nature climate change

SUPPLEMENTARY INFORMATION

https://doi.org/10.1038/s41558-019-0600-z

In the format provided by the authors and unedited.

Changing risks of simultaneous global breadbasket failure

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Changing risks of simultaneous global breadbasket failure

Supplementary Information

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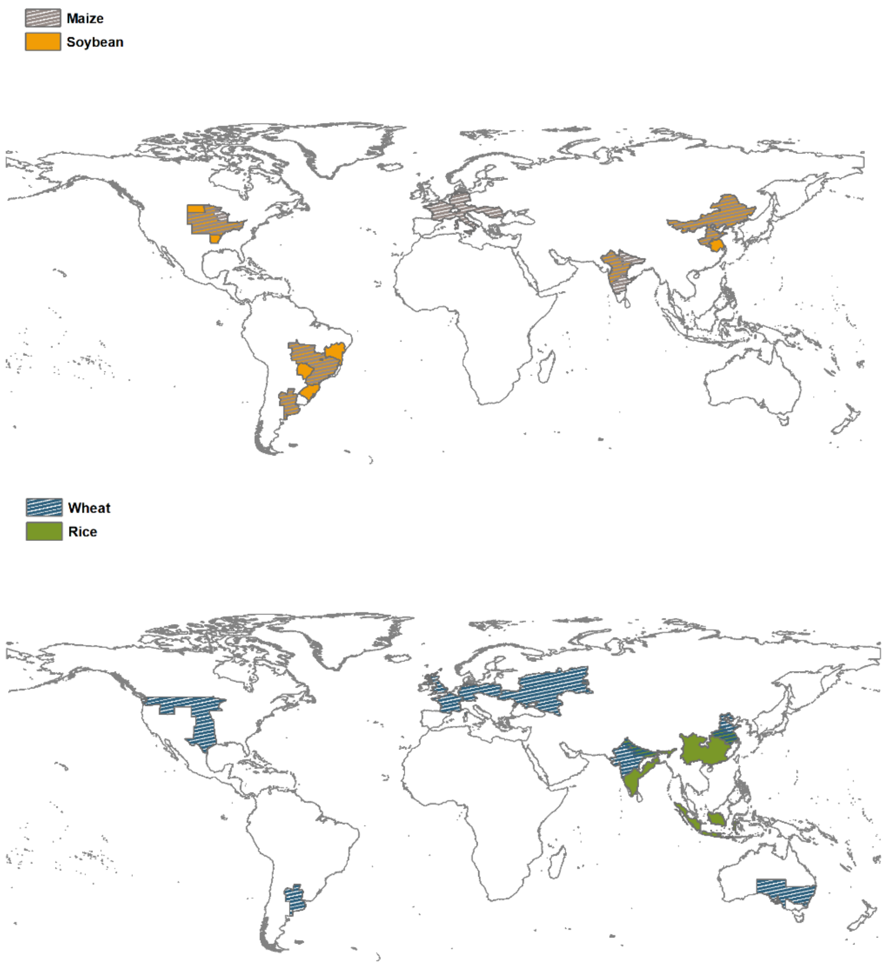


1.1. Supplementary figure SF1: Global breadbaskets

The global breadbaskets include the following states/provinces (for Europe, we included entire countries as European countries are comparable in size with most states/provinces in other breadbaskets):

Wheat:

China: Shandong, Hebei, Henan, Jiangsu, Anhui
USA: Kansas, North Dakota, Idaho, Washington, Montana, Oklahoma, South Dakota, Minnesota, Nebraska, Texas
Argentina: Buenos Aires, Cordoba, Entre Rios, Santa Fe
Australia: New South Wales, South Australia
India: Uttar Pradesh, Madhya Pradesh, Rajasthan, Maharashtra, Gujarat, Bihar, Haryana, Punjab
Europe: France, Germany, Poland, United Kingdom
Russia/Ukraine: Central Federal District, Southern Federal District (from 2010 on sum of new Southern Federal District and North Caucasian Federal District), Volga Federal District, Ukraine

Wheat in this study's breadbaskets covers 74% of the breadbasket countries' production (2012) and 56% of global wheat production (FAOSTAT, 2017). For Russia, only winter wheat was considered.

Maize:

China: Shandong, Hebei, Henan, Jilin, Liaoning, Heilongjiang, Inner Mongolia
USA: Kansas, Iowa, Illinois, Indiana, Wisconsin, Missouri, South Dakota, Minnesota, Nebraska, Ohio
Argentina: Buenos Aires, Cordoba, Entre Rios, Santa Fe
Brazil: Goias, Mato Grosso, Parana, Sao Paulo, Minas Gerais
India: Madhya Pradesh, Rajasthan, Uttar Pradesh, Bihar, Maharashtra, Karnataka, Andhra Pradesh
Europe: Austria, France, Germany, Hungary, Italy, Romania

Maize in this study's breadbaskets covers 74% of the breadbasket countries' production (2012) and 56% of global maize production.

Soybean:

China: Shandong, Hebei, Henan, Jilin, Inner Mongolia, Anhui, Jiangsu, Heilongjiang, Liaoning
USA: Kansas, Iowa, Illinois, Indiana, Missouri, South Dakota, North Dakota, Minnesota, Nebraska, Ohio, Arkansas
Argentina: Buenos Aires, Cordoba, Entre Rios, Santa Fe
Brazil: Goias, Mato Grosso, Rio Grande do Sul, Parana, Santa Catarina, Sao Paulo, Minas Gerais, Bahia, Mato Grosso do Sul
India: Madhya Pradesh, Maharashtra, Rajasthan

Soybean in this study's breadbaskets covers 81% of the breadbasket countries' production (2012) and 73% of global soybean production.

Rice:

China: Anhui, Guangdong, Guangxi, Guizhou, Henan, Hubei, Hunan, Jiangsu, Jiangxi, Sichuan, Yunnan
India: Andhra Pradesh, Assam, Bihar, Haryana, Karnakata, Punjab, Uttar Pradesh, West Bengal, Orissa, Tamil Nadu (only Kharif rice is considered as it accounted for 88% of total rice production in 2012)
Indonesia: Sumatra (weighted average of North Sumatra, West Sumatra, Jambi, South Sumatra, Lampung, Aceh), Java (West Java, Central Java, East Java), Nusa Tenggara (West Nusa Tenggara), Kalimatan (West, Central and South Kalimatan), Sulawesi (South Sulawesi)

Compared to the other crops, rice has usually multiple seasons per year. In our Chinese breadbasket, the typical cropping system is double rice cultivation consisting of early (May-July) and late (July to October) rice[1]. Due to a lack of harvest specific crop data, we combined the two seasons in our analysis. Rice in India refers to kharif, wet-season rice only which accounts for 88% of all Indian rice[2]. In Indonesia, the dominant season is the wet season which is planted between October and December and harvested before April when the second dry season rice is planted[3]. Best results in the climate-yield correlation analysis were achieved for climate indicators relevant to the wet season (see Pearson_correl_all_table).

The breadbasket rice production covers 74% of total rice production in those countries and 38% of global total rice production.

1.2 Supplementary table ST1:

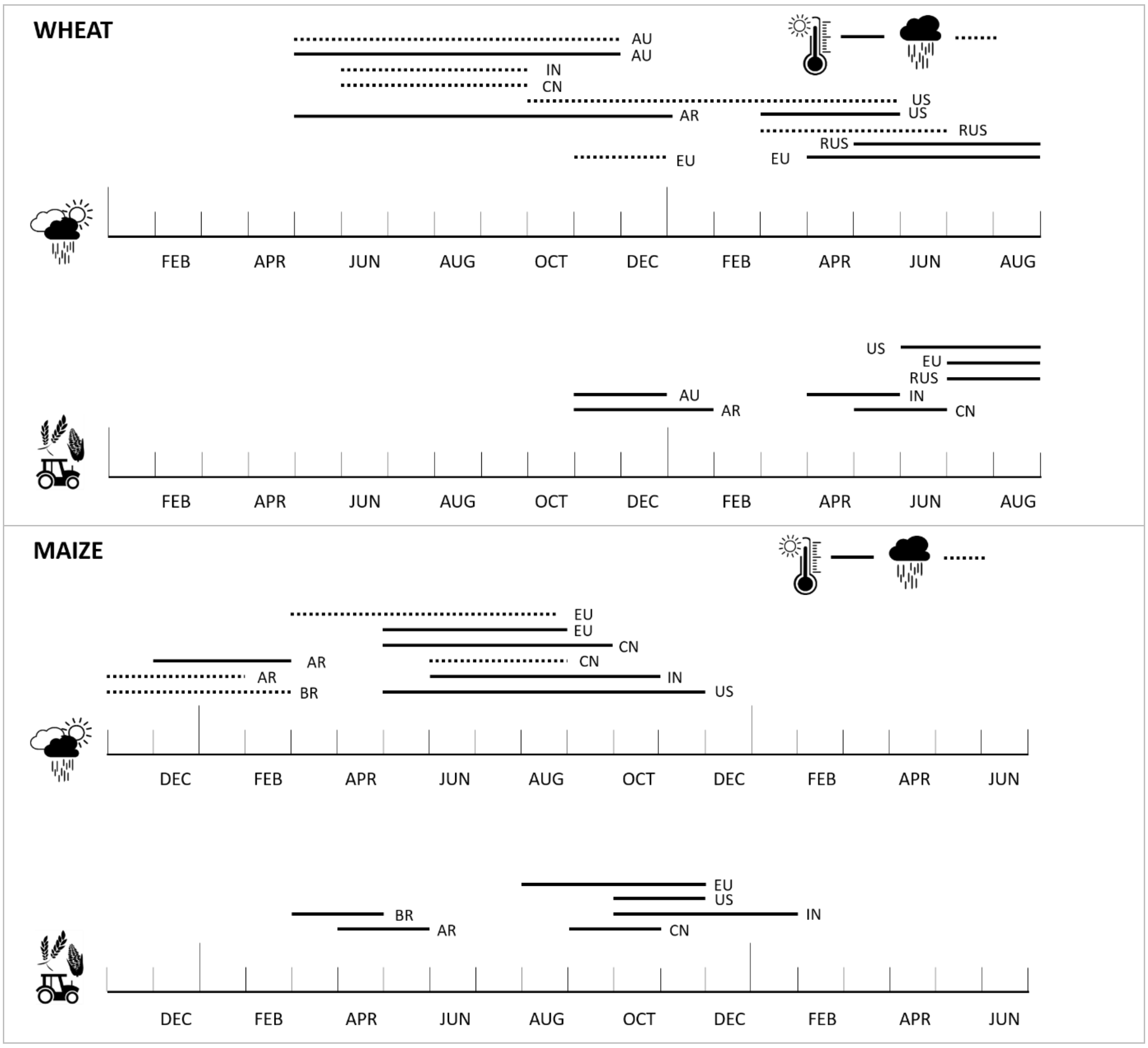
Literature used for climate risk indicators selection.

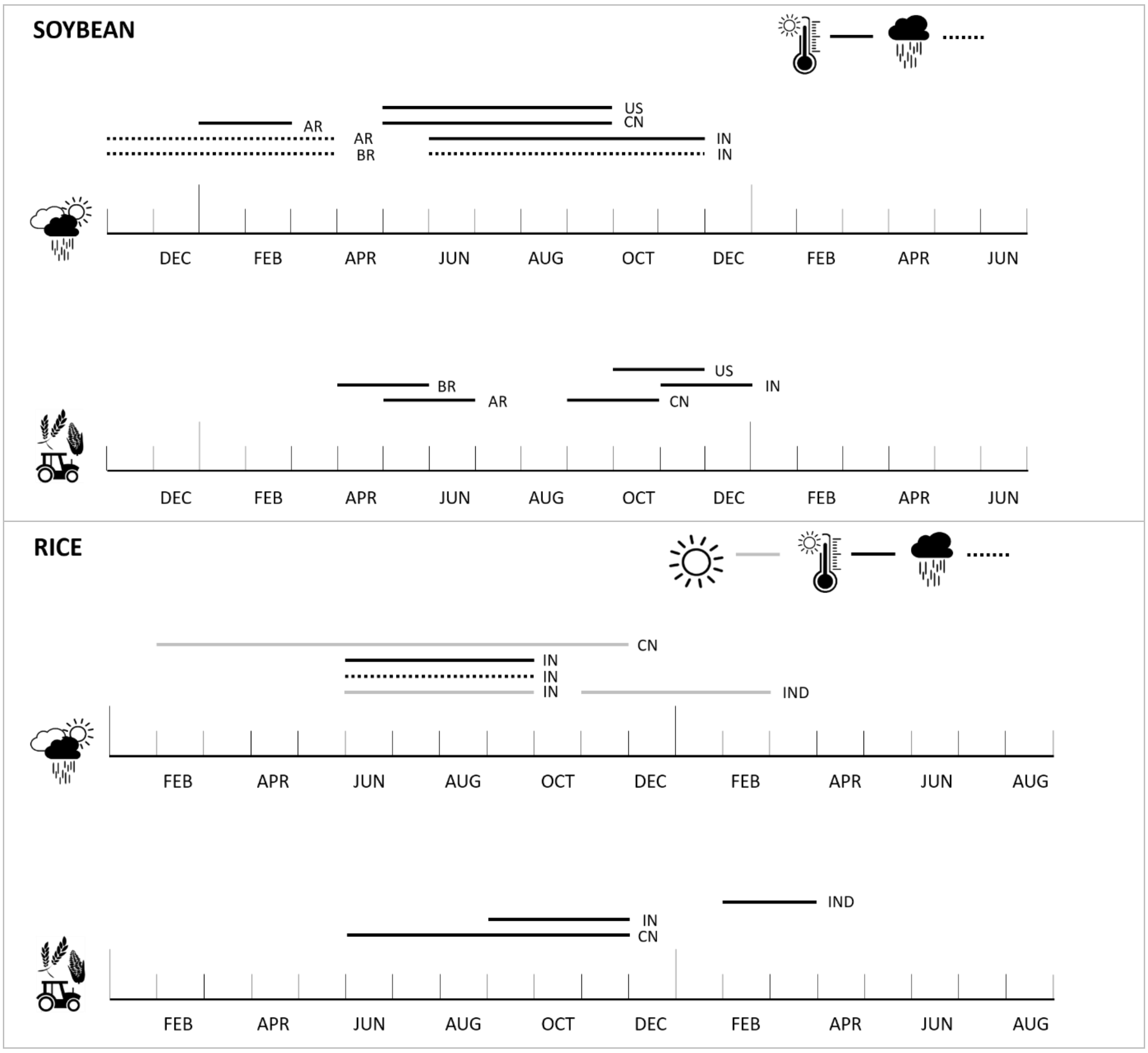
Literature was selected in a systematic way: We searched Google Scholar for the crop name, in combination with the country/region name, different climate stress factors such as "drought" and with climate variables such as "temperature" or "precipitation". Only empirical studies which had found a significant impact of climate indicators on crop yields in the past were chosen. The following literature are studies whose climate-yield relationship was confirmed in our correlation analysis using observed detrended yield and re-analysis climate indicators.

Crop:	Breadbasket:	Indicator:	Literature influencing climate indicator choice:
Wheat	▪ India	SPI-1 averaged over June, July, August and September	Kumar et al (2004)[4]Subash and Ram (2011)[5]
	▪ China	Cumulative precipitation (cp) between June and September of the previous year (rainy season)	Liu et al (2007)[6] Wang et al (2001)[7] You et al (2009)[8]
	▪ Australia	Cp between May and Nov (growing season) Maximum temperature (tmax) between May to November	Potgieter et al (2002)[9] Yu et al (2014)[10] Innes et al (2015)[11] Luo (2005)[12] Wardlaw and Wrigley (1994)[13]
	▪ USA	Cp between October and May (growing season) Number of days above 34°C (t34) between March and May	Zhang et al (2015)[14] Tack et al (2015)[15]
	▪ Argentina	Minimum temperature (tmin) between May and December (growing season)	Magrin et al (2009)[16] Hernandez et al (2015)[17] Licker et al (2013)[18] Gammans et al (2017)[19]
	▪ Europe	Cp between November and December T34 between April and August	Soltani et al (2016)[20] Pirttioja et al (2015)[21] Olesen (2011)[22]
	▪ Russia/Ukraine	Cp between March and June Average Temperature (tmean) between May and August	Sannikova (2007)[23] Belyaeva (2017)[24] Licker et al (2013)[18] Sannikova et al (2007)[23] Mueller (2016)[25]
Maize	▪ India	Maximum temperature (tmax) between June	Kumar et al (2011)[26]

		and October (kharif season)	
	▪ USA	Number of days above 29°C between May and November (t29)(growing season)	Schlenker and Roberts (2009)[27] Zhang et al (2015)[14]
	▪ China	Cp between June and August Tmax between May and September (growing season)	Matsumura et al (2015)[28] Heimfarth et al (2011)[29] Liu et al (2012)[30]
	▪ Argentina	Cp between November and January Tmax between December and February	Magrin et al (2005)[31] Podesta et al (2009)[32] Llano et al (2015)[33]
	▪ Brazil	Cp between November and February	Llano et al (2015)[33] Chen and Fonseca (1980)[34]
	▪ Europe	Cp March to August Tmean between May and August	Pravalies (2014)[35] Pravalies (2016)[36] Pinke (2017)[37] Ceglar (2016)[38] Pinke (2017)[37]
Soybean	▪ USA	Number of days above 30°C between May and September (t30)(growing season)	Schlenker and Roberts (2009)[27] Zhang et al (2015)[14] McCarl (2008)[39]
	▪ Brazil	Cp between November and March	Llano et al (2015)[33]
	▪ Argentina	Cp between November and March Tmax between January and February (flowering)	Magrin et al (2005)[31] Penalba et al (2007)[40] Llano et al (2015)[33]
	▪ India	Cp between June and November (growing season) T30 between June and November	Lal et al (1999)[41] Ramteke et al (2015)[42]
	▪ China	T30 between May and September (growing season)	Zheng et al (2015)[14] Yin et al (2016)[43]
Rice	▪ China	Solar radiation (rad) between February and November (combined growing season of two harvests in South China)	Zhang et al (2010)[44]
	▪ India		

		Cp between June and September	Auffhammer et al (2012)[45] Auffhammer et al (2006)[46] Duncan et al (2017)[47] Pattanayak and Kumar(2014)[48]
		Tmax between June and September	Pattanayak and Kumar(2014)[48]
		Rad between June and September	Duncan et al (2017)[47] Pattanayak and Kumar(2014)[48]
	▪ Indonesia	Rad between November and February	Welch et al (2010)[49]

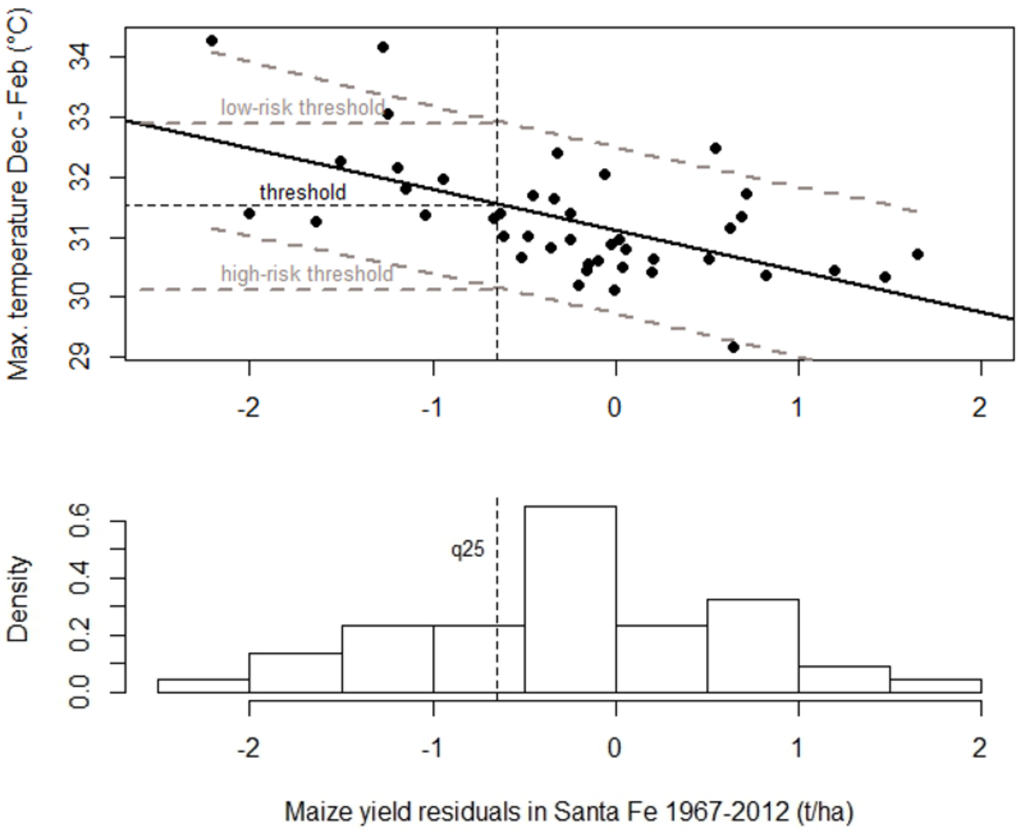




1.3 Supplementary figure SF2:

Crop calendar and climate indicators.

Temperature, precipitation and solar radiation based climate indicators for each crop are shown on the top. For details about the exact indicators, see ST1. On the bottom, harvest periods are shown, taken from USDA[50]. Our agricultural year starts with a harvest in the Southern hemisphere and corresponding climate followed by breadbaskets in the Northern hemisphere.

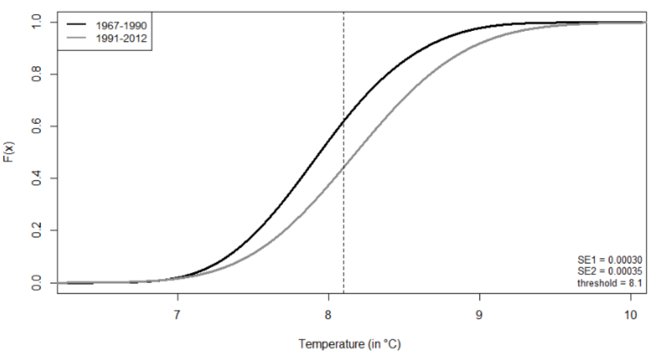


1.4 Supplementary figure SF3: Definition of a climate indicator threshold. Maize-climate relationship in Santa Fe province, Argentina. Regression on the top includes a 90% prediction interval.

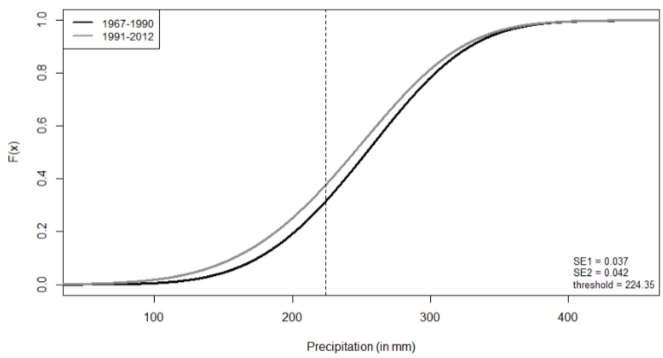
To define the climate indicator thresholds we use a simple linear regression between climate indicator and detrended crop yield for each crop and state/province. The threshold is set at the climate value corresponding to the 25th percentile of detrended yields. 25% was set as indicator of low yields indicating significant crop losses following [51].

Wheat

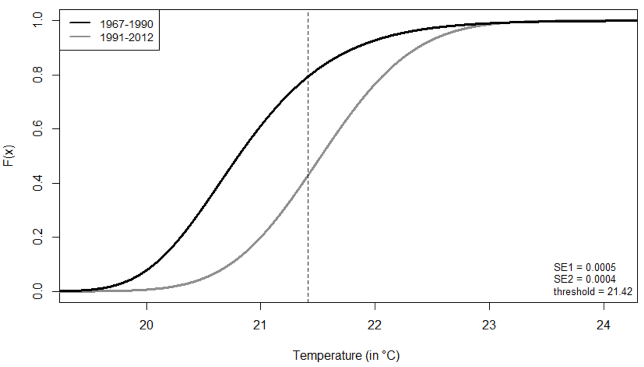
Minimum temperature in Argentina May-Dec



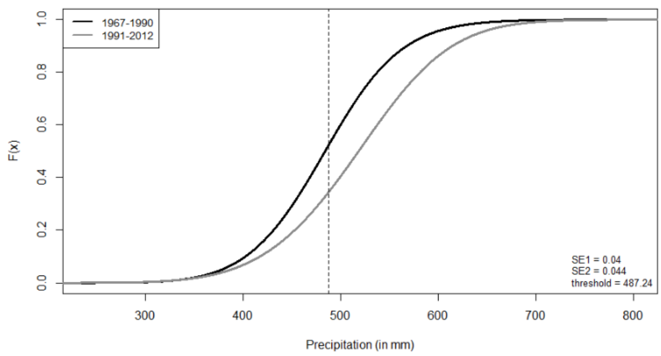
Cumulative precipitation in Australia May-Nov



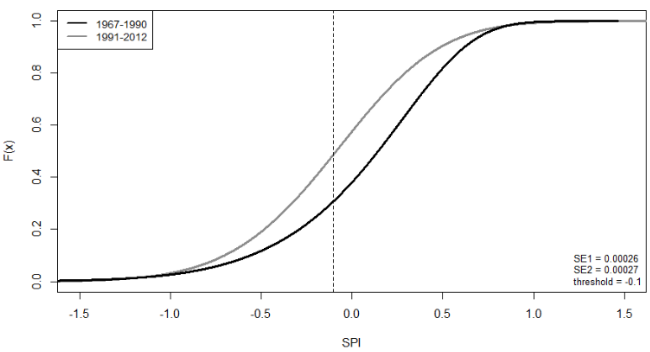
Maximum temperature in Australia May-Nov



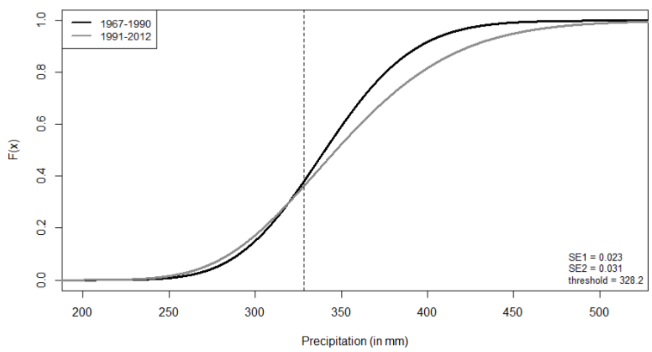
Cumulative precipitation in China Jun-Sep



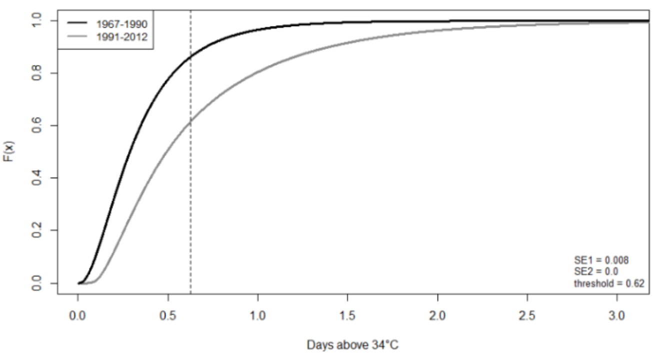
SPI in India Jun-Sep



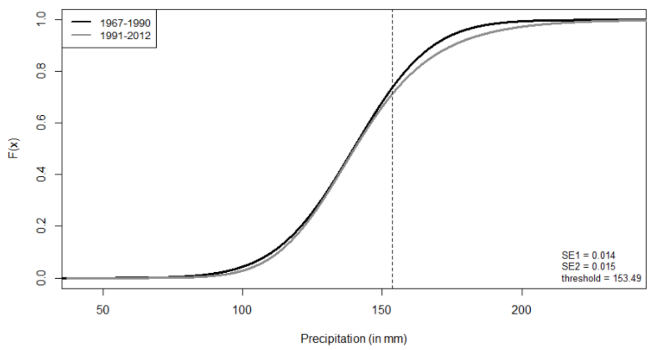
Cumulative precipitation in the USA Oct - May

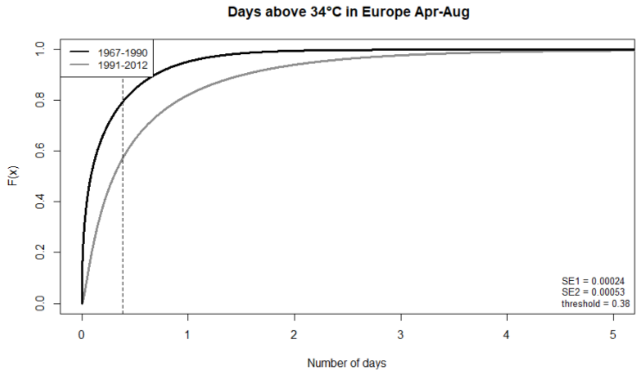


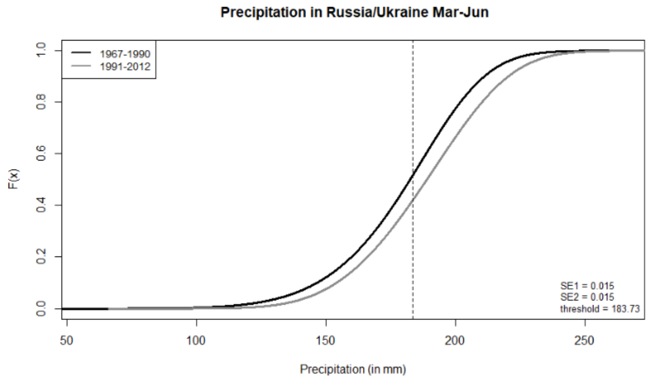
Days above 34°C during growing season USA

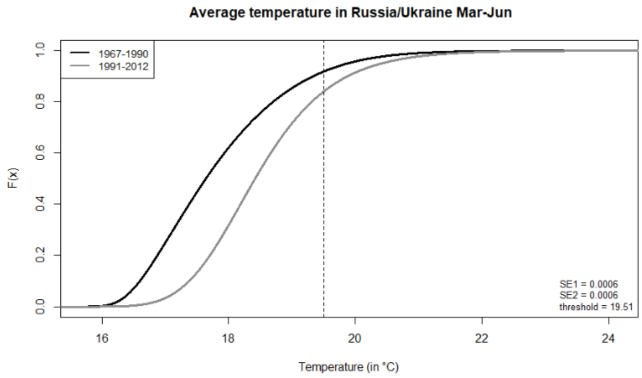


Cumulative precipitation in Europe Nov-Dec

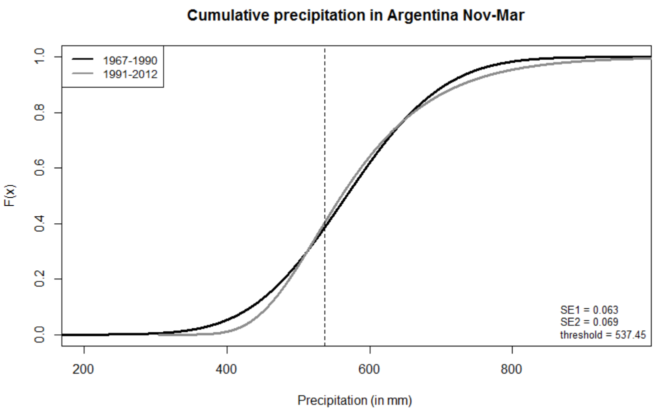


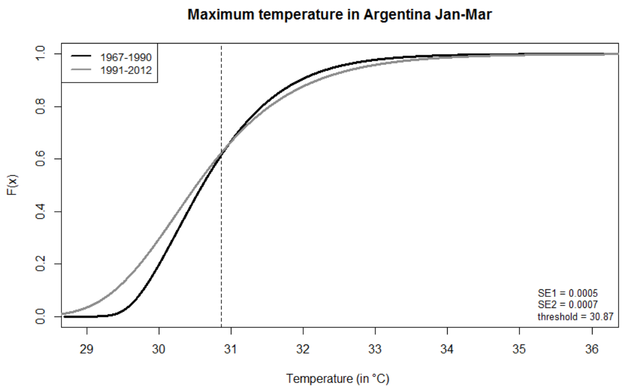

Days above 34°C in Europe Apr-Aug
1967-1990
1991-2012
F(x)
SE1 = 0.00024
SE2 = 0.00053
threshold = 0.38
Number of days

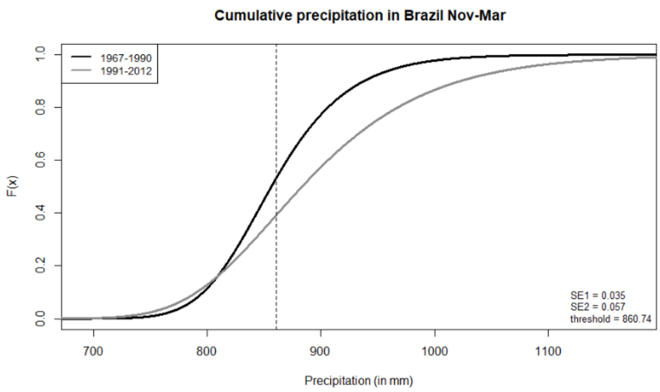

Precipitation in Russia/Ukraine Mar-Jun
1967-1990
1991-2012
F(x)
SE1 = 0.015
SE2 = 0.015
threshold = 183.73
Precipitation (in mm)

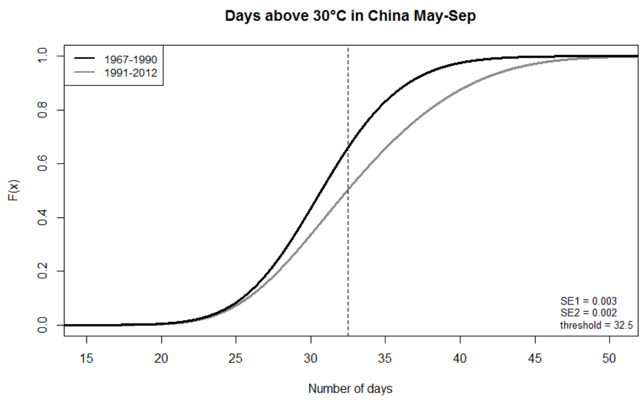

Average temperature in Russia/Ukraine Mar-Jun
1967-1990
1991-2012
F(x)
SE1 = 0.0006
SE2 = 0.0006
threshold = 19.51
Temperature (in °C)

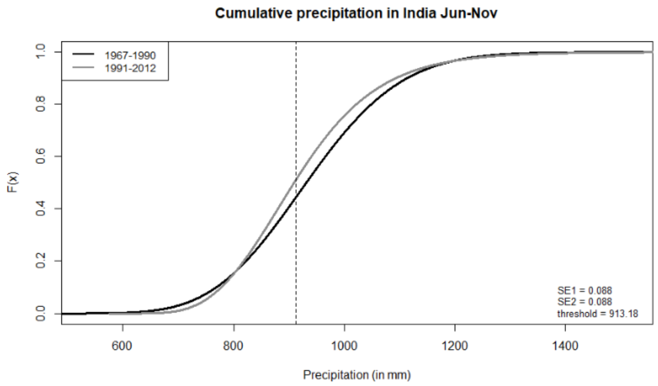
Soybean

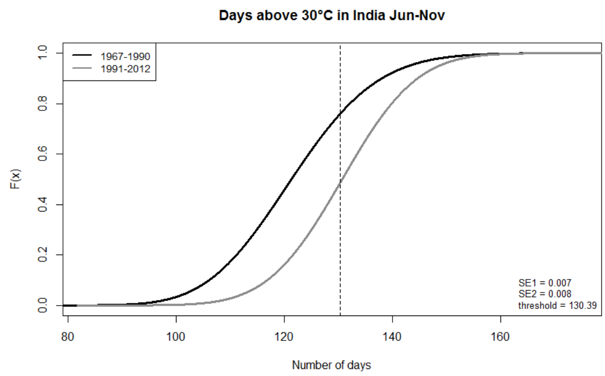

Cumulative precipitation in Argentina Nov-Mar
1967-1990
1991-2012
F(x)
SE1 = 0.063
SE2 = 0.069
threshold = 537.45
Precipitation (in mm)

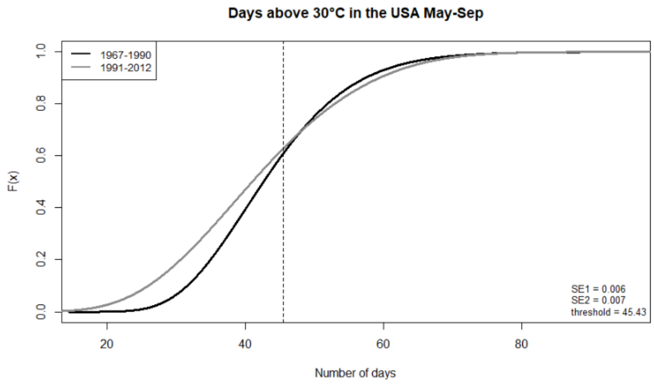

Maximum temperature in Argentina Jan-Mar
1967-1990
1991-2012
F(x)
SE1 = 0.0005
SE2 = 0.0007
threshold = 30.87
Temperature (in °C)


Cumulative precipitation in Brazil Nov-Mar
1967-1990
1991-2012
F(x)
SE1 = 0.035
SE2 = 0.057
threshold = 860.74
Precipitation (in mm)

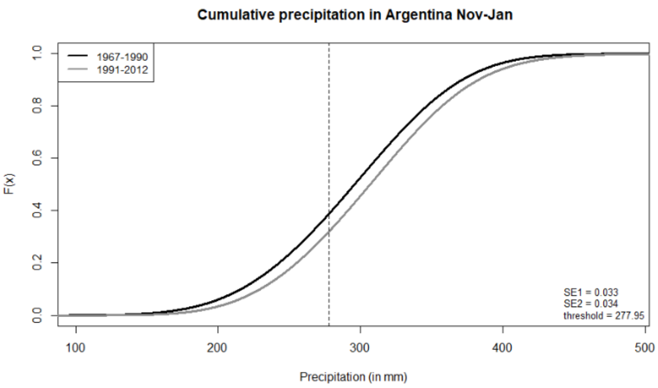

Days above 30°C in China May-Sep
1967-1990
1991-2012
F(x)
SE1 = 0.003
SE2 = 0.002
threshold = 32.5
Number of days

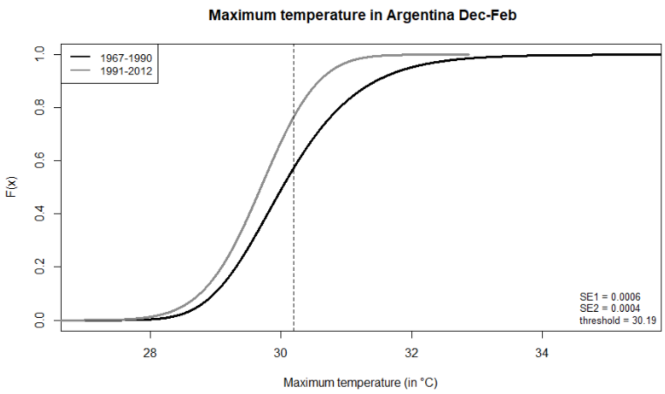

Cumulative precipitation in India Jun-Nov
1967-1990
1991-2012
SE1 = 0.088
SE2 = 0.088
threshold = 913.18
F(x)
Precipitation (in mm)

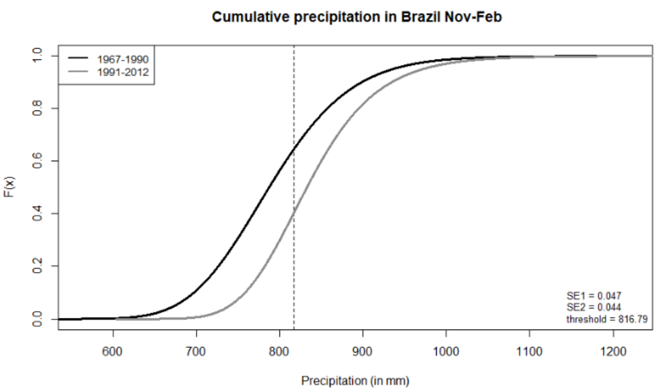

Days above 30°C in India Jun-Nov
1967-1990
1991-2012
SE1 = 0.007
SE2 = 0.008
threshold = 130.39
F(x)
Number of days

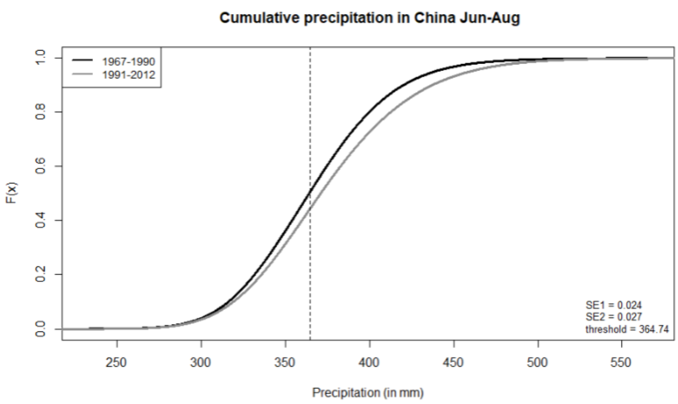

Days above 30°C in the USA May-Sep
1967-1990
1991-2012
SE1 = 0.006
SE2 = 0.007
threshold = 45.43
F(x)
Number of days

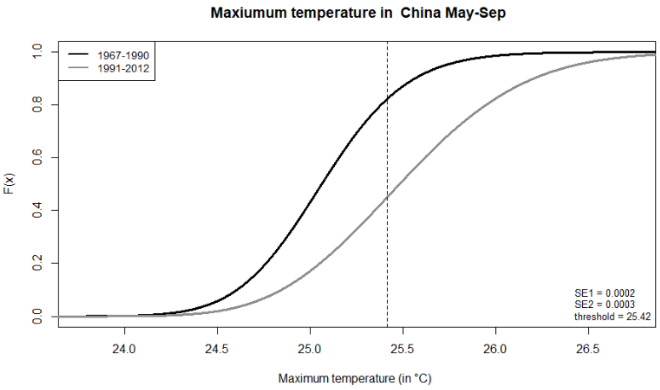
Maize


Cumulative precipitation in Argentina Nov-Jan
1967-1990
1991-2012
SE1 = 0.033
SE2 = 0.034
threshold = 277.95
F(x)
Precipitation (in mm)

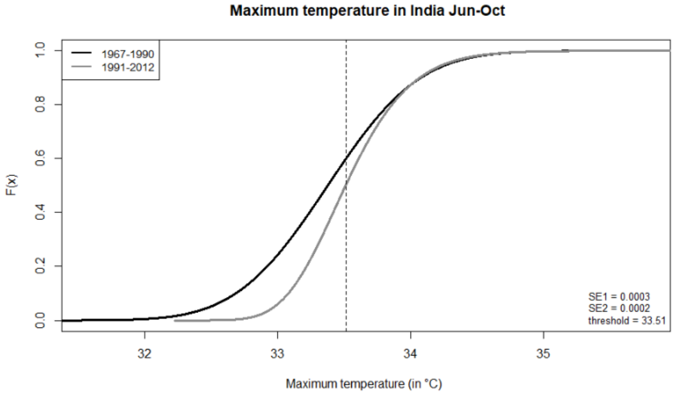

Maximum temperature in Argentina Dec-Feb
1967-1990
1991-2012
SE1 = 0.0006
SE2 = 0.0004
threshold = 30.19
F(x)
Maximum temperature (in °C)


Cumulative precipitation in Brazil Nov-Feb
1967-1990
1991-2012
SE1 = 0.047
SE2 = 0.044
threshold = 816.79
F(x)
Precipitation (in mm)

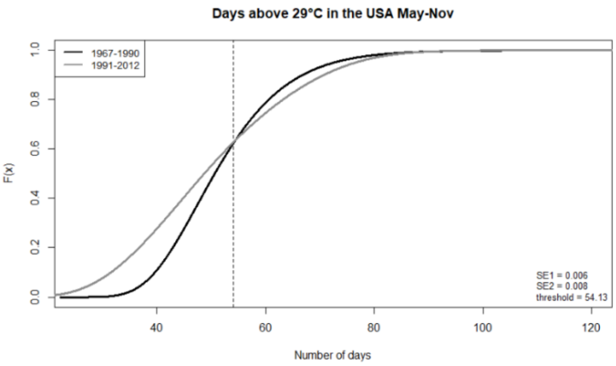

Cumulative precipitation in China Jun-Aug
1967-1990
1991-2012
SE1 = 0.024
SE2 = 0.027
threshold = 364.74
F(x)
Precipitation (in mm)



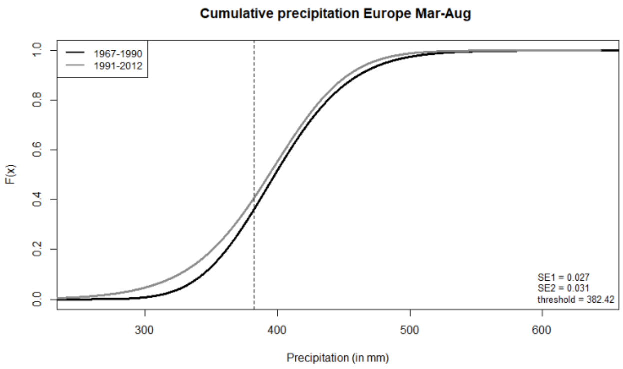
Maxiumum temperature in China May-Sep
1967-1990
1991-2012
F(x)
0.0
0.2
0.4
0.6
0.8
1.0
24.0
24.5
25.0
25.5
26.0
26.5
Maximum temperature (in °C)
SE1 = 0.0002
SE2 = 0.0003
threshold = 25.42



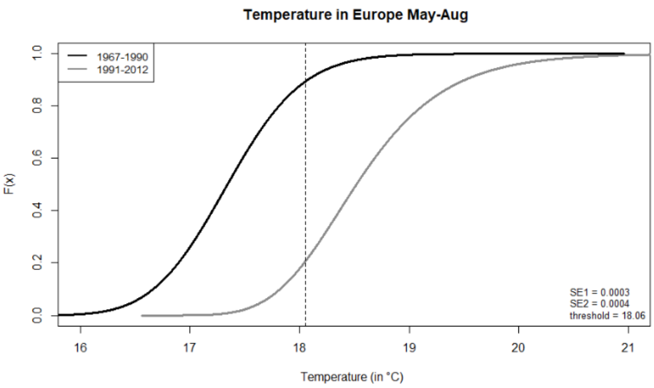
Maximum temperature in India Jun-Oct
1967-1990
1991-2012
F(x)
0.0
0.2
0.4
0.6
0.8
1.0
32
33
34
35
Maximum temperature (in °C)
SE1 = 0.0003
SE2 = 0.0002
threshold = 33.51



Days above 29°C in the USA May-Nov
1967-1990
1991-2012
F(x)
0.0
0.2
0.4
0.6
0.8
1.0
40
60
80
100
120
Number of days
SE1 = 0.006
SE2 = 0.008
threshold = 54.13

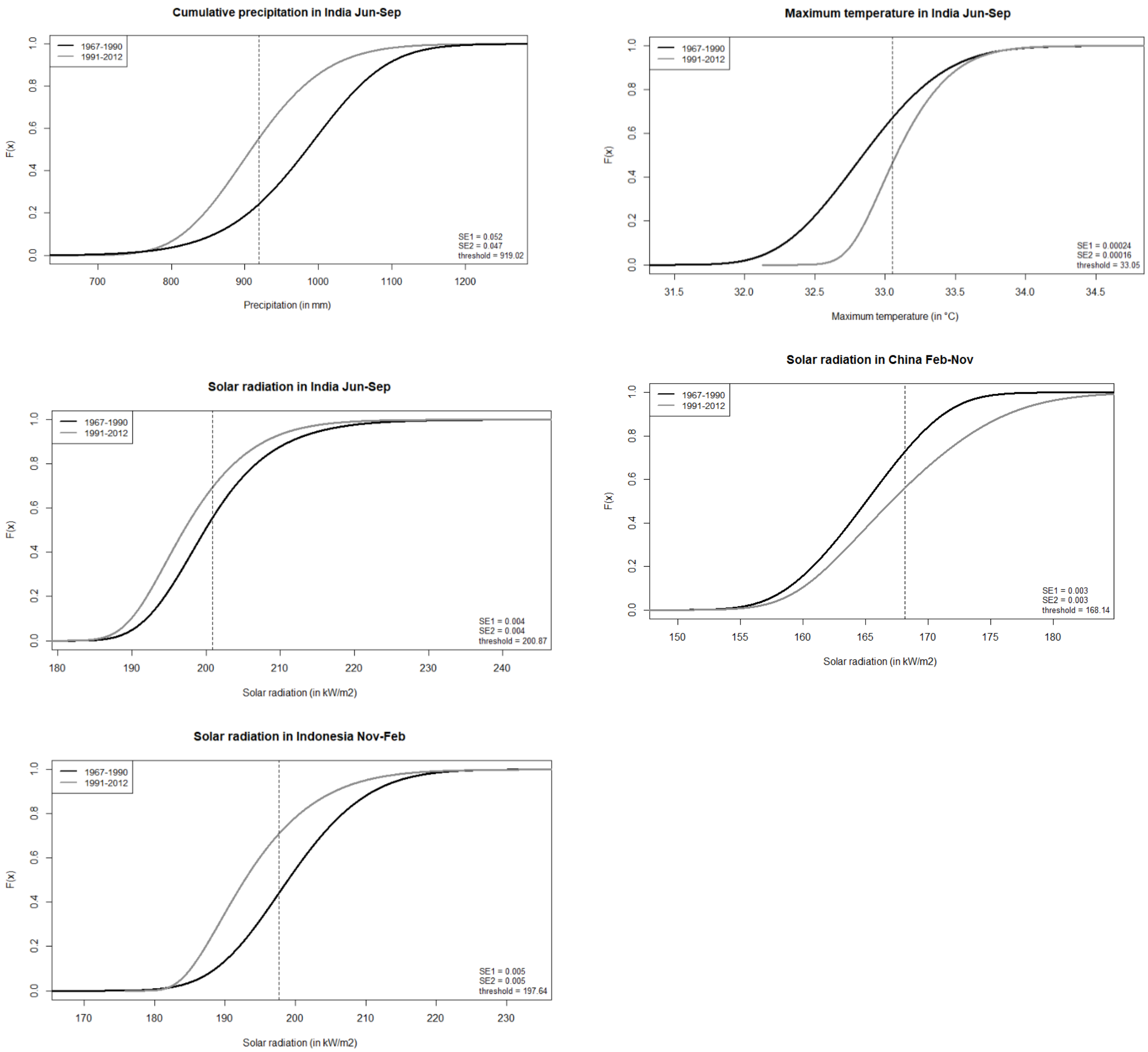


Cumulative precipitation Europe Mar-Aug
1967-1990
1991-2012
F(x)
0.0
0.2
0.4
0.6
0.8
1.0
300
400
500
600
Precipitation (in mm)
SE1 = 0.027
SE2 = 0.031
threshold = 382.42



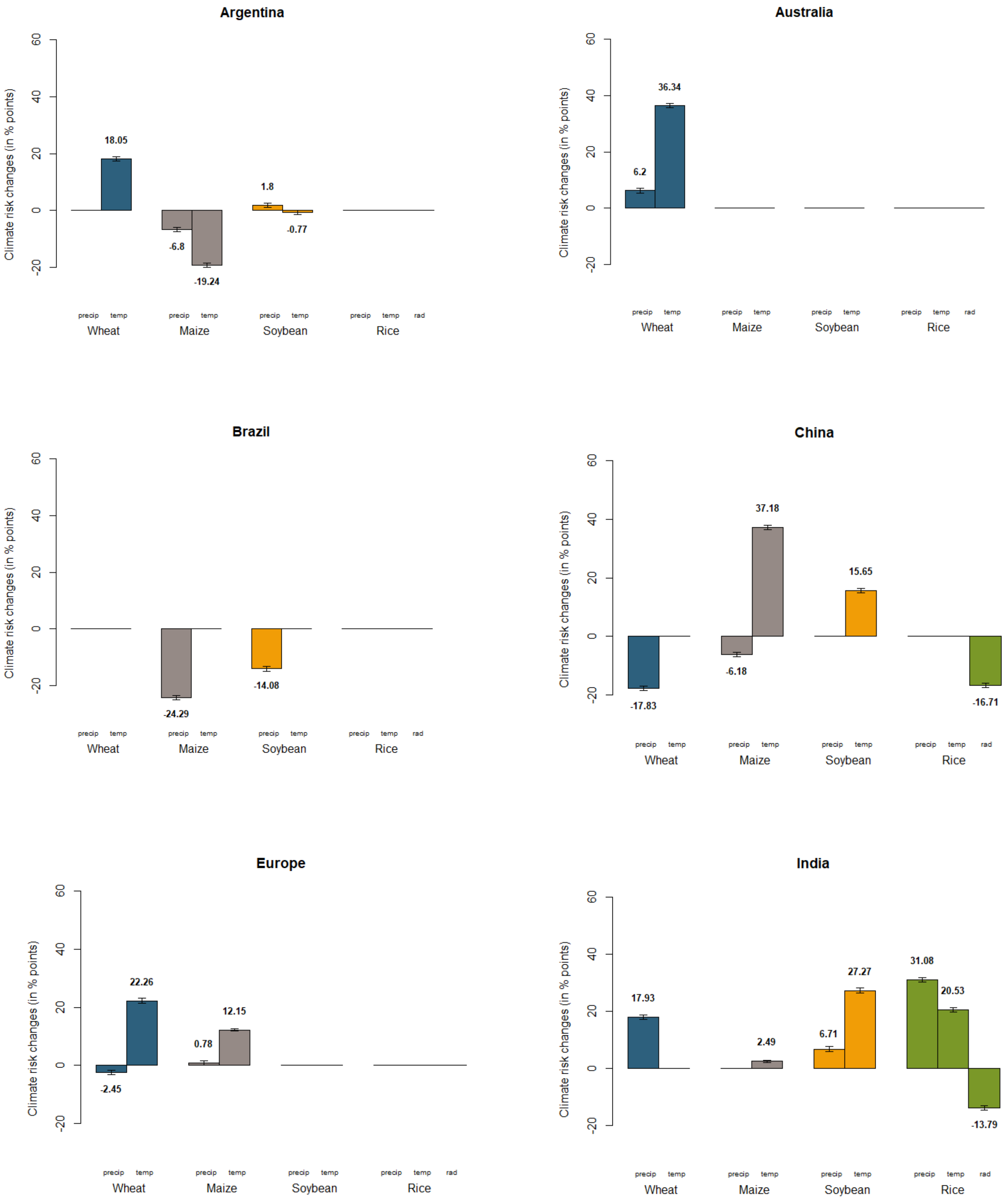
Temperature in Europe May-Aug
1967-1990
1991-2012
F(x)
0.0
0.2
0.4
0.6
0.8
1.0
16
17
18
19
20
21
Temperature (in °C)
SE1 = 0.0003
SE2 = 0.0004
threshold = 18.06

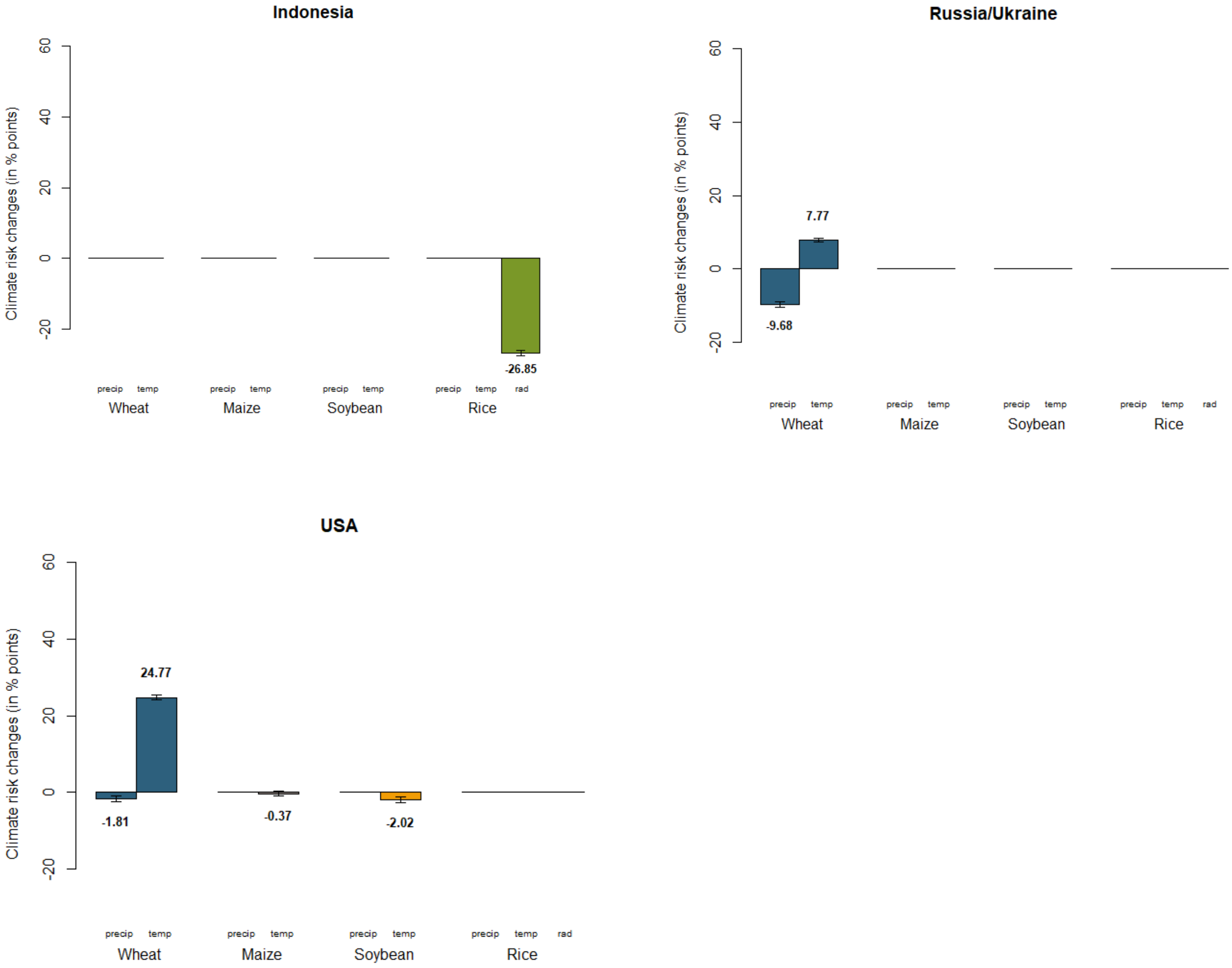
Rice



1.5 Supplementary figure SF4: Climate indicator distributions for period 1 and period 2 for each crop and breadbasket including the indicator-specific threshold.

The distributions include dependencies between states/provinces of the breadbaskets resulting from the copula analysis. Standard errors for both periods (SE1 and SE2) indicate the sampling error resulting from 1000 iterations,


Argentina
Climate risk changes (in % points)
18.05
-6.8
-19.24
1.8
-0.77
precip temp
Wheat
precip temp
Maize
precip temp
Soybean
precip temp rad
Rice
Australia
Climate risk changes (in % points)
6.2
36.34
precip temp
Wheat
precip temp
Maize
precip temp
Soybean
precip temp rad
Rice
Brazil
Climate risk changes (in % points)
-24.29
-14.08
precip temp
Wheat
precip temp
Maize
precip temp
Soybean
precip temp rad
Rice
China
Climate risk changes (in % points)
-17.83
-6.18
37.18
15.65
-16.71
precip temp
Wheat
precip temp
Maize
precip temp
Soybean
precip temp rad
Rice
Europe
Climate risk changes (in % points)
-2.45
22.26
0.78
12.15
precip temp
Wheat
precip temp
Maize
precip temp
Soybean
precip temp rad
Rice
India
Climate risk changes (in % points)
17.93
2.49
6.71
27.27
31.08
20.53
-13.79
precip temp
Wheat
precip temp
Maize
precip temp
Soybean
precip temp rad
Rice



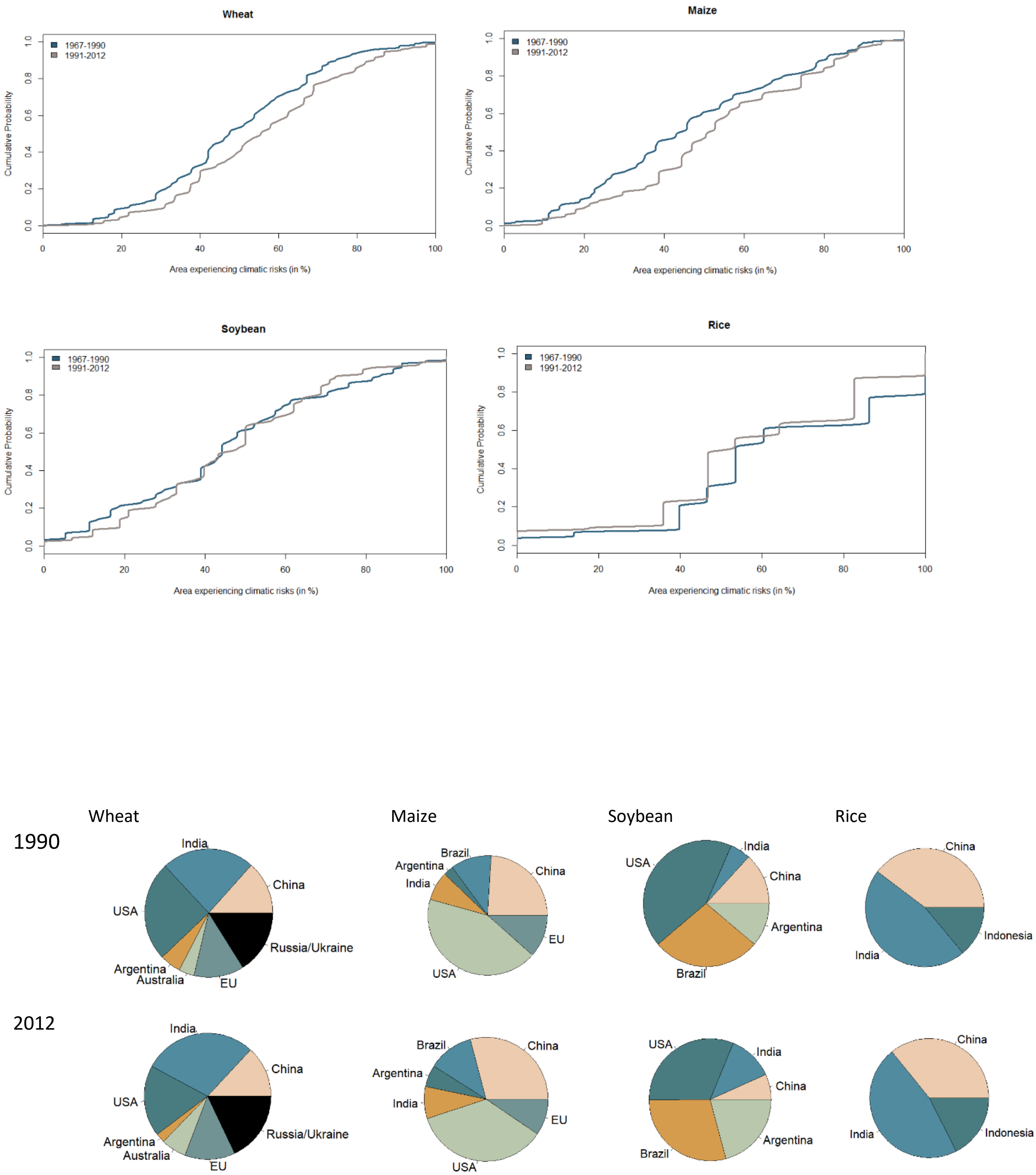
1.6 Supplementary figure SF5: Climate risk changes in percentage points between 1967-1990 and 1991-2012. Error bars reflect the sampling errors.

Changes between 1967-1990 and 1991-2012 in more detail:

Wheat: Climate risks increased in Argentina due to a strong warming of night-time temperatures[52] which negatively effects wheat growth. Wheat climate risks have increased in the Southwest of the Indian wheat breadbasket and decreased in the Northwest. Ramteke et al. (2015)[42] suggest that in the future, wheat as a rabi season crop will become more vulnerable due to large increase in temperature and higher rainfall uncertainties. In the Chinese breadbasket, climate risks have decreased due to an increase in monsoon precipitation[53]. In the US, climate risks have slightly increased in some states and slightly decreased in others. In Australia, wheat climate risks increased in New South Wales and decreased in South Australia.

Maize and Soybean: In Brazil, summer precipitation has a positive correlation with soybean and maize yields, except for Mato Grosso which is the wettest province in the breadbasket. An increasing precipitation therefore reduced climate risks for soybean and maize except Mato Grosso province where excess soil moisture can disturb root growth and thereby nutrient and water uptake[54]. In the US breadbasket, soybean and maize climate risks have slightly decreased with changes in maize risks smaller than the standard error. Looking in more detail at the region, climate risks for both soybean and maize have mostly declined in the Northwest and increased toward the Southeast of the breadbasket. This can be explained by stronger negative correlation between temperature and soybean and maize crops towards the Southeast compared to the Northwest as well as by an overall decrease in temperature in the centre of the US' maize and soybean belts[55,56]. In China, a clear positive temperature trend, especially in the Northeast of China's soybean and maize breadbaskets[43], increased temperature based climate risks to the crop. Precipitation trends, on the other hand, are not as clear (Lobell, 2011). On an aggregate breadbasket scale, precipitation-based climate risks decreased slightly. In India, maximum temperatures during maize and soybean growing seasons show an increasing trend[57] which is why climate risks are increasing except for states that show a positive correlation between high temperatures and yield such as Bihar and Maharashtra for maize. One possible reason for the positive correlation between maize and hot days in Bihar is the highest irrigation rate within the Indian maize breadbasket. Soybean, on the other hand, is mostly rainfed[58]. The precipitation-based risk indicator for soybean in India decreases slightly. Although the overall precipitation stays the same across the two periods, precipitation exceeds the breadbasket's climate threshold slightly more often in the first period.

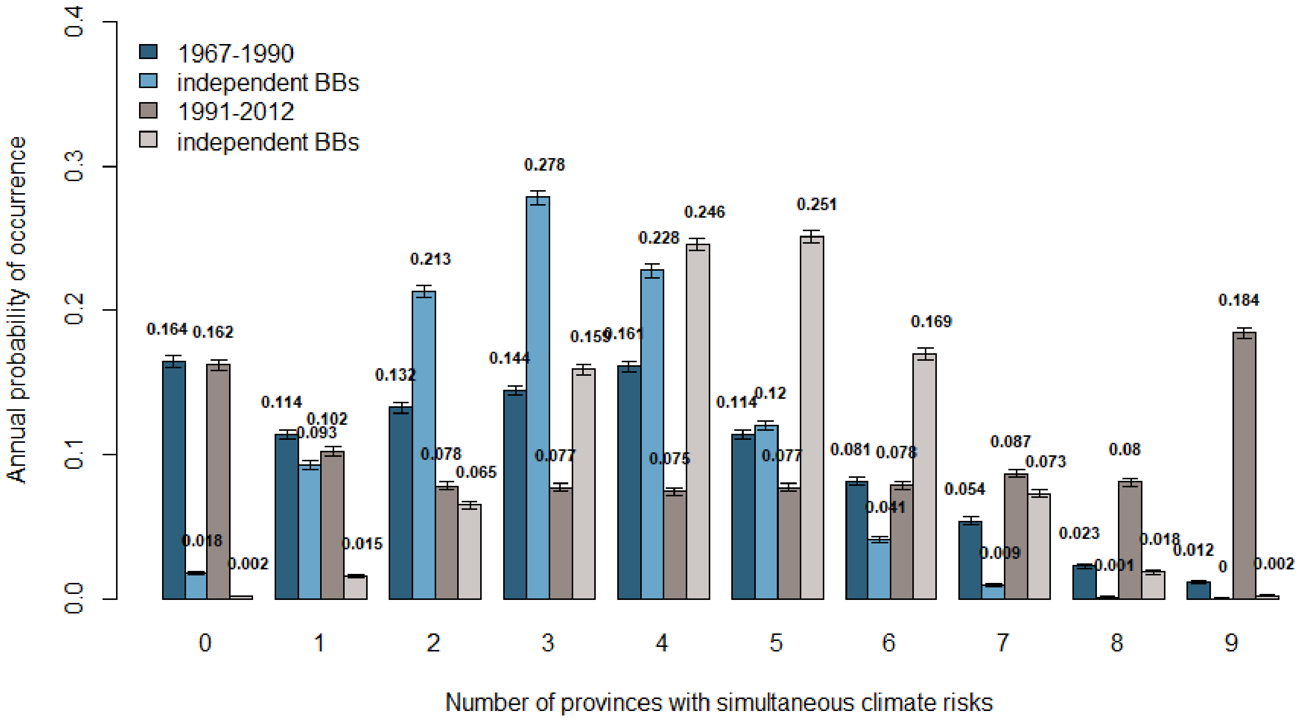
Rice: Owing to the limited explanatory power of temperature and precipitation, solar radiation was added as a climate indicator for rice. Although solar radiation is generally assumed to have a positive effect on rice yields as increased radiation improves photosynthesis[46,59,60], studies found a negative correlation between rice and solar radiation in India and Indonesia[48,49]. One explanation could be the already high levels of radiation that exceed the optimum at different growth stages[48]. Owing to the negative correlation, radiation based climate risks have decreased as a consequence of the so-called "global solar dimming"[49,61,62], a phenomena which is believed to result from increased cloudiness caused by regional brown clouds of aerosol pollution and of global warming[61,63,64]. In China, on the other hand, solar radiation is positively correlated with rice yields in our rice breadbasket in the Southeast[44]. Compared to other regions, many studies suggest that in China, there has been a "dimming to brightening" before and after 1990[61,65] or at least a stabilization of solar radiation[66]. This agrees with increases of solar radiation in our re-analysis data. Thus, radiation-based climate risks have decreased in the Chinese breadbasket as well.



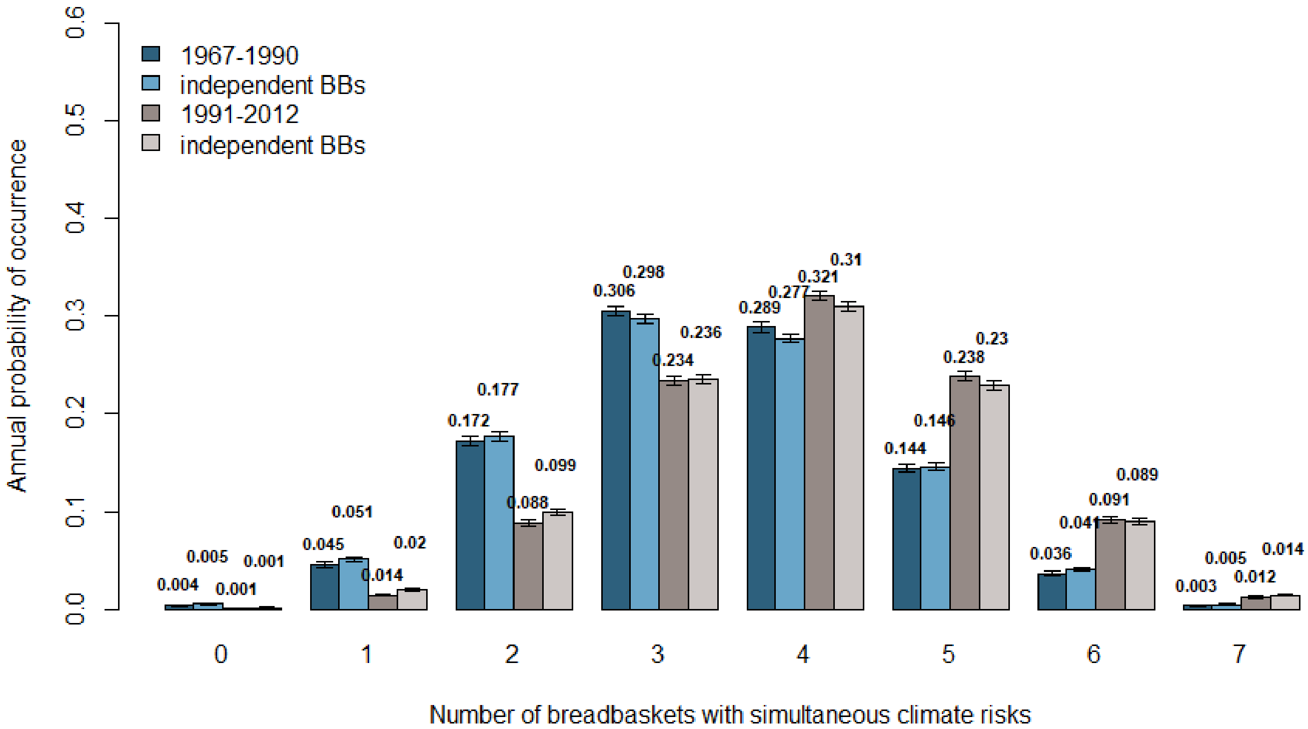
1.7 Supplementary figure SF6: Area affected by climatic risks in the global breadbaskets. Area (in percentage of total breadbasket crop area) experiencing simultaneously climate risks. For period 1 (1967-1990), harvested area in 1990 was aggregated over breadbaskets experiencing simultaneous climate risks. In period 2 (1991-2012), harvested area in 2012 was used. Pie charts on the bottom show the ratios of harvested area of different countries of the global breadbaskets.

The area analysis is consistent with results in Figure 2. For wheat, maize and soybean the percentage of area suffering from adverse climatic conditions increased in the second period. For soybean, however, the changes in area under risk are smaller than when looking at the number of breadbaskets. For crop area under risk between 70-85% of the breadbaskets, the area under risk has even decreased. For rice, the area under risk decreased (except for a small part between 60 and 70% crop area experiencing climatic risks). Looking at the lower part of the figure, one can see for wheat, the US and Indian breadbaskets cover nearly 50% of harvested area and therefore have a higher weight than Argentina or Australia. As the area distributions stays nearly constant between the two periods but climate risks increase in most breadbasket regions, the overall area under climate risks increases. For maize, increases in climate risk in China play a larger role as China has a large area share and the area weight of China increases between the periods. The US has a large share of harvested area but they share slightly decreases between the periods which reduces the weight of the slightly decreasing climate risks. For soybean, the increase in area experiencing climate risks is rather small which has to do with the fact that decreasing climate risks in the US and Brazilian breadbaskets are weighted more than the other breadbaskets. On the other hand, increasing risks in the Indian breadbasket and increasing precipitation-based risks in Argentina are weighted more in the second period as the area share of those countries increases whereas the share of the US decreases. For rice, the area shares stay fairly constant between the periods with India having the biggest share but decreasing climate-risks in China and Indonesia together still weighting more than 50%.

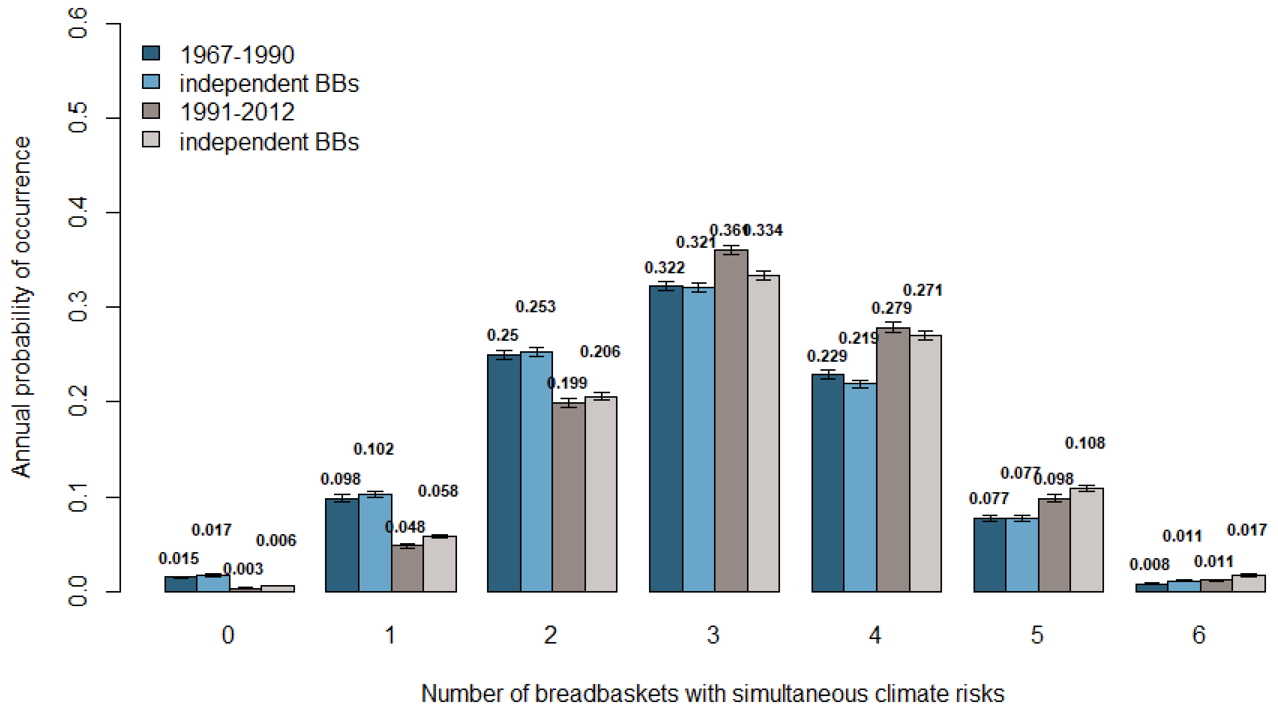
a Soybean in China



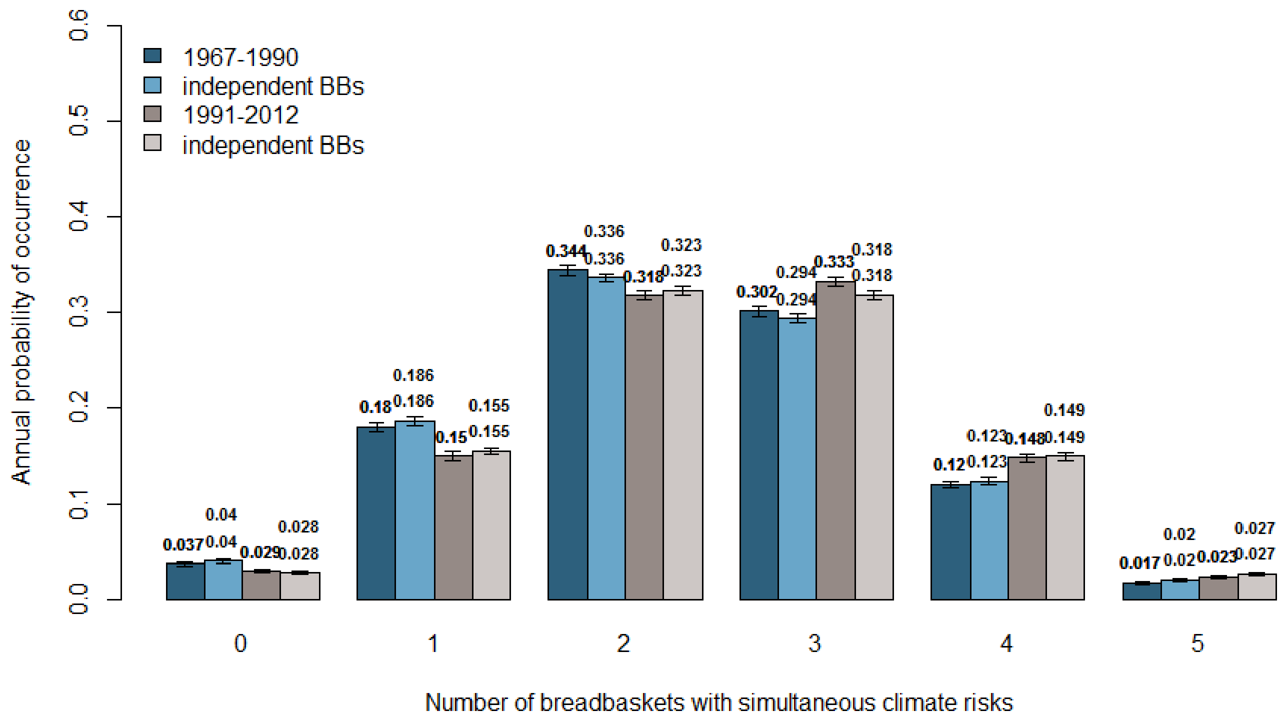
b Wheat



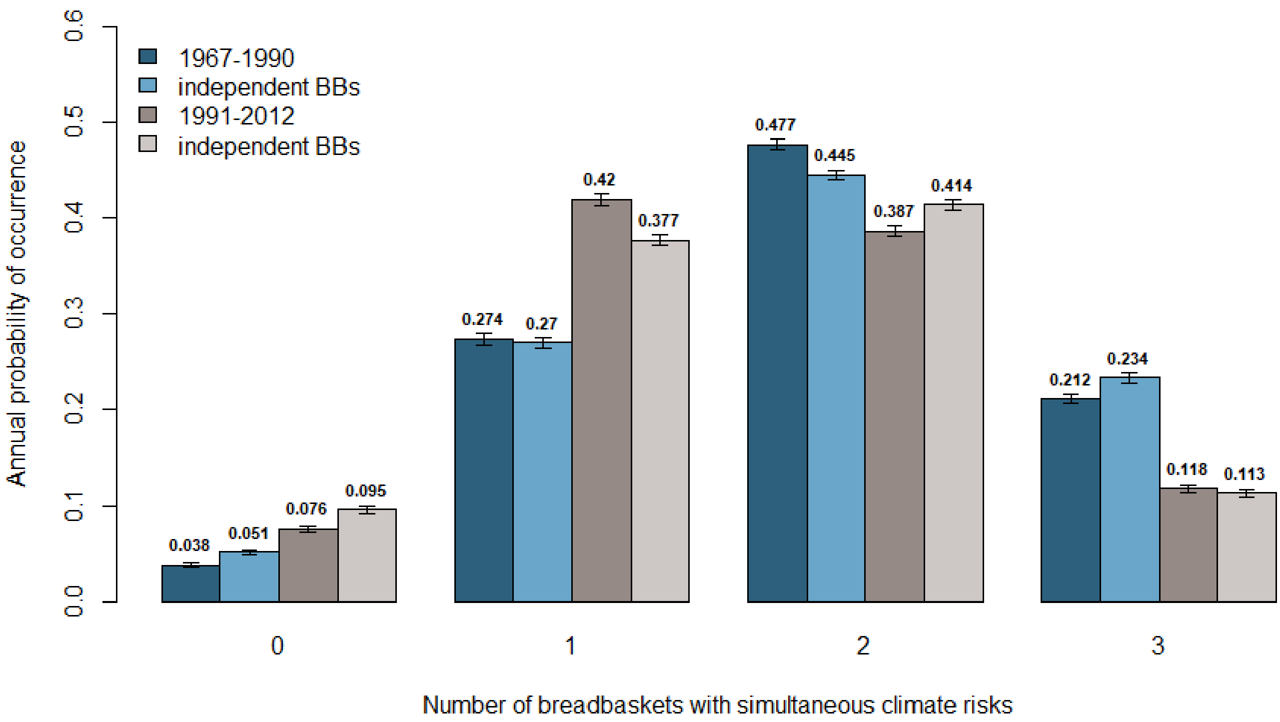
c Maize



d Soybean



e Rice



1.8 Supplementary figure SF7: Comparison with independent breadbaskets and provinces.

Comparison between climate risks to crops when historical dependencies are included and when independence between the breadbaskets are assumed (keeping the dependence between different climate indicators in the same breadbasket as well as the internal dependence structure between states/provinces of a breadbasket). Period 1 refers to 1967-2012 and period 2 to 1991-2012. Error bars reflect the sampling errors determined in 1000 iterations.

Results in detail:

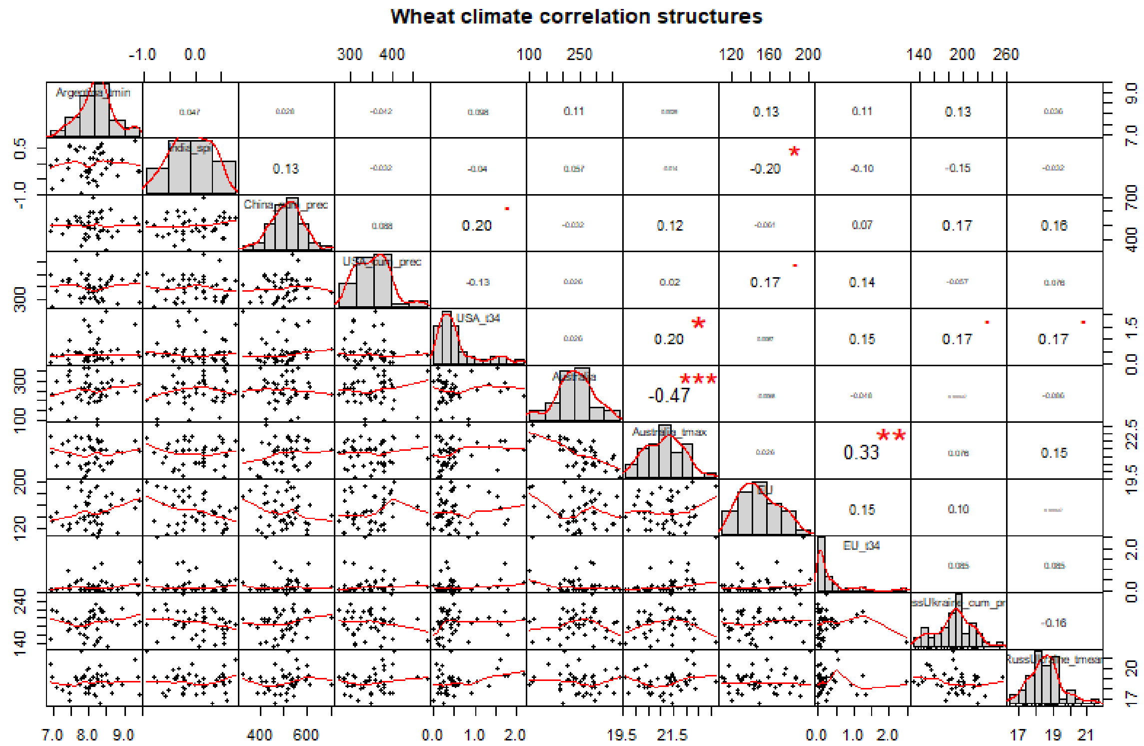
a) Soybean in China: There is a significant difference between period 1 and period 2 with period 2 having a larger mean than period 1 (significance refers here to parametric (e.g. t-tests) and non-parametric tests (e.g Wilcoxon), if not otherwise stated both type of tests found to be significant). There was no significant difference in mean between the dependent and independent case. However, there is a clear and significant difference (e.g. using the Poisson test) between the dependent and independent case if each occurrence is examined separately (e.g. the likelihood of simultaneous climate risks in 3 provinces differs significantly from the likelihood of simultaneous climate risks in 3 provinces if they are assumed to be independent).

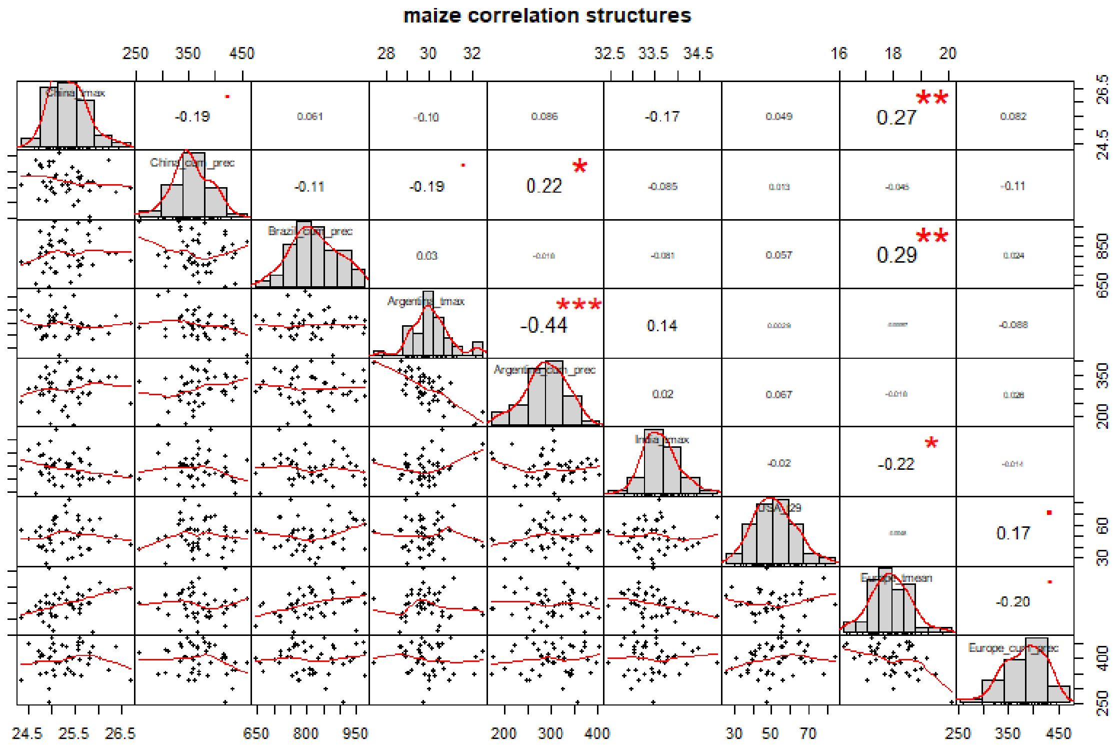
b) Wheat: Period 2 is on average significantly greater than period 1 at 0.001 significance level for all dependencies. When dependencies between breadbaskets are ignored, simultaneous risks are, in period 2, on average significantly lower than when dependencies are considered. In period 1, there is no significant difference. The same applies if we look at each simultaneous risk case separately. There are significant differences between all dependent and independent cases for both periods.

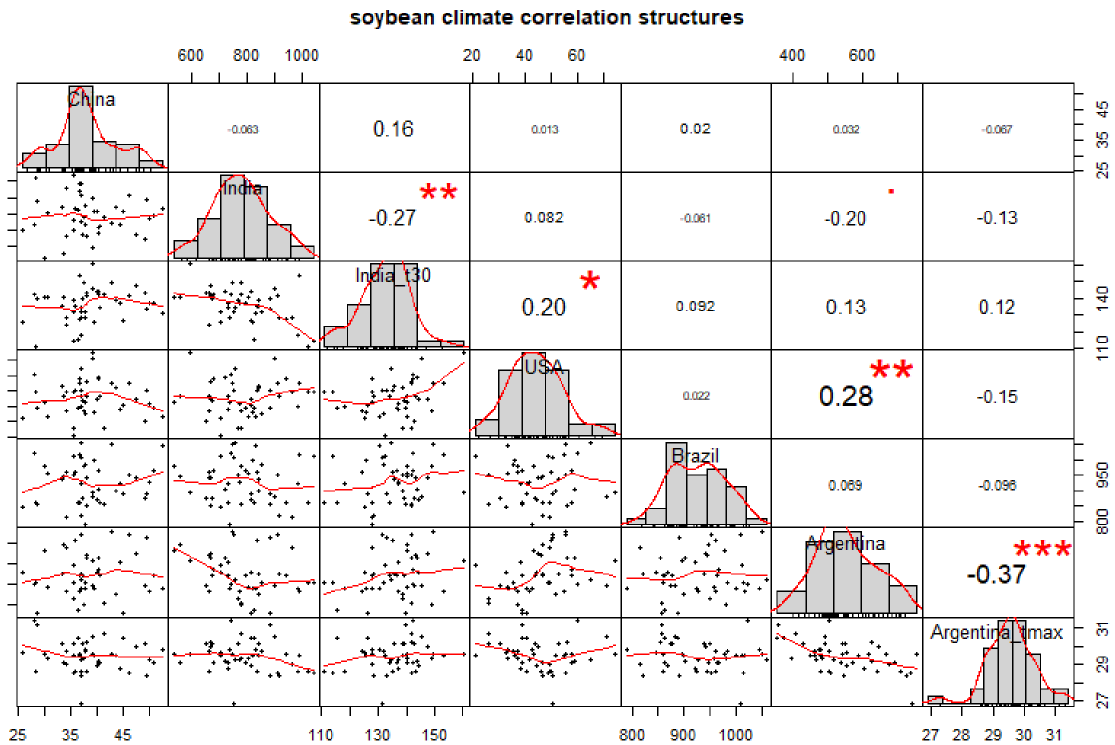
c) Maize: It was found that Period 2 has a significantly larger mean than period 1. Looking at the dependencies, maize shows no significant difference in mean between the dependencies. However, figure SF6 shows that the independent case is larger in the extremes (0 and 1 simultaneous breadbasket failures for low risks and 5 and 6 simultaneous risks for high risks). Hence, there are also cases that climate risks in the global maize breadbaskets can level each other out. This may be an important observation in regards how to manage the risk of breadbasket failures on the global scale.

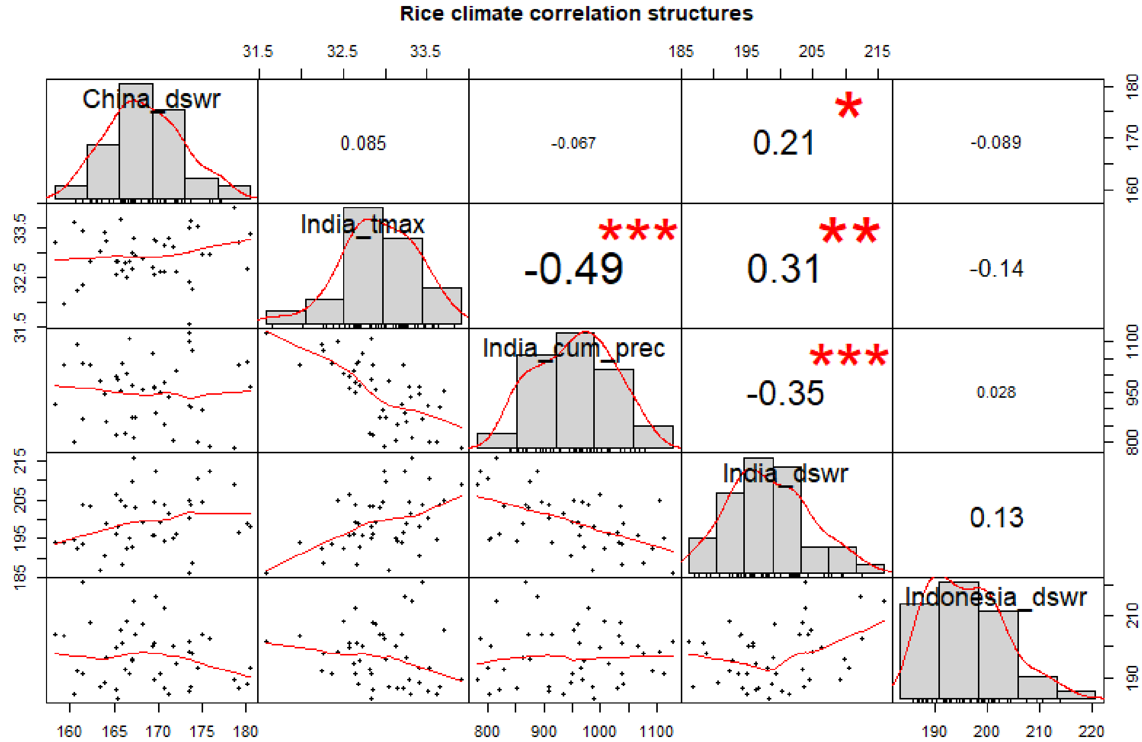
d) Soybean: Period 2 was found to have a significantly higher mean than period 1. Comparing each likelihood of simultaneous occurrence between the two periods, there are significant differences between the periods for all simultaneous climate risks. Comparing dependencies, there are no significantly different means in the case of independence between BBs. However, there are significant differences between the dependencies for period 2 and for period 1.

e) Rice: On average, period 1 shows significantly higher climate risks than period 2. Between the dependencies, there is no difference in average risks. When each simultaneous risk is compared individually, however, significant differences between the dependencies in both periods were found.




maize correlation structures
China_tmax
China_corn_prec
Brazil_corn_prec
Argentina_tmax
Argentina_corn_prec
India_tmax
USA_29
Europe_tmean
Europe_corn_prec
-0.19
0.061
-0.10
0.086
-0.17
0.049
0.27
0.082
-0.11
-0.19
0.22
-0.085
0.013
-0.045
-0.11
0.03
-0.010
-0.081
0.057
0.29
0.024
-0.44
0.14
0.0029
-0.088
0.02
0.067
-0.010
0.026
-0.02
-0.22
-0.014
0.17
-0.20


soybean climate correlation structures
China
India
India_t30
USA
Brazil
Argentina
Argentina_tmax
-0.063
0.16
0.013
0.02
0.032
-0.067
-0.27
0.082
-0.061
-0.20
-0.13
0.20
0.092
0.13
0.12
0.022
0.28
-0.15
0.069
-0.096
-0.37



1.9 Supplementary figure SF8: Correlation structure between climate indicators using Kendall's tau. The plots include a scatterplot matrix with histograms, kernel density overlays, correlation coefficients and significance asterisks (0.05, 0.01, 0.001).

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