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Flood Risk and Adaptation Strategies for Soybean Production Systems on the Flood-Prone Pampas under Climate Change

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Abstract: In recent decades, multiple flood events have had a devastating impact on soybean production in Argentina. Recent advances suggest that the frequency and intensity of destructive flood events on the Argentinian Pampas will increase under pressure from climate change. This paper provides bottom-up insight into the flood risk for soybean production systems under climate change and the suitability of adaptation strategies in two of the most flood-prone areas of the Pampas region. The flood risk perceptions of soybean producers were explored through interviews, translated into climatic indicators and then studied using a multi-model climate data analysis. Soybean producers perceived the present flood risk for rural accessibility to be of the highest concern, especially during the harvest and sowing seasons when heavy machinery needs to reach soybean lots. An analysis of climatic change projections found a rising trend in annual and harvest precipitation and a slight drying trend during the sowing season. This indicates that the flood risk for harvest accessibility may increase under climate change. Several adaptation strategies were identified that can systemically address flood risks, but these require collaborative action and cannot be undertaken by individual producers. The results suggest that if cooperative adaptation efforts are not made in the short term, the continued increase in flood risk may force soybean producers in the case study locations to shift away from soybean towards more robust land uses.

Keywords: climate change impacts; flood risks; Argentina; Pampas; soybean; climate change adaptation; production systems

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1. Introduction

Since the 1970s, soybean production in Argentina has experienced stark growth. In less than half a century, the production of soybean increased from several hundred thousand tons to almost 60 million metric tons per year and it has become the dominant crop in Argentina [1]. As of 2017, the country accounted for roughly 20% of the global soybean production [2]. In addition, the wider Argentinian soybean sector has developed in recent decades into an export-oriented production and processing complex. The majority of nationally grown soybean is processed into soymeal, soy oil and biodiesel [3,4]. The export value of the total soybean chain is most recently estimated at US $17 billion [5] and accounts for 5.5% of the national GDP [6]. The soybean sector is hence an important pillar of the Argentinian national economy.

More than 85% of Argentinian soybean is cultivated on the vast and fertile planes of the Pampas [7,8]. The Pampean region, and by extension the Argentinian soybean production, has historically been susceptible to flooding at times of excessive rainfall [7,8]. Since the 1960s, the region has faced an annual precipitation increase of more than 5 mm/year and the frequency of extreme rainfall events has nearly tripled [9,10]. The frequency of damaging flood events has increased likewise over the last decades [11,12]. Their destructive potential was exemplified in the 2016/2017 soybean season when almost 10% of the total Argentinian soybean was damaged as a result of extensive flooding in the Pampas region [13,14]. The loss of yield translated into a peak in global soybean prices [13,15] and an economic loss equivalent to 0.25% of the national GDP [16]. Similar floods have occurred in the periods 2000/2002 and 2012/2013 [17] and most recently on a smaller scale in the 2018/2019 season [18].

Climate change is likely to globally exacerbate the societal threat that floods may pose, largely due to increasing extreme weather events [19]. Climate projections for South America's Southern Cone similarly indicate that the increasing precipitation trends are likely to continue until the end of the century [9,20] and flood events are expected to further increase in frequency and intensity as well [21,22]. Yet, various studies have found adaptive flood management practices in the agricultural sector of Argentina to be inadequate and of a reactive character [9,10,12,22,23]. The lack of anticipatory public adaptation has led to autonomous adaptation at the production level, fragmenting the adaptation process and causing negative externalities [10,22]. The compounding factors are a cause for a multitude of studies to conclude that the agricultural sector of Argentina, including soybean production, appears vulnerable in the face of climate change [9–11,21,22,24], with the effects of the changing precipitation patterns singled out as particularly threatening [11,25]. This vulnerability may extend to the wider soybean sector as well [26].

Integrated and anticipatory adaptation planning in the wider Argentine agricultural sector is therefore essential to reduce the risk that floods may pose to Pampean soybean production under climate change [9,12]. However, a key issue obstructing such an approach is a mismatch between the current body of scientific work related to flood development and the needs of decision makers and producers [11,22]. Although abundant information is available regarding regional climatic change, its effects on the frequency and intensity of flood events and the generic implications for flood vulnerabilities, there is scarce insight into how climatic trends may actually impact the flood risks for soybean production systems from the point of view of their operators. The lack of a bottom-up understanding of potential future flood risks subsequently casts doubts on the suitability of adaptation strategies [11] and has been shown to hinder the adaptation decision-making process [27]. Several studies hence call for more participative research into climate risks and vulnerabilities for agricultural systems in Argentina and into the collaborative assessment of appropriate adaptation measures [9,11,22].

The objective of this paper is to construct a bottom-up understanding of the impact of climate change on the flood risk for soybean production systems on the flood-prone Pampas and to explore potential adaptation strategies. For this purpose, interviews were held with soybean producers, in which it was inquired how floods affect soybean production and what climatic conditions bring about these types of flood risks. The development of these critical climatic conditions was then studied using a multi-model ensemble of climate change projections. Based on the improved understanding of the development of flood risks, we provide a qualitative overview of suitable adaptation strategies that may aid in adaptation planning and water management.

2. Materials and Methods

2.1. Study Area

The Pampas region is characterised by its vast flatness and fertile agricultural land. The humid Pampas are home to year-round precipitation of about 1000 mm, mild temperatures and a limited number of frost days [28]. In combination with the fertility of its soils, the climatological circumstances make the Pampas region highly suitable for agriculture, including the cultivation of soybean [29]. However, the absence of almost any form of slope and the poorly developed natural water network of the Pampas greatly hinder run-off [7]. Consequently, horizontal fluxes are negligible and evapotranspiration is the most important water outlet. During wet cycles, sustained periods of positive precipitation anomalies exceed the evapotranspiration potential of the Pampas. The ensuing excess water is stored in the system by driving the water table towards the surface and by the expansion of surface water bodies. As a result, the Pampas are prone to slow-onset flooding that can last multiple weeks or months to even years [17]. Due to their slow and vertical nature, the definition of floods in the Pampas region is closely linked to the term 'hydrological excesses' and also entails phenomena such as waterlogging [7,30].

Soybean is the dominant crop on the Pampas. It is cultivated either as a single rotation or as a double crop with wheat or corn. It is, however, rather vulnerable to anoxic conditions. Soybean can generally sustain complete submergence for 48 to 96 h. Any period longer than this will lead the soybean plant to die [31]. Even so, a less severe flood impact such as waterlogging can also have a devastating effect on soybean production [31–33]. The long time span on which the slow-onset floods of the Pampas occur is thus highly damaging to soybean production [17].

Within the Pampas region (see Figure 1), the Pampa Interior and the Pampa Deprimida sub-regions are the flattest, being classified as a hyperplains, and subsequently the most flood-prone [7]. A study by Kuppel et al. [17] found that on account of differences in geography and soil characteristics, the precipitation patterns that lead up to slow-onset floods in the Pampa Interior and Pampa Deprimida differ (see Figure 2). Floods in the Pampa Interior are mostly groundwater driven due to the high groundwater connectivity of its sandy soils. In this region, long-term, above-average precipitation is stored sub- surface, driving up the groundwater table. If storage reaches its limits, additional precipitation excesses lead to sustained flood episodes. Meanwhile, floods in the Pampa Deprimada with its more clay-rich soils are surface water driven due to a lower connectivity between the surface water and groundwater [2]. Here, excess water is stored in the existing surface water bodies, resulting in floods that occur on a timescale of weeks or months of extreme precipitation. Two representative case study locations were therefore selected for the most vulnerable sub-regions; the Partido General Juan de Madariaga (PGJdM) in the Pampa Deprimida and the Departamento General López (DGL) in the Pampa Interior (see Figure 1).

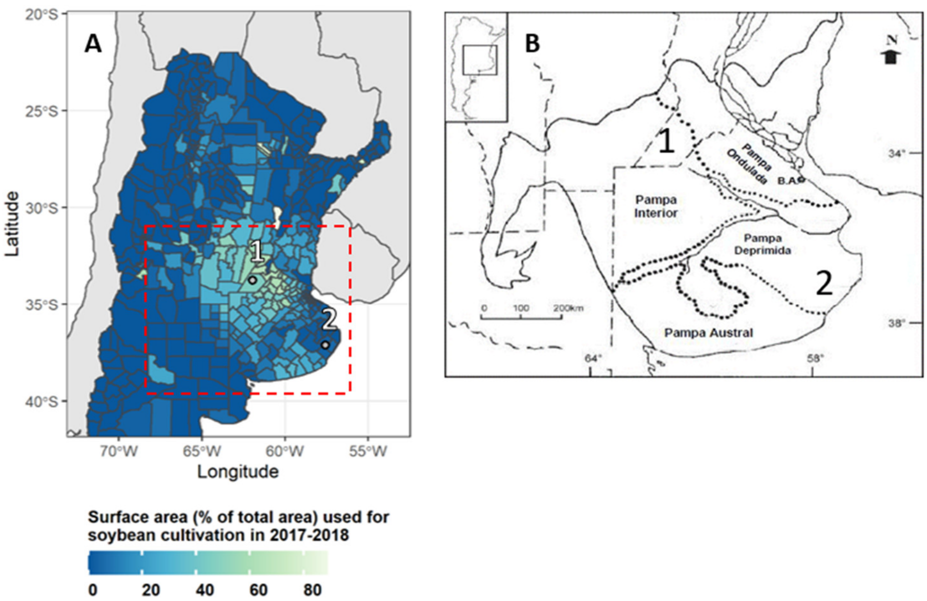

Figure 1. Intensity of soybean cultivation at the department level as a share of the total department area in Argentina (**A**) and sub-regions of the Pampas (**B**). Case study locations are shown in both figures as 1 (Departamento General López) and 2 (Partido General Juan de Madariaga). The red box in sub-figure A illustrates the area shown in map B. The sub-region map is adapted from Vilardo [34], with the original from León et al. [35]. The soybean intensity map is made by the authors based on the agricultural estimation dataset of the Argentinian Ministry of Agriculture [1].

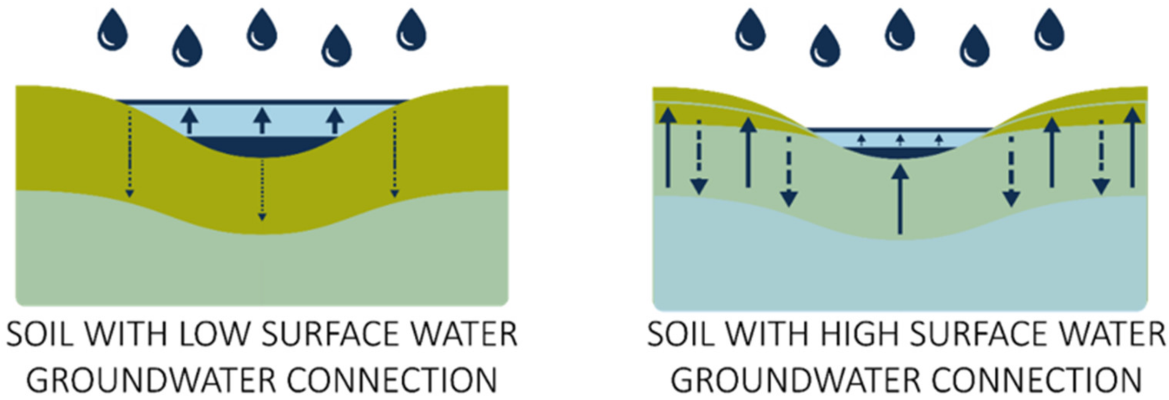

Figure 2. Graphic illustration of slow-onset flood dynamics on the Pampas. The Pampa Deprimida (left) is characterised by low connectivity between the surface water and groundwater, resulting in surface-water-driven pulse floods over the course of weeks or months of excess precipitation. The Pampa Interior, instead, has a high surface water–groundwater connection, which leads to floods as a result of the water table superseding the surface over the course of months or years of excess precipitation to dominate. Nonetheless, Kuppel et al. [17] state that pulse floods can also occur in the Pampa Interior and groundwater floods in the Pampa Deprimida.

2.2. Methodology

The first step in the research consisted of a bottom-up assessment of contemporary flood risks for soybean production systems in the case study locations. To do so, we conducted eight in-depth expert interviews (see Table A2) with soybean producers, four in each case study location. The soybean acreage of the interviewees ranged between 500 and 3000 hectares, with an average of 2300 hectares. Interviewees were approached based on referrals from earlier interviewees and were selected to represent both producers that cultivate almost exclusively soybean and producers with more diverse cropping systems. The interview sample thereby provides a diverse subset of soybean producers. All interviews except one were conducted in person and lasted between an hour to two hours.

During each interview, producers were asked how the occurrence of floods has affected their production in recent years and what they identify as the most important and most problematic flood impacts for the performance of their organisations. This resulted in the specification of flood risks that may occur during various phases and processes of the agricultural season, which, according to soybean producers, have the greatest potential to disturb the functioning of the soybean production systems in the study area.

To study the impact of climate change on the flood risks identified by the producers, the climatological factors that cause these flood risks were additionally explored. Soybean producers were therefore also asked during the interviews to specify what climatic conditions, in their experience, are associated with or bring about these flood risks. Historical years and time periods in which flood impacts had happened were hereby also indexed for cross-reference.

The interviewed producers universally expressed the climatic conditions that cause flood risk in terms of precipitation intensities and frequencies over varying time periods. Previous research by Kuppel et al. [17] in the study area similarly found that positive precipitation anomalies of 200 mm/year correspond to sustained flood events. Alternative research on flood dynamics on the Pampas by Seiler et al. [36] also demonstrated that positive precipitation anomalies on the multi-monthly scale can adequately explain flood occurrences.

The producer-defined climatic conditions were therefore validated and, if necessary, adjusted using observed precipitation quantities during historically problematic periods indicated by the producers. The historical climatological data were obtained from regional agricultural associations [37,38] that collectively operate rain gauges within or adjacent to the study areas (see Figure A1). The bottom-up perspective on flood risk accordingly led to the identification of several phases of the year in which the production of soybean is at its most vulnerable to flood impacts and to corresponding quantitative indicators of climatic conditions that are a cause for flood risk in these periods.

To study the impact of climate change on the identified flood risks, we conducted a climate data analysis spanning from 1971 to 2100 in which the development of the corresponding climatic indicators was investigated. For the future climatic projections, we used bias-corrected daily precipitation projections that were aggregated to monthly values from an ensemble of five bias-corrected ISIMIP Global Climate Models (GCMs; see Collins and Knutti [39], Table A1 and Figure A3) under the RCP4.5 and RCP8.5 scenarios. The GCMs were selected based on availability.

Future projections were validated with the ground truth by comparing the ensemble mean of the models with the historical observations for the common period of 1971–2010 collected from the regional agricultural associations. Various correlation coefficients such as Pearson's, Spearman and Kendall were employed to validate the simulations with the ground truth, a step that constitutes a key point in studies that assess the present and future climate conditions [40]. Analysis results can be found in Figure A2.

Following validation of future projected data, we then compared for both scenarios the precipitation distributions during the time period in which flood risks occur to the respective precipitation distributions of the baseline 1971–2010 period. Additionally, for each of the indicators of flood risk climatic conditions, we assessed the development of the return period and compared this to the 1971–2010 baseline. The analysis allowed us to determine whether, and to what degree, the producer-defined flood risks will exacerbate under pressure from climate change.

Lastly, we used our improved insight into the development of flood risks for soybean systems in the study area to identify adaptation strategies and evaluate their advantages and challenges from the perspective of the producers. Hereby, both structural (i.e., infrastructural investments such as additional drainage and access roads) and non-structural (cropping and land-use changes) were explored. Adaptation strategies on the farm level were indexed during the same eight interviews with soybean producers in which flood impact conditions were established (see Table A2). Additional adaptation strategies were identified during interviews with an expert in local sustainable agronomy and two experts of the National Agricultural Knowledge Institute (INTA) (see Table A3). The advantages and disadvantages of the adaptation strategies were assessed during the interviews and supplemented with a literature review.

3. Results

3.1. Interviews in the Partido General Juan de Madariaga, Buenos Aires, Argentina

The interviewed soybean producers in the PGJdM unanimously acknowledged that floods pose a significant threat and are a key consideration for the management of their organisations. The interviewees stated that their choice to grow soybean is largely driven by financial incentives and that the flood impact on soybean production over the last decade is already close to the limits of what is financially feasible. Significant production losses occurring more frequently than is currently the case would therefore be unacceptable. Some producers indicated that they are considering a change away from soybean, opting to increase the share of other, more robust land uses instead. Other interviewees have already decreased their soybean acreage over the last years, switching to the cultivation of corn and cattle ranching. In agreement with the findings of Kuppel et al. [17], all producers in the PGJdM region explained floods to manifest themselves by the direct expansion of the lakes in the area and identified several months of extreme precipitation as the most suitable climatic predictor for the occurrence of such floods. Nonetheless, two producers also perceived the annual precipitation patterns to be relevant as an enabling factor. If a year is dry or normal, the lakes and topsoil could have the capacity to buffer excess seasonal precipitation. Several specific flood risks were identified that could impede the viability of soybean production:

- The flood risk that was identified by all producers as the most problematic for soybean production is the reduction in accessibility of the countryside. The rural infrastructure in the Pampas is underdeveloped, mostly consisting of dirt roads [22]. In the Pampa Deprimida, the main access roads are located in the relatively lower-lying areas on the edges of soybean lots. Slow-onset floods can saturate or submerge these roads and turn them into a thick mud, rendering the local infrastructure and by extension the countryside nearly impassable and causing transportation costs to rise steeply. Inaccessibility was stated to be especially problematic during the harvest and sowing seasons (i.e., March to May and October to December, respectively), when heavy machinery needs to reach the soybean lots. If floods occur in either period, soybean cannot be sown or harvested in time, leading to serious production losses and in some cases total losses. Producers indicated that the current level of inaccessibility has already reached the limits of what is economically feasible. For rural inaccessibility, producers stated that either the sowing or the harvest season must be wet, exceeding at least 300 to 350 mm of precipitation in the three-month period. Enabling problematic annual conditions were estimated at 1100 to 1200 mm. The 2015/2016 and 2016/2017 seasons were identified to be representative for harvest inaccessibility and 2017 for sowing inaccessibility.
- Direct soybean losses due to slow-onset floods were stated to be of concern as well, albeit as a secondary problem as soybean is sown in relatively higher areas. In recent years, surface water expansion has affected the edges of soybean lots, leading to about 7% or 8% of the total acreage to be submerged for longer time periods, leading to the loss of soybean crops. However, historically, near total losses have also occurred, with the 2001/2002 season provided as an example (see Kuppel et al. [17]). Producers indicated that the current level of direct impact is still manageable but that if structural losses were to increase soybean cultivation would not be viable. For flood impact to directly impact yield, interviewees described that there must be a sustained period of extremely high precipitation during the soybean season (October to May). For direct yield losses, no specific figure could be established but producers mentioned that this requires several consecutive extremely wet months.
- Specific mention was also made regarding the risk of flood for the germination of soybean, as this is the most vulnerable growing stage [31]. Producers stated that if the time period between sowing and the emergence of soybean is exceptionally wet and the topsoil layer of the soybean lots becomes inundated, the seeds might never germinate or break the surface. Although sizeable losses during the germination stage have not yet occurred, producers feared that an increase in extreme precipitation could cause problems in this stage as well at some point.

The 2000/2002 period was also presented as a general period that contained highly destructive floods. No representative climatic conditions could be established for germination.

3.2. Interviews in the Departamento General López, Santa Fe, Argentina

The interviewed soybean producers in the DGL also confirmed that floods have been highly damaging to their operations and are of major concern for the future. However, the magnitude of flood impact was expressed as a product of consecutive years with flooded conditions, on account of the groundwater-driven flood dynamics of the region [17]. Each additional year with floods was explained to be more damaging than the preceding one, since the water table would not get the chance to recede again. Producers believed the impact of three or four consecutive wet years to be insurmountable for their organisations. On the other hand, in the case of individual flood years, the groundwater table was stated to perform a moderating function. Subsequently, long-term positive precipitation anomalies were stated by producers to be the most suitable climatic predictor for the occurrence of floods. Above-average seasonal precipitation was also stated to be a relevant indicator for seasonal accessibility. Several specific flood risks were established:

- Like the PGJdM, all producers stated that the primary issue limiting and threatening soybean production in the region is the impact of floods on the accessibility of the countryside during the harvest and sowing periods. General accessibility in the other months of the year was also considered a problem as it prevented personnel from transporting themselves between the rural communities and the local population centre. The interviewees stated that the impact of floods on accessibility is already high, perhaps even unacceptable, but that they have not yet made a change away from soybean, since it is still the most lucrative crop. Nevertheless, if inaccessibility would become more severe or more frequent, the cultivation of soybean would, in their opinion, no longer be viable. The climatic conditions for rural inaccessibility to occur were stated to lay above 1150 mm of the annual precipitation and more than 300 to 350 mm, falling in the harvest or sowing season.
- Direct crop yield reduction was also a factor of secondary, yet significant, concern in the DGL. The excessive rainfall of the last years has caused crop losses in the range of 10% to 15% for the organisation of the interviewed soybean producers, while for several of their colleagues, crop losses exceeded 60%. The 2015 to 2018 period was provided as an example of such heavy rain occurring. The interviewees stated that direct crop losses appeared in years with heavy annual rainfall. They defined this at above 1300 to 1350 mm.
- Lastly, the groundwater-driven nature of floods was indicated to be a driver of salinisation in the region. When the groundwater table rises, it brings deeper and saltier waters onto the surface [17]. Due to the negligible amount of surface run-off, this salty water can only leave by means of evapotranspiration. Once the floods have receded, this leaves behind a layer of salt. Producers demonstrated that several of their plots consequently are now barren or have greatly reduced yields.
- Losses during the germination stage were also identified to be of increasing concern but had so far not caused substantial problems.

The 2015-to-2018 period was indicated as a continuous wet period that contained serious direct and accessibility-related impacts on the production of soybean. For germination and salinisation, no climatic conditions could be defined.

3.3. Representative Climatic Indicators

Comparing producer-defined climatic conditions that cause flood risk to historical observations (see Table 1) in the PGJdM demonstrates that the observed peak three-month precipitation during problematic harvest and sowing seasons reached 400 mm, far exceeding the average of around 300 mm. The annual precipitation during these years averaged 1190 mm, considerably higher than the 1043 annual average. The highest three-month peak during the 2001/2002 soybean season was registered at 540 mm. The climatic indicators for flood risk for the PGJdM region were therefore defined at the high-end of producer estimates, meaning more than 350 mm of harvest or sowing seasonal precipitation and more than 1200 mm annually (Table 1). More than 540 mm of accumulated three-month precipitation during the soybean season was used as a representative condition for direct losses.

Table 1. Climatic conditions supplied by producers and assessed using historical precipitation observations for the impact of slow-onset floods on soybean production in the PGJdM, whereby μ stands for mean and ppt stands for precipitation.

Flood Risk	Climatic Conditions			Flood Risk Indicator
	Producer	Statistics	Problematic Years	
Sowing of soybean being impossible in productive areas due to flooding of access roads and difficulties with heavy machinery	Wet sowing season (>300 to 350 mm ppt in the sowing season)	1971–2011: μ 300 mm ppt in the sowing season	2017: 384 mm ppt during the sowing season	>350 mm ppt during the sowing season (October, November, December)

Table 1. *Cont.*

Flood Risk	Climatic Conditions			Flood Risk Indicator
	Producer	Statistics	Problematic Years	
Harvest of soybean being too expensive or impossible due to the flooding of access roads and difficulties with heavy machinery	Wet harvest season (>300 to 350 mm ppt in the harvest season)	1971–2011: µ 284 mm ppt in the harvest season	2015–2018: between 286 and 384 mm, with µ 336 mm during the harvest season	>350 mm ppt during the harvest season (March, April, May)
General rural inaccessibility problems	Wet year (>1100 to 1200 mm ppt annually)	1971–2011: µ 1043 mm ppt annually	2001–2003 and 2016–2017: between 987 and 1393 mm, with µ of 1190 mm ppt annually	>1200 mm ppt annually
Floods directly reducing yields too much, either by damaging or by killing soybean plants	Very wet period (significantly more ppt than accessibility climatic condition)	1971–2011: µ 286 mm ppt in the three months preceding any months of the soybean season	2001–2003: between 215 and 538 mm, with µ of 406 mm ppt in the three months preceding the soybean season months	>540 mm ppt in the three months preceding any month of the soybean season (October to May)

A comparison between the producer-defined conditions and historical conditions in the DGL demonstrated that the observed annual precipitation over the problematic 2015-to-2018 period averaged above 1460 mm (see Table 2). The observed seasonal precipitation during the harvest and sowing months of these critical years averaged 377 mm and has peaked above 680 mm, far higher than the producer-defined conditions. However, when compared to the 1971–2010 reference period, the 2015-to-2018 period was unprecedentedly wet (see Figure A1). The flood risk indicators during the harvest and sowing seasons were therefore increased to 400 mm. For annual precipitation, both 1200 mm as an enabling factor and the direct-impact 1350 mm figures were maintained.

Table 2. Climatic conditions supplied by producers and assessed using historical precipitation observations for the impact of slow-onset floods on soybean production in the DGL, whereby µ stands for 'mean' and ppt stands for 'precipitation'.

Flood Risk	Climatic Conditions			Flood Risk Indicator
	Producer	Precipitation Statistics	Problematic Years	
Sowing of soybean being impossible in productive areas due to flooding of access roads and difficulties with heavy machinery	Wet year (1100 to 1200 mm ppt annually) and wet sowing season (300 to 400 mm ppt during the sowing season)	1971–2010: µ 962 mm ppt annually µ 322 mm ppt in the sowing season	2015 to 2018: between 1026 and 1902 mm, with µ of 1548 mm ppt annually; between 252 and 680 mm, with µ of 377 mm ppt during the sowing season	>1200 mm ppt annually and >400 mm ppt during the sowing season (October, November, Dec.ember)
Harvest of soybean being too expensive or impossible due to the flooding of access roads and difficulties with heavy machinery	Wet year (1100 to 1200 mm ppt annually) and wet harvest season (300 to 400 mm ppt during the harvest season)	1971–2010: µ 962 mm ppt annually µ 270 mm ppt in the harvest season	2015 to 2018: between 1026 and 1902 mm, with µ of 1548 mm ppt annually; between 124 and 657 mm, with µ of 428 mm ppt during the harvest season	>1200 mm ppt annually and >400 mm ppt during the harvest season (March, April, May)
Floods directly reducing yields too much, either by damaging or by killing soybean plants	Very wet year (1300 to 1350 mm of annual ppt)	1971–2010: µ 962 mm ppt annually	2015 to 2018: between 1026 and 1902 mm, with µ of 1548 mm ppt annually	>1350 mm ppt annually

3.4. Flood Risk Development under Climate Change

An analysis of the development of seasonal precipitation patterns in the PGJdM (see Figure 3A,B and Table 3) and relevant climatic conditions demonstrated that both mean annual precipitation and harvest season precipitation will increase throughout the century. The increases were found to be more pronounced in the RCP8.5 scenario than in the RCP4.5 scenario. The increase is most pronounced in the harvest season. However, the spread between the models is high, as for both annual and harvest season precipitation, some models also demonstrate a decrease compared to the historical baseline. The mean development of sowing season precipitation is projected to decrease slightly for both RCP4.5 and RCP8.5 scenarios. Nonetheless, the spread for this season is high as well, as some models show a slight increase for the RCP8.5 scenario. Likewise, the return period of flood risk climatic conditions during the harvest shows a decrease, almost halving towards the end of the century in the RCP8.5 scenario. This indicates that climatic conditions that are associated with flood risk during harvests are likely to occur more frequently over the course of the century. The frequency of extremely wet periods shows a steep increase as well under the RCP8.5 scenario.

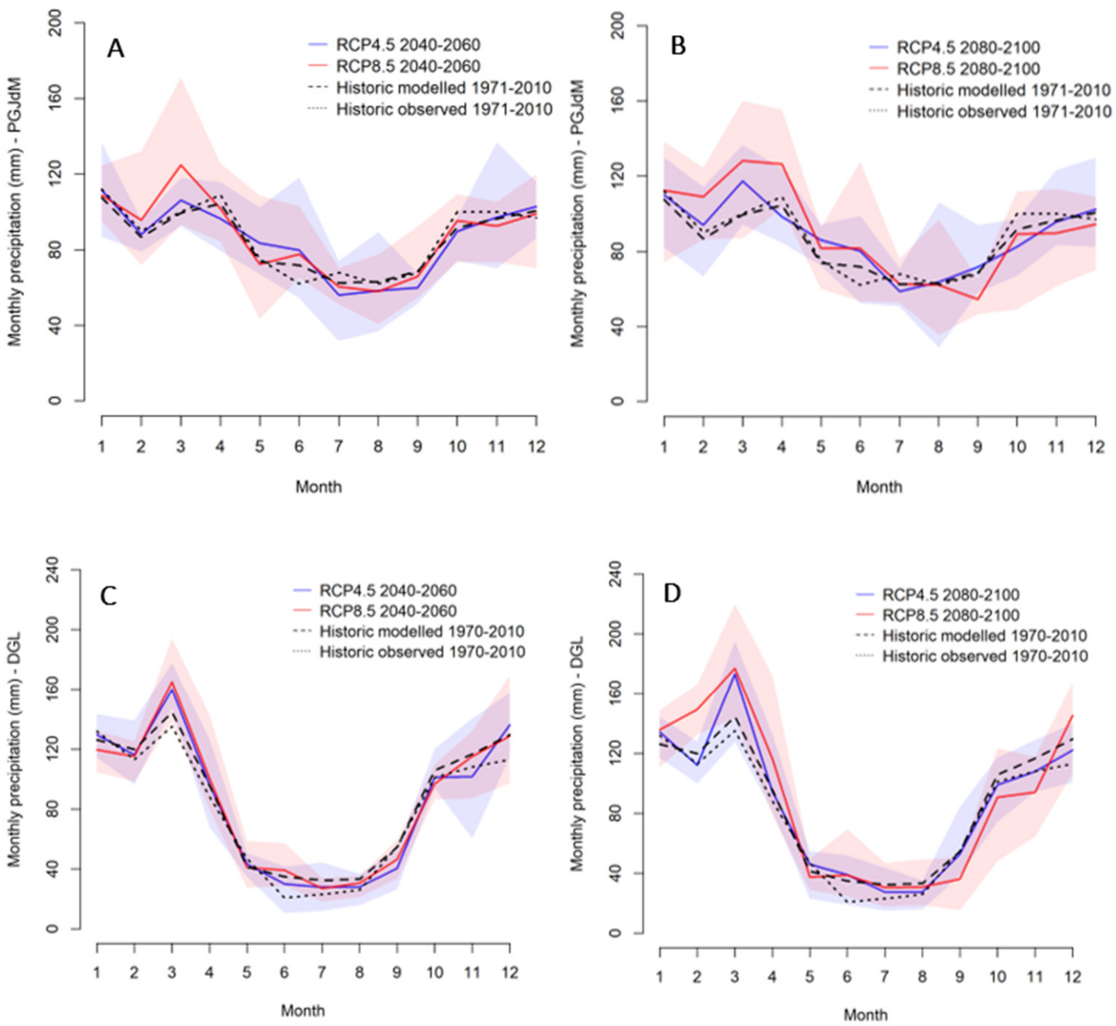

Figure 3. Monthly precipitation change (mm) in the PGJdM in 2040–2060 (**A**) and 2080–2100 (**B**) and monthly precipitation change (mm) in the DGL in 2040–2060 (**C**) and 2080–2100 (**D**) compared to modelled historic precipitation (1971–2010). The future precipitation figures are based on the RCP4.5 (blue) and RCP8.5 (red) scenarios, with respective solid lines representing the ensemble average (mean of means per month) and the transparent field representing the ensemble extremes (most extreme mean).

Table 3. Annual and seasonal precipitation change in the PGJdM (A) and the DGL (C) and return period for flood risk climatic conditions in the PGJdM (B) and the DGL (D) for 2040–2060 and 2080–2100 based on the RCP4.5 and RCP8.5 scenarios. The tables indicate the average ensemble change and the ensemble extremes. In addition, historical modelled precipitation is compared to historical observed precipitation in both locations. For the PGJdM, the modelled historical precipitation contains a correlation of R2 of 0.94 with observed data using the Pearson correlation coefficient (Figure A2). A similar analysis for the DGL demonstrated an R2 of 0.97 (Figure A2).

Partido General Juan de Madariaga

Climatology During Periods of Interest	Average Annual Precipitation (mm)			Average Harvest Precipitation (mm)			Average Sowing Precipitation (mm)		
	Ensemble			Ensemble			Ensemble		
Time Step	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Observed 1971–2010		1043			284			297	
Modelled 1971–2010		1025			278			287	
RCP4.5 2040–2060	921	1030	1100	244	286	319	231	290	335
RCP8.5 2040–2060	1010	1053	1107	257	299	341	252	287	328
RCP4.5 2080–2100	957	1057	1124	269	302	327	226	281	341
RCP8.5 2080–2100	939	1098	1184	268	336	380	194	273	339

Return Time (Years) of Climatic Conditions That Cause Flood Risk	Wet Year (Annual ppt > 1200 mm)	Extremely Wet Period (October to May 3mt. ppt > 540 mm)	Wet Harvest Season (March to May ppt > 350 mm)	Wet Sowing Season (October to December ppt > 350 mm)
Time Step	Mean	Mean	Mean	Mean
Observed 1971–2010	4	4	5.7	3.1
Modelled 1971–2010	5.7	13	5.1	4
RCP4.5 2040–2060	4.6	26	3.6	5.25
RCP8.5 2040–2060	5.25	10	3.8	5.25
RCP4.5 2080–2100	5.6	10	3.6	4.8
RCP8.5 2080–2100	3.2	5.5	2.3	4.2

Departamento General López

Climatology during Periods of Interest	Average Annual Precipitation (mm)			Average Harvest Precipitation (mm)			Average Sowing Precipitation (mm)		
	Ensemble			Ensemble			Ensemble		
Time Step	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Observed 1971–2010		962			270			322	
Modelled 1971–2010		1029			285			348	
RCP4.5 2040–2060	902	1011	1060	273	299	325	293	339	392
RCP8.5 2040–2060	981	1025	1111	260	306	371	271	341	411
RCP4.5 2080–2100	989	1036	1088	303	313	324	270	329	362
RCP8.5 2080–2100	1036	1082	1110	297	331	378	242	330	391

Return Time (Years) of Climatic Conditions That Cause Flood Risk	Wet Year (Annual ppt > 1200 mm)	Extreme Wet Year (Annual ppt > 1350 mm)	Wet Harvest Season (March to May ppt > 400 mm)	Wet Sowing Season (October to December ppt > 400 mm)
Time Step	Mean	Mean	Mean	Mean
Observed 1971–2010	8	-	5	4.4
Modelled 1971–2010	4.4	13	7.4	3.6
RCP4.5 2040–2060	4.6	20	4.2	3.9
RCP8.5 2040–2060	5.6	17	5.3	3.9
RCP4.5 2080–2100	4.8	11	4.2	4.2
RCP8.5 2080–2100	3.8	9.6	4.4	4

The analysis of precipitation in the DGL region (see Figure 3C,D and Table 3) demonstrated a similar increase in annual and harvest season precipitation towards the end of the century for both scenarios. The wetting trend is especially noticeable in the RCP8.5 scenario, as all models project annual and harvest season precipitation figures at the end of the century to be higher than the current modelled mean. Here, too, the relative increase in precipitation is most pronounced in the harvest season. Precipitation in the sowing season is, on average, expected to decrease in both the RCP4.5 and the RCP8.5 scenario. This drying trend is also noted in an increase in the return period of problematic sowing conditions taking place. Similar to the PGJdM, the return period of climatic conditions that cause flood risk during the harvest season show a decrease in both scenarios. The frequency of wet years occurring also demonstrates an increase under the RCP8.5 scenario. Interesting to note is that the return period for an extreme wet year in the observational reference period (1971–2010) could not be determined, as the respective climatic conditions had not occurred. Figure A2 demonstrates, however, that this annual precipitation threshold has only been crossed more recently in the exceptionally wet 2012, 2015, 2016 and 2017 years. An observational reference period from 1971–2018 would thereby contain an extreme-wet-year return period of 9.6 years instead.

3.5. Adaptation Strategies

Based on interviews with producers and local experts, and a literature review, four types of adaptation strategies were identified:

- **Improve the hydrological infrastructure.** Given that one of the root causes behind the flood proneness of the Pampas is their lack of horizontal run-off [17], the most thorough structural strategy for flood risk reduction in both case study locations was stated by local experts to be the revision and expansion of the hydrological infrastructure. The existing infrastructure is almost a century old and consists of small, scattered channels that do not provide enough outflow capacity for contemporary hydrological excesses. The lack of capacity can even make the flooding problems on the local scale worse, as the channels frequently overflow with water from the upstream regions [12]. The problems are aggravated further by the scattered informal channels that exist as a result of informal adaptation as they deregulate the outflow of water [9]. According to one local expert, integrating the informal channel would be the first step for flood adaptation in the region, in addition to the construction of additional channels and peak water reservoirs. This strategy would thus require shared decision making between producers and public institutions. However, experts and producers alike stated that the magnitude of revising the hydrological infrastructure is so big that such a decision-making process can only be initiated by the national government.
- **Service crops.** A secondary adaptation strategy that influences the root cause of flood risk on the Pampas in a non-structural manner is the introduction of service or cover crops. These are crops that are not necessarily planted for any direct monetary gain but instead as a measure to help achieve adequate conditions for growing other types of crops. An extra service crop, such as alfalfa, in rotation with single soybean or double-cropped soybean increases the annual evapotranspiration of soybean lots, reversing to some extend the reduced evapotranspiration of soybean compared to the original grassland [41]. Indeed, research in Argentina has shown that land-use management can significantly decrease water tables and subsequently reduce flood risks [42,43]. The decision to sow an extra crop in rotation has the added advantage that it can be taken on a relatively short notice, which means that in dry years, one can simply opt to not sow service crops. In addition to water regulation, service crops may additionally provide other benefits, such as nitrogen fixation, increased biodiversity and strengthened soil quality [44]. This strategy may thus contribute to healthier ecosystems and thereby a sustainable production system in the long term [45]. In practice, some producers in the DGL were already conducting citizen science with service crops. Several producers were running combined experiments by working with various new crop rotations on their lots, collecting the data and sharing best practices from their observations. Producers in the PGJdM recognised the options and acknowledged the potential but had so far not initiated tests themselves. A study by García and Menénendez [42] showed that the modulating effect of service crops on the water table is most effective when implemented on a regional scale and that strong

interdependencies exist between neighbouring land users. Soybean producers and experts alike consequently stated that this contains a high free-rider potential. Governmental coordination, support or legislation is therefore an essential pre-requisite to influence the decision making of producers towards adopting service crops.

- **Improve rural infrastructure.** Since accessibility of soybean lots was found to be the weakest link in both case study locations, improving the rural infrastructure was mentioned by all producers to be an important structural adaptation measure. Such investments do not only ensure that accessibility is improved during times of precipitation excesses but were also stated to improve the general economic position of rural communities. However, the sole improvement of transportation infrastructure only diminishes the risk that floods pose for accessibility. It does not affect the hydrological imbalance dynamic that is at the root of flood risk on the Pampas, meaning that other flood impacts such as direct yield losses and salinisation remain an issue for the soybean production system. Additionally, experts stated that infrastructural works are only feasible if initiated by the provincial or national government.
- **Change crops or production system.** Experts stated that autonomous farm-level adaptation to floods can be undertaken by reducing the acreage of relatively vulnerable soybean production in favour of more robust land uses. This is an especially relevant non-structural strategy for the DGL, as it consists of a near monoculture of soybean [1]. Suggested options included the cultivation of the sturdier corn crop and even dropping the cultivation of crops all together in the most vulnerable areas towards raising livestock. Indeed, some interviewees in the PGJdM have already reduced their soybean acreage in favour of corn, while others have started raising cattle for beef production. Soybean producers in the DGL had not yet made such a switch, but several interviewees did indicate that regional acreage must be diversified. Reverting to the original pastures has the added benefit of increased evapotranspiration compared to soybean production, indirectly also reducing flood risk [43].

4. Discussion

The results demonstrate that the soybean production system on the flood-prone Pampas faces considerable flood risk, in particular through its disrupting effect on rural seasonal accessibility, and that this risk is likely to increase under climate change. Interviewed soybean producers moreover indicated that flood impacts on accessibility during the harvest and sowing seasons in recent years have already reached the limits of what is economically feasible. This suggest that if adequate adaptive action is not taken, climate change may drive flood risk to further affect the economic viability of the soybean production system.

4.1. Limitations and Uncertainties

More detailed temporal insight into the development of flood risk, however, could not be established. This can largely be ascribed to two factors. Firstly, the high interannual and interdecadal variability of precipitation patterns, on which flood risks are based in this study, inhibit the assessment of a clear trend. Similarly, there exists significant uncertainty in relation to the development of positive precipitation anomalies between the used climatic projections. Although in the majority of analyses, the investigated climatic conditions did demonstrate a rising trend, these trends were much less accentuated than the historical development of precipitation described by previous research [9,23]. Additionally, historical precipitation increases have concentrated in the austral summer and spring [30], while in this study, the most significant wetting trend was found in early austral autumn. The assessed risk may hence be an underestimation and excessively focused on the harvest season.

In part, this uncertainty can be explained by the fact that global climate change projections were used. Local models or downscaled models that use historical climate change patterns might be able to present more accurate and consistent patterns of precipitation development and shift the most critical season to the sowing season. However, even at regional scales, precipitation still cannot be simulated precisely and the assessment is hampered by observational uncertainties [46]. In the current study, observed extremes were more severe and frequent than the extremes found in the reference period over the same time frame. The analysis indicated that internal and inter-model variabilities were the dominant sources of uncertainty in extreme climate projections. However, the global climate models did adequately simulate the climatological patterns and averages, which builds confidence in the general projected trends observed in this study.

Moreover, the simplified representation of climatic flood risk conditions may have led to an overestimation of future flood risk. Flood dynamics in the Pampas region are highly complex and not yet fully understood [17]. Although positive precipitation anomalies have been indicated in multiple studies to be an adequate predictor of flood occurrences on the Pampas [17,36], other myriad factors are also understood to influence the occurrence and timescale of floods. Some of these, such as soil composition, geography and groundwater connectivity, were taken into account implicitly by using different temporal patterns and quantities of accumulated precipitation. Yet others that were identified as significant were not taken into consideration. The most influential of these is evapotranspiration, which, due to the flatness of the Pampas, is the main outlet of the water balance [17]. With temperatures expected to rise under climate change, evapotranspiration is expected to increase as well [9]. This process may alter the development of flood risk in the region. Some local modelling efforts already exist to better understand flood dynamics in relation to evapotranspiration and land use on the Pampas [42]. Combining the output of these projects with the producer perspective of this study is key to further improving the understanding of the influence of climate change on the flood risks for soybean production systems.

The compounding effects of climatic change may similarly also affect the vulnerability of the production system via its effects on soybean yields. Some studies indicate crop yields per hectare to rise as a result of more water availability and higher temperatures [9,47], while others expect them to reduce due to sea level rise and increasing precipitation variances [22,48]. Since the interviewed producers expressed flood risk in terms of viability and economic losses, such variations can have an effect on the coping capacity, and thereby the experienced flood risk, for soybean production.

Additionally, the producer-centric approach used in this study has the intrinsic limitation that the assessment is largely focused on flood risks that are known to be a problem. Although the present flood dynamics and impacts identified by producers are in line with those found in model-based studies on the Pampas [17,42], the stated future concerns were also based on their previous experiences with floods. This producer perspective is key to the goals of the investigation but thereby does not account for unknown problems, meaning problems that might occur with more climate change pressure in the future and have not occurred yet. Such unknown problems may significantly affect the vulnerability of the system but are currently not considered. Other future vulnerability analyses have used a purely scientific basis to assess future climatological risk factors (e.g., [49,50]). A likewise assessment for the soybean production systems of the Pampas could present a valuable addition to the results of this study.

4.2. Implications and Recommendations

Despite the outlined limitations, the results do provide a deep understanding of the potential flood risks faced by soybean production systems under climate change. The producer perspective applied in the interviews offered a novel, more detailed valuation of the manner and degree in which soybean production systems are at risk to floods than any type of literature has provided so far, shifting the focus from the direct yield impact predominantly found in previous vulnerability assessments [9,22] towards the impact on rural accessibility. This perspective also allowed us to zoom into specific periods of the year in which these risks are exacerbated. The unique interview results were corroborated in the climate data analysis. Although at the annual scale, a rising precipitation trend could be noted, the wetting trend was found to be more pronounced in the months of the harvest season. Additionally, the frequency of climatic conditions indicative of flood risk occurring during the harvest demonstrated a rising trend in both climate change scenarios and in both case study locations.

Given the fact that producers in the DGL region consider the present-day flood impact already at the limits of what is feasible and that they are considering a change to more robust land uses, it can be argued that an increase in flood risk for harvest accessibility may form a limitation for the viability of the soybean production system here in the short term if adaptive action is not undertaken. In the PGJdM area, some interviewees have already reduced their soybean acreage, indicating that the flood impact here has already surpassed the threshold of what can be dealt with. This suggests that contemporary hydrological management practices are already unsatisfactory and that new measures aiming to improve rural accessibility are imminently required. Although direct crop losses were not yet considered a problem of major concern, the climate data analysis does indicate that the climatic conditions that are associated with such issues may increase in frequency as well. Adaptive actions that target this more systemic issue are therefore also necessary so that these potentially even more disruptive risks can be dealt with.

The evaluation of adaptation strategies, meanwhile, demonstrated that adequate measures are available that could adapt the soybean production system in such a manner that the risks posed by floods are diminished or that their occurrences are reduced altogether. Yet, for such strategies to be successfully implemented, systemic adaptive changes to the setting in which soybean is produced are required, which can only be organised under the guidance of public leadership and the improved cooperation between public and private actors [11]. If the adaptation process remains fragmented and lagging behind from the public side [9], and adaptation will continue to be chiefly the responsibility of private producers, flood risks for soybean production may force producers to decrease the share of soybean significantly and decide in favour of less vulnerable land uses and crops. Although this does make the individual farmers more robust, the end result is still a reduction in soybean production in Argentina, which can have consequences for the rest of the soybean sector. Several recommendations can therefore be made:

- The implementation of adaptive strategies is urgent. Improving the infrastructure, both for transportation as well as for hydrological purposes, appears an essential structural intervention to guarantee that an increase in flood risk under climate change can be managed. However, this intervention must consider for the large amount of clandestine drainage systems that have been developed autonomously by producers, as they have a great influence on regional hydrology. These canals, and thereby the producers that maintain and operate them, must be integrated within the formal hydrological decision-making process to structurally reduce flood risk.
- More research should be conducted into the effect, viability and governance of service crops. This method has the potential to influence flood problems at one of its key points, which is reduced evapotranspiration due to soybean production replacing grassland [43]. Since local agricultural organisations are already conducting citizen science experiments with service crops, there is clear support from the target group. The integration of such bottom-up initiatives within existing hydrological management strategies has been shown to hold mutual benefits, such as reduced costs, larger quantities of observational data and improved access to information [51]. Additional research on the integration, communication and coordination of service crops as a regional adaptation strategy is hence an important follow-up step.

5. Conclusions

In this paper, we provide a bottom-up understanding of the implications of climate change for the flood risk faced by soybean production systems on the flood-prone Pampas of Argentina. In both case study locations, the inaccessibility of soybean lots due to floods rendering the rural infrastructure impassable was identified to be the premier flood risk of concern to producers. Rural infrastructural breakdown was deemed especially problematic during the sowing and harvest seasons, when heavy machinery needs to reach the fields. Direct crop losses due to floods were also indicated to be a risk of some concern, although the current impact was indicated to still be manageable. An analysis of precipitation development under climate change projected the general wetting trend to continue towards the end of the century for annual and harvest season precipitation, while the sowing season demonstrated a slight drying trend. Additionally, the return period of climatic conditions that cause flood risk during the harvest was shown to shorten.

Our analysis therefore suggests that contemporary flood risk for harvest accessibility is already a major issue for the viability of the soybean production system of the Pampas region and that these flood risks may exacerbate under climate change. Adaptive action is hence a necessity. An analysis of adaptation strategies demonstrated that multiple strategies are suggested that can address flood risk at its core. However, such strategies require legislative and coordinative leadership from provincial and national governments. If adaptation, however, remains predominantly the responsibility of the private sector, an increase in flood risk due to climate change may force agricultural organisations to shift away from soybean to more robust land uses.

Author Contributions: All authors contributed to the design and scoping of the study. W.J.S. was responsible for the data collection in Argentina and writing of the manuscript. S.P. and W.J.S. designed and performed the climate data analysis. S.W. and F.L. supervised the study. All authors discussed the results and contributed to the final manuscript. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the internal review committee of the Water Systems and Global Change group at Wageningen University for implementation (07 January 2017), thereby conforming to all the ethical guidelines required for a Master Thesis research at Wageningen University.

Informed Consent Statement: The interviews and processing of the respective data were in accordance with the ethical standards of the Wageningen University and the Netherlands Organisation for Scientific Research and with the 1975 Declaration of Helsinki, as revised in 2000. Informed consent was obtained from all interviewees for being included in the study, and interview results were anonymised.

Data Availability Statement: Observed and simulated precipitation data are available with the author upon requests. Interview transcripts are also available upon request.

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Conflicts of Interest: The authors state that there are no conflicts of interests.

Appendix A. Precipitation Data

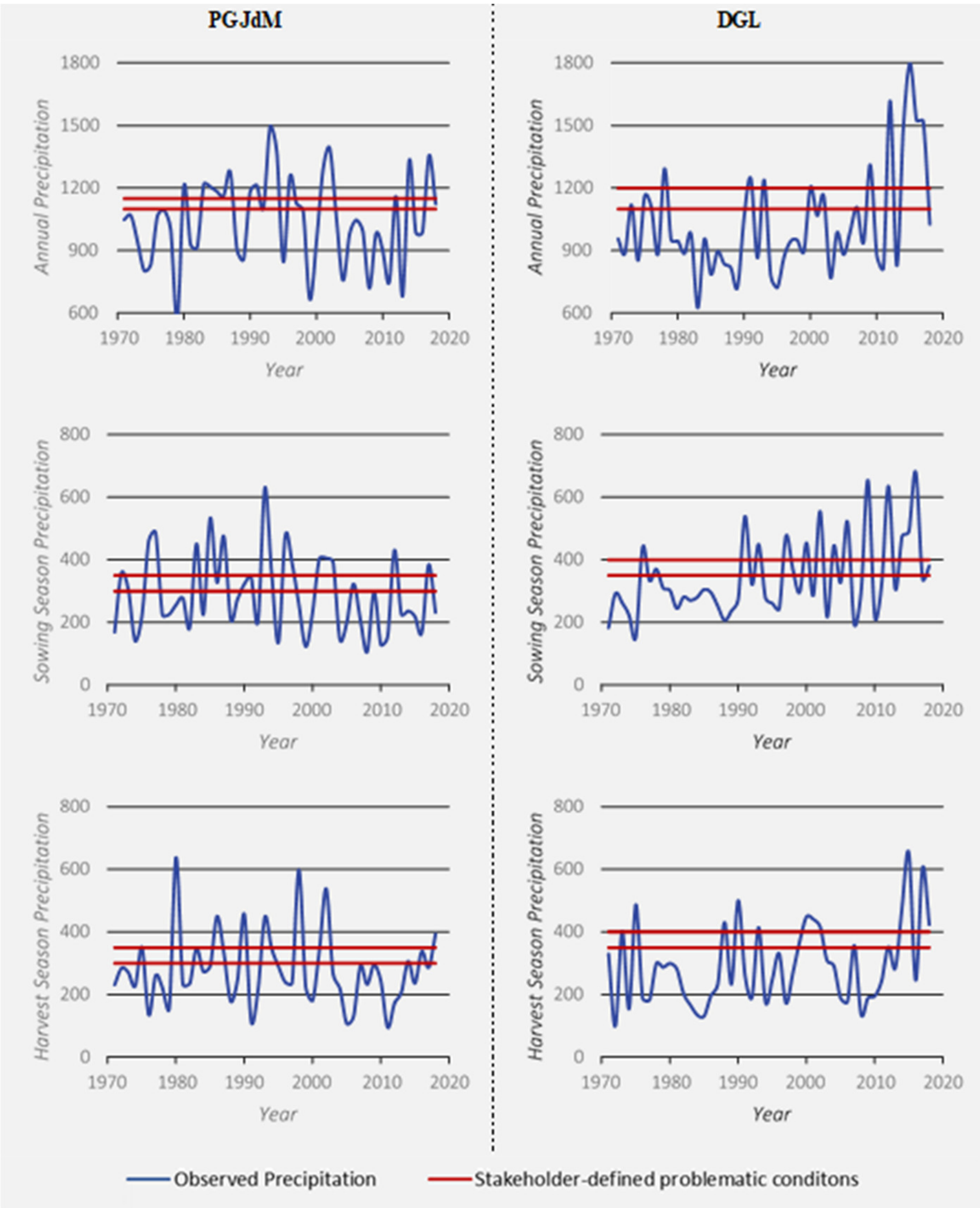

Figure A1. Historical precipitation data in the two case study locations in relation to soybean-producer-defined upper and lower thresholds.

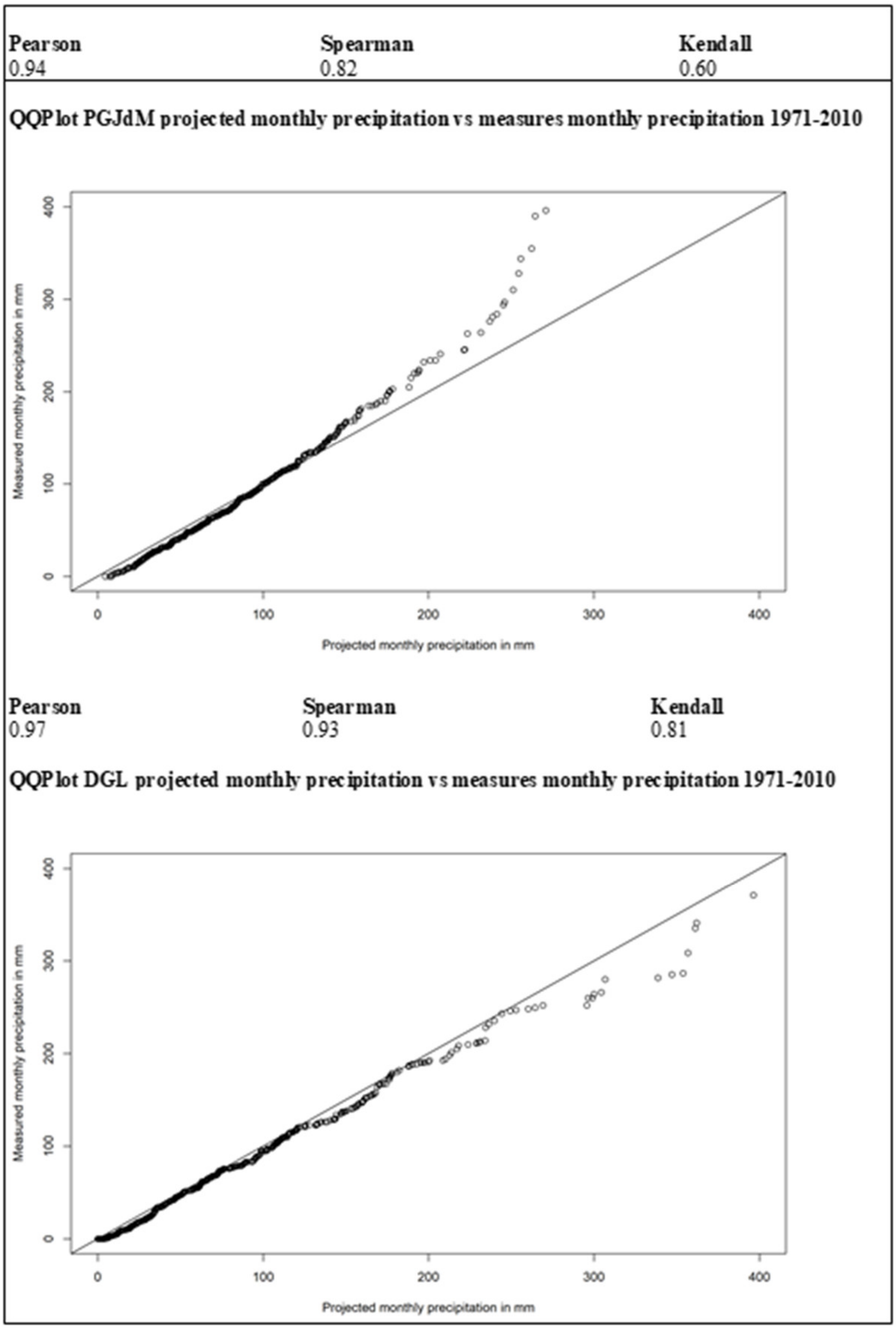

Figure A2. Comparison of sorted monthly precipitation in the PGJdM (top) and the DGL (bottom): historical vs. modelled (1971–2010).

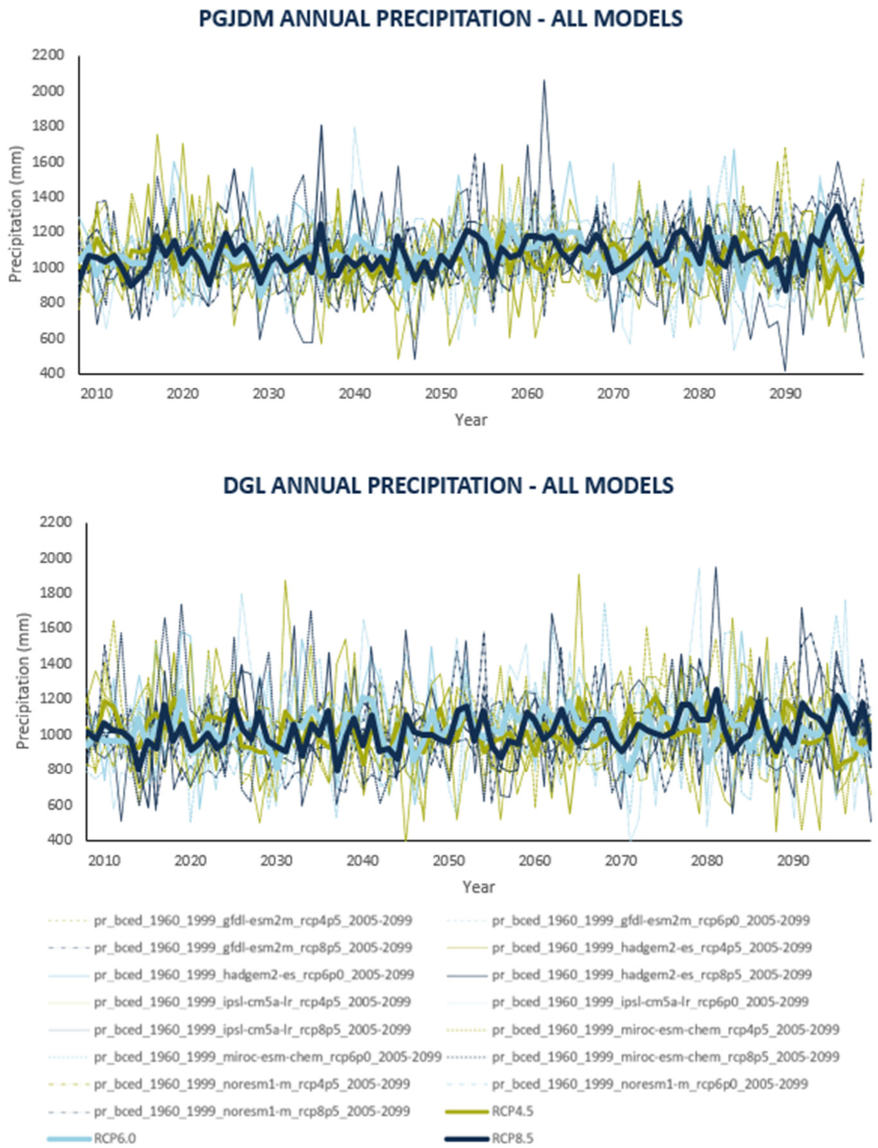

Figure A3. Model spread for annual precipitation and average between models per scenario: PGJdM (top) and DGL (bottom).

Table A1. GCMs and scenarios used in this assessment and initially acquired from the climate data store, whereby X indicates that the climate dataset was used, while/indicates that the dataset was acquired but not used.

Global Circulation Model	RCP4.5	RCP6.0	RCP8.5
GFDL-ESM2M	X	/	X
HADGEM2-ES	X	/	X
IPSL-CM5A-LR	X	/	X
MIROC-ESM-CHEM	X	/	X
NORESM1-M	X	/	X

Appendix B. Expert Interviews

Table A2. Characteristics of the soybean producers interviewed in this research.

#	Description	Location
1	Producer 1 is an agricultural engineer who works in a pool de siembra (planting pool) that cultivates soybean. The planting pool covers a total of 4500 hectares.	PGJdM
2	Producer 2 is the director of a large agricultural enterprise that produces and processes a multitude of agricultural products, including soybean. To do so, they rent fields from large landowners. In the last campaign, they rented 7500 hectares for crop cultivation purposes, 3000 of which were implanted with soybean.	PGJdM
3	Producer 3 is an agricultural engineer. He has almost 20 years of experience working with agriculture in the Madariaga region. His organisation is a mixed agriculture and livestock organisation that has more than 500 hectares of soybean. Historically, the organisation has had more than 2500 hectares of soybean.	PGJdM
4	Producer 4 is the director of the same soybean production organisation as producer 3.	PGJdM
5	Producer 5 is an agricultural engineer of a soybean production organisation that has 4400 hectares, of which 1700 are in use for soybean. The organisation has a second function doing applied research and experimentation with novel crops and land uses.	DGL
6	Producer 6 is the director of the same production organisation as producer 5.	DGL
7	Producer 7 is the owner and engineer of an agricultural organisation that has 5000 hectares, of which 66% is used for the cultivation of soybean.	DGL
8	Producer 8 manages an agricultural organisation that has approximately 5000 hectares, of which two-thirds are allocated to the cultivation of soybean.	DGL

Table A3. Characteristics of the adaptation experts interviewed in this research.

#	Description
1	Expert 1 is a local representative of the National Research Institute for Agriculture of Argentina in the Partido General Juan de Madariaga, Buenos Aires, Argentina. As an agricultural engineer, this expert has decades of experience advising farmers and agricultural organisations all over Argentina and has experienced at first hand the rapid growth in dominance of the soybean production system on the Argentinean Pampas.
2	Expert 2 is a researcher at the National Agricultural Knowledge Institute (INTA) specialised in grassland dynamics.
3	Expert 3 is a researcher connected to the AAPRESID institute. AAPRESID is a non-governmental organisation that aims to promote agricultural innovations and management practices that can increase productivity and sustainability. This expert is specialised in the field of the integrated management of agricultural systems on the Pampas.

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