo, Clima y Decisiones de Cultivo en Chile. Master's Thesis, Facultad de Ciencias Económicas y Administrativas, Universidad de Concepción, Concepción, Chile, 2018.
72. Malhi, G.S.; Kaur, M.; Kaushik, P. Impact of climate change on agriculture and its mitigation strategies: A review. *Sustainability* **2021**, *13*, 1318. [CrossRef]
73. Notari, C.M.; Valenzuela, R.A. Cambio climático y producción de cultivos anuales esenciales. Una mirada desde la seguridad alimentaria en Chile. *Rev. Política Estrateg.* **2017**, *129*, 157–187.