Methodology to assess the changing risk of yield failure due to heat and drought stress under climate change – Supplementary Material

Supplementary S1

The relative distribution $g(r)$ was obtained as the ratio of the density of the comparison population (yields) to the density of the reference population evaluated at the rth quantile of the reference distribution (Equation 1):

$$g(r)_{(cl,s)} = \frac{f(y_r)_{(cl,s)}}{f_0(y_r)_{(cl)}}; 0 \leq r \leq 1, y_r \geq 0 \qquad (1)$$

where $f(y_r)$ is the probability density function of the comparison population and $f_0(y_r)$ the density of the reference one, both evaluated at the *r*th quantile of the reference distribution, *cl* is the spatial cluster and *s* the climate scenario. Such relative density encodes the differences between two distributions of crop yields in a single curve. When there are no changes between the two distributions, $g(r)$ equals to 1 for all quantiles. Values higher (lower) than 1 indicate an increase (decrease) share of yields in the comparison distribution at the level identified by the *r*th quantile of the reference distribution.

The relative distribution methods further allowed to isolate the differences between yields under baseline and climate change scenarios that can be attributed to the change in mean yield (*location* effect) from differences involving higher order moments of the distribution (*shape* effect). These two effects were separated through the definition of an intermediate population (Y_A) as the reference population (Y_0) location-adjusted to have the same mean of the comparison distribution (Y). The location and shape effects were quantified as the relative density (Equation 1) of Y_A to Y_0, and Y to Y_A, respectively. The changes in the distribution of crop yields were summarized by the Kullback-Leibler divergence measure (Handcock and Morris 1998, 1999).

Supplementary S2

Table S2. Schematic overview of the models, simulation treatments and data from Webber et al. (2018a) used in this study.

a) Crop models

model name	***simulated crops***	***simulation of canopy temperature***
FASSET	Maize, Wheat	y
SIMPLACE	Maize, Wheat	y
HERMES	Maize, Wheat	y
4M	Maize, Wheat	n
SSM	Wheat	y
SiriusQuality version 3	Wheat	y
SIRIUS 2015	Wheat	y
DSSAT_IX	Maize	n

b) Simulation treatments

Treatment code	***Yield level***	***irrigation***	***heat stress***
T1	Potential	y	n

T2	Heat limited with air temperature	y	y
T3	Heat limited with canopy temperature	y	y
T4	Drought limited	n	n
T5	Drought-heat limited with air temperature	n	y
T6	Drought-heat limited with canopy temperature	n	y

c) Spatial extent

Crop	***simulation units with > 500 ha rainfed area***
Maize	3104
Wheat	4790

d) Future climate scenarios (2040-2069)

Climate forcing (RCP)	***Climate models***
2.6	HadGEM2-ES, MPI-ESM-MR
4.5 and 8.5	GFDL-CM3, GISS-E2-R, HadGEM2-ES, MIROC5, MPI-ESM-MR

Supplementary S3

Table S3.1 Return periods of yield failure aggregated for the clusters identified for maize and wheat under baseline climate and climate change scenarios (RCPs 2.6, 4.5 and 8.5). The return periods are reported as the average and standard deviation (in brackets) across the simulation units comprised in the cluster. Cluster names indicate the category of the four ensemble estimates in the simulation unit, ordered as follows: Y_{WHL} (first letter), Y_{POT} (second letter), WS (third letter), and HS (last letter). “A” identifies the “best” category (highest yield or lowest stress), “B” intermediate and “C” worst.

	Maize				**Wheat**			
Cluster	**Baseline**	**RCP 2.6**	**RCP4.5**	**RCP 8.5**	**Baseline**	**RCP 2.6**	**RCP4.5**	**RCP 8.5**
AAAA	-	-	-	-	3.65 (1.06)	3.85 (0.89)	3.86 (0.89)	3.84 (0.78)
AAAB	3.13 (0)	2.69 (0.04)	2.78 (0)	2.6 (0.13)	3.47 (0.81)	3.58 (1.06)	3.4 (0.89)	3.42 (0.9)
AABA	2.85 (0.48)	2.71 (0.48)	2.63 (0.45)	2.56 (0.27)	3.08 (0.53)	3.16 (0.51)	3.18 (0.46)	3.3 (0.52)
AABB	2.88 (0.45)	2.75 (0.31)	2.58 (0.24)	2.55 (0.24)	3 (0.41)	3.14 (0.36)	3.08 (0.35)	3.14 (0.39)
AACA	2.27 (0.25)	2.28 (0.24)	2.32 (0.09)	2.27 (0.13)	2.85 (0.5)	2.82 (0.21)	2.88 (0.17)	3.18 (0.3)
AACB	2.54 (0.18)	2.29 (0.12)	2.43 (0.11)	2.43 (0.11)	3.13 (0)	2.78 (0)	2.78 (0)	3.13 (0)
ABAA	3.15 (0.54)	2.93 (0.38)	2.94 (0.38)	2.99 (0.42)	3.68 (0.96)	3.87 (0.93)	3.96 (0.79)	4 (0.77)
ABAB	3.27 (0.46)	3.01 (0.38)	2.96 (0.36)	2.96 (0.34)	3.62 (0.93)	3.63 (0.77)	3.7 (0.64)	3.74 (0.77)
ABBA	2.89 (0.45)	2.69 (0.35)	2.67 (0.35)	2.63 (0.33)	3.21 (0.48)	3.39 (0.56)	3.37 (0.5)	3.56 (0.56)
ABBB	2.98 (0.41)	2.77 (0.36)	2.74 (0.4)	2.71 (0.4)	3.09 (0.36)	3.35 (0.61)	3.33 (0.6)	3.41 (0.58)
ABCA	3.57 (0)	2.94 (0)	2.5 (0)	2.5 (0)	-	-	-	-
ABCB	3.13 (0)	2.5 (0)	2.27 (0)	2.27 (0)	-	-	-	-
ACAA	3.07 (0.4)	3.03 (0.5)	2.93 (0.41)	2.95 (0.42)	3.61 (1.75)	3.52 (0.99)	3.66 (1.1)	3.7 (0.99)
ACAB	3.13 (0.22)	3.02 (0.15)	2.79 (0.22)	2.71 (0.12)	-	-	-	-
ACBA	2.92 (0.47)	2.56 (0.22)	2.6 (0.34)	2.55 (0.22)	3.03 (0.51)	3.02 (0.46)	3.17 (0.45)	3.31 (0.6)

ACBB	2.78 (0)	2.63 (0)	2.5 (0)	2.27 (0)	-	-	-	-
BABA	2.49 (0.32)	2.44 (0.27)	2.45 (0.28)	2.37 (0.24)	2.77 (0.37)	2.83 (0.31)	2.77 (0.32)	2.83 (0.35)
BABB	2.59 (0.28)	2.45 (0.18)	2.39 (0.17)	2.39 (0.16)	2.94 (0.55)	2.9 (0.43)	2.91 (0.4)	2.93 (0.32)
BACA	2.27 (0.29)	2.3 (0.3)	2.3 (0.28)	2.23 (0.26)	2.82 (0.51)	2.8 (0.45)	2.76 (0.39)	2.76 (0.4)
BACB	2.31 (0.29)	2.25 (0.2)	2.25 (0.15)	2.28 (0.15)	3.01 (0.65)	2.9 (0.51)	2.87 (0.54)	2.84 (0.49)
BBAA	2.88 (0.33)	2.86 (0.3)	2.83 (0.28)	2.89 (0.29)	3.48 (0.68)	3.41 (0.55)	3.53 (0.56)	3.55 (0.5)
BBAB	3.07 (0.4)	2.74 (0.2)	2.83 (0.29)	2.9 (0.31)	3.39 (0.67)	3.35 (0.48)	3.4 (0.47)	3.42 (0.48)
BBBA	2.69 (0.39)	2.59 (0.35)	2.55 (0.28)	2.54 (0.3)	2.84 (0.38)	2.84 (0.31)	2.89 (0.36)	2.94 (0.39)
BBBB	2.69 (0.33)	2.57 (0.33)	2.56 (0.39)	2.53 (0.36)	2.86 (0.38)	2.82 (0.3)	2.84 (0.31)	2.85 (0.33)
BBCA	2.46 (0.27)	2.36 (0.25)	2.31 (0.24)	2.27 (0.21)	2.75 (0.42)	2.75 (0.35)	2.76 (0.33)	2.8 (0.32)
BBCB	2.4 (0.31)	2.35 (0.2)	2.28 (0.17)	2.26 (0.13)	2.69 (0.34)	2.68 (0.33)	2.67 (0.28)	2.7 (0.36)
BCAA	3 (0.48)	2.97 (0.43)	2.88 (0.36)	2.91 (0.34)	3.22 (0.57)	3.06 (0.54)	3.2 (0.5)	3.27 (0.58)
BCAB	2.99 (0.34)	2.8 (0.24)	2.76 (0.22)	2.76 (0.34)	3.19 (0.42)	2.95 (0.24)	3.19 (0.38)	3.24 (0.39)
BCBA	2.69 (0.34)	2.58 (0.24)	2.53 (0.23)	2.54 (0.25)	2.9 (0.41)	2.82 (0.39)	2.94 (0.37)	2.96 (0.39)
BCBB	2.6 (0.28)	2.56 (0.24)	2.54 (0.24)	2.55 (0.29)	2.87 (0.37)	2.75 (0.19)	2.8 (0.34)	2.75 (0.2)
BCCA	-	-	-	-	3.29 (0.21)	3.02 (0.31)	3.23 (0.19)	3.1 (0.3)
BCCB	-	-	-	-	3.13 (0)	3.13 (0)	3.13 (0)	3.57 (0)
CABA	2.25 (0.07)	2.04 (0.21)	2.03 (0.12)	2.03 (0.11)	3.57 (0)	3.57 (0)	3.57 (0)	3.57 (0)
CABB	2.08 (0)	2 (0)	2.08 (0)	2.08 (0)	3.57 (0)	3.13 (0)	3.57 (0)	3.57 (0)
CACA	2.33 (0.26)	2.27 (0.21)	2.26 (0.21)	2.24 (0.22)	2.57 (0.37)	2.57 (0.3)	2.59 (0.32)	2.58 (0.33)
CACB	2.35 (0.28)	2.28 (0.22)	2.27 (0.2)	2.21 (0.23)	2.78 (0.56)	2.71 (0.47)	2.72 (0.48)	2.68 (0.42)
CBAA	-	-	-	-	2.5 (0)	2.78 (0)	3.13 (0)	3.13 (0)
CBBA	2.44 (0.24)	2.3 (0.21)	2.23 (0.18)	2.3 (0.22)	2.86 (0.39)	2.79 (0.26)	2.83 (0.26)	2.89 (0.29)
CBBB	2.69 (0.27)	2.64 (0.41)	2.43 (0.24)	2.34 (0.3)	2.84 (0.33)	2.84 (0.28)	2.83 (0.33)	2.88 (0.28)
CBCA	2.19 (0.19)	2.2 (0.18)	2.17 (0.15)	2.15 (0.14)	2.73 (0.41)	2.67 (0.3)	2.69 (0.31)	2.75 (0.34)
CBCB	2.47 (0.24)	2.38 (0.3)	2.36 (0.32)	2.34 (0.25)	2.85 (0.5)	2.79 (0.42)	2.76 (0.36)	2.84 (0.4)
CCAA	2.84 (0.35)	2.74 (0.31)	2.75 (0.31)	2.77 (0.33)	3.14 (0.73)	3.38 (0.8)	3.55 (0.76)	3.6 (0.8)
CCAB	3.01 (0.5)	2.6 (0.23)	2.64 (0.22)	2.62 (0.2)	6.25 (0)	6.25 (0)	8.33 (0)	7.14 (0)
CCBA	2.55 (0.27)	2.48 (0.24)	2.47 (0.25)	2.44 (0.26)	2.87 (0.51)	2.92 (0.56)	3.04 (0.53)	3.05 (0.55)
CCBB	2.43 (0.31)	2.39 (0.18)	2.26 (0.1)	2.29 (0.15)	2.6 (0.35)	2.61 (0.2)	2.6 (0.24)	2.74 (0.25)
CCCA	2.25 (0.19)	2.29 (0.16)	2.29 (0.19)	2.23 (0.22)	2.81 (0.42)	2.74 (0.43)	2.86 (0.48)	2.88 (0.48)
CCCB	2.34 (0.19)	2.23 (0.1)	2.3 (0.19)	2.3 (0.23)	2.47 (0.07)	2.59 (0.12)	2.74 (0.09)	2.74 (0.09)

Table S3.2 Return periods of yield failure aggregated at the country level for maize and wheat under baseline climate and climate change scenarios (RCPs 2.6, 4.5 and 8.5). The return periods are reported as the average and standard deviation (in brackets) across the simulation units comprised in the country.

	Maize				**Wheat**			
Country	**Baseline**	**RCP 2.6**	**RCP4.5**	**RCP 8.5**	**Baseline**	**RCP 2.6**	**RCP4.5**	**RCP 8.5**
Austria	3.03 (0.47)	2.86 (0.38)	2.88 (0.36)	2.84 (0.39)	3.36 (0.81)	3.27 (0.74)	3.24 (0.52)	3.29 (0.75)
Belgium	2.9 (0.36)	2.69 (0.32)	2.64 (0.29)	2.59 (0.3)	3.46 (0.95)	3.49 (0.5)	3.68 (0.59)	3.71 (0.7)
Bulgaria	2.2 (0.3)	2.2 (0.23)	2.22 (0.22)	2.21 (0.23)	2.7 (0.34)	2.7 (0.28)	2.73 (0.32)	2.79 (0.35)
Croatia	3.04 (0.24)	2.69 (0.26)	2.61 (0.15)	2.58 (0.19)	3.16 (0.36)	3.12 (0.46)	3.15 (0.45)	3.16 (0.39)
Czech Republic	2.65 (0.27)	2.53 (0.22)	2.52 (0.22)	2.59 (0.23)	2.84 (0.41)	2.83 (0.36)	2.85 (0.36)	2.87 (0.4)
Denmark	2.81 (0.28)	2.82 (0.34)	2.7 (0.38)	2.78 (0.4)	2.89 (0.43)	2.76 (0.31)	2.9 (0.36)	2.88 (0.36)
Estonia	2.7 (0)	2.6 (0)	2.94 (0)	2.78 (0)	3.03 (0.33)	2.99 (0.28)	3.28 (0.28)	3.27 (0.32)

Finland	-	-	-	-	3.13 (0.97)	3.45 (1.18)	3.49 (1.13)	3.53 (1.06)
France	2.76 (0.45)	2.55 (0.33)	2.48 (0.3)	2.46 (0.29)	3.12 (0.63)	3.29 (0.7)	3.27 (0.67)	3.37 (0.7)
Germany	2.89 (0.49)	2.88 (0.44)	2.84 (0.38)	2.91 (0.41)	3.27 (0.94)	3.22 (0.66)	3.3 (0.64)	3.36 (0.59)
Greece	2.4 (0.31)	2.3 (0.21)	2.28 (0.13)	2.23 (0.13)	3.37 (0.6)	3.26 (0.48)	3.13 (0.42)	3.16 (0.35)
Hungary	2.62 (0.37)	2.48 (0.23)	2.46 (0.21)	2.43 (0.21)	2.79 (0.26)	2.71 (0.22)	2.71 (0.22)	2.68 (0.22)
Ireland	-	-	-	-	5.65 (1.94)	5.31 (1.59)	5.06 (1.47)	4.57 (0.81)
Italy	2.28 (0.25)	2.25 (0.23)	2.21 (0.21)	2.2 (0.2)	3.15 (0.55)	3.05 (0.46)	3.05 (0.46)	3.04 (0.43)
Latvia	2.58 (0.26)	2.55 (0.25)	2.68 (0.24)	2.64 (0.26)	3.01 (0.4)	2.78 (0.29)	2.89 (0.37)	2.88 (0.31)
Lithuania	2.96 (0.45)	2.57 (0.18)	2.59 (0.16)	2.61 (0.19)	3 (0.32)	2.71 (0.26)	2.88 (0.32)	2.92 (0.3)
Luxembourg	3.09 (0.25)	2.75 (0.22)	2.83 (0.27)	2.68 (0.24)	3.6 (0.87)	3.48 (0.53)	3.63 (0.52)	4.05 (0.57)
Malta	-	-	-	-	3.35 (0.22)	2.78 (0)	2.78 (0)	2.95 (0.17)
Netherlands	2.92 (0.46)	2.83 (0.4)	2.82 (0.42)	2.75 (0.42)	3.68 (2.11)	3.49 (1.08)	3.61 (1.6)	3.62 (1.61)
Norway	-	-	-	-	3.59 (0.59)	3.55 (0.52)	3.72 (0.5)	3.62 (0.55)
Poland	2.7 (0.4)	2.54 (0.26)	2.58 (0.31)	2.65 (0.31)	3.02 (0.47)	2.99 (0.37)	3.14 (0.45)	3.19 (0.44)
Portugal	2.11 (0.19)	2.18 (0.25)	2.14 (0.19)	2.01 (0.18)	2.55 (0.29)	2.5 (0.23)	2.52 (0.2)	2.5 (0.18)
Romania	2.65 (0.46)	2.57 (0.43)	2.55 (0.41)	2.51 (0.39)	2.76 (0.36)	2.7 (0.25)	2.71 (0.26)	2.76 (0.28)
Slovakia	2.67 (0.27)	2.48 (0.29)	2.45 (0.25)	2.4 (0.25)	2.68 (0.24)	2.61 (0.18)	2.63 (0.23)	2.66 (0.21)
Slovenia	2.99 (0.29)	2.8 (0.24)	2.66 (0.23)	2.63 (0.16)	3.45 (0.53)	2.95 (0.42)	2.91 (0.35)	2.96 (0.49)
Spain	2.31 (0.25)	2.22 (0.26)	2.2 (0.26)	2.11 (0.25)	2.55 (0.38)	2.54 (0.32)	2.52 (0.29)	2.51 (0.31)
Sweden	-	-	-	-	3.06 (0.36)	3.11 (0.51)	3.25 (0.47)	3.29 (0.49)
United Kingdom	2.84 (0.37)	2.81 (0.35)	2.75 (0.36)	2.79 (0.39)	3.11 (0.74)	3.23 (0.63)	3.35 (0.65)	3.48 (0.66)

Supplementary S4

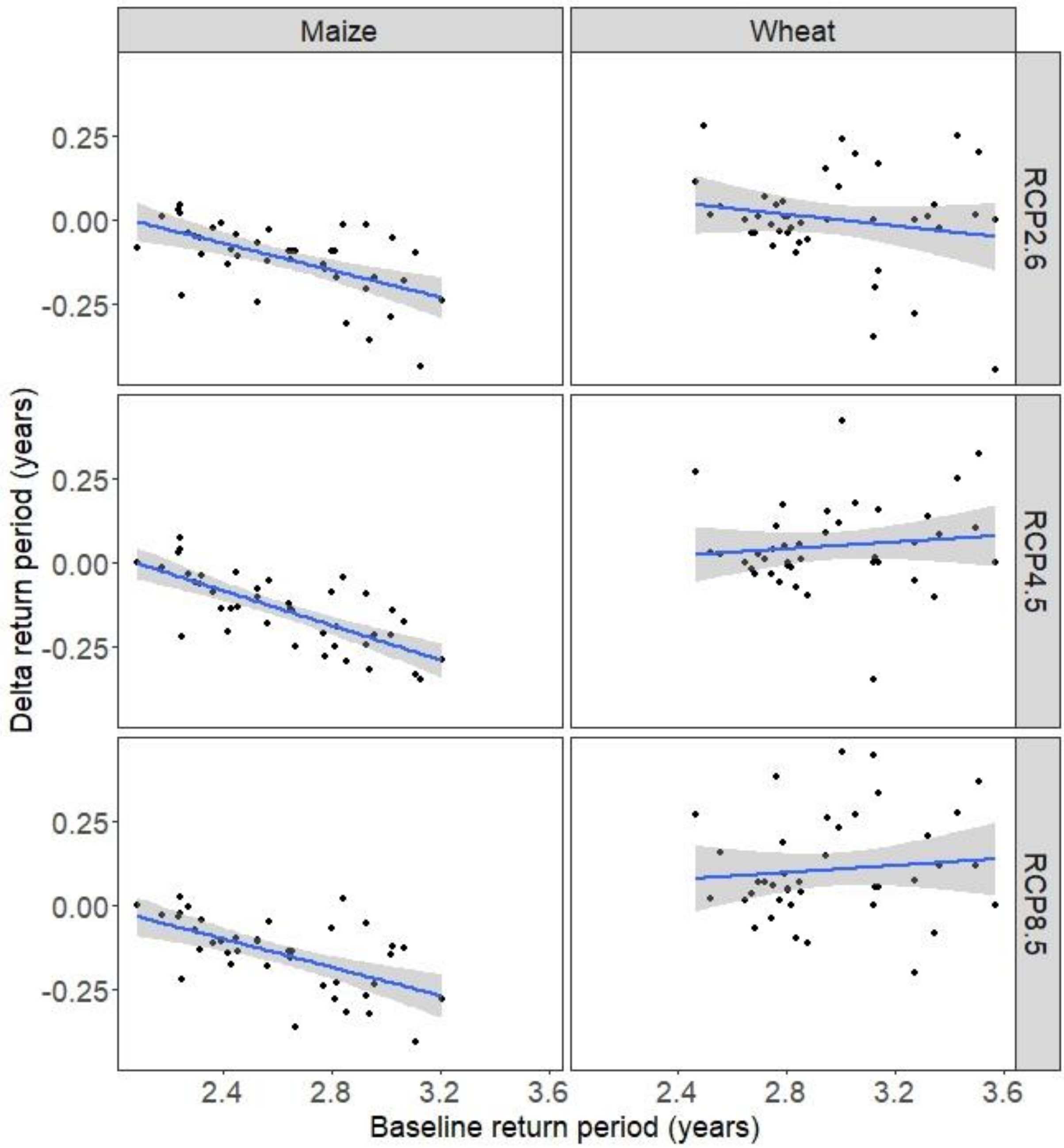

Figure S4. Relation between yield failure frequency (average return period between two failures) in the baseline and its changes under climate change scenarios across the spatial clusters identified for maize and wheat. Delta return period is calculated as the difference between future and baseline return period in each cluster.

Table S4. Coefficients of the linear regressions presented in Fig. S4.

Crop	RCP		Estimate	Standard error	Significance
Maize	2.6	Intercept	0.411	0.119	**
		Baseline RF	-0.201	0.045	***
	4.5	Intercept	0.533	0.100	***
		Baseline RF	-0.257	0.038	***
	8.5	Intercept	0.405	0.125	**
		Baseline RF	-0.211	0.048	***
Wheat	2.6	Intercept	0.256	0.218	n.s
		Baseline RF	-0.086	0.073	n.s
	4.5	Intercept	-0.101	0.203	n.s
		Baseline RF	0.050	0.068	n.s
	8.5	Intercept	-0.050	0.243	n.s
		Baseline RF	0.052	0.081	n.s

Signif. codes: 0 ‘***’ 0.001 ‘**’

Supplementary S5

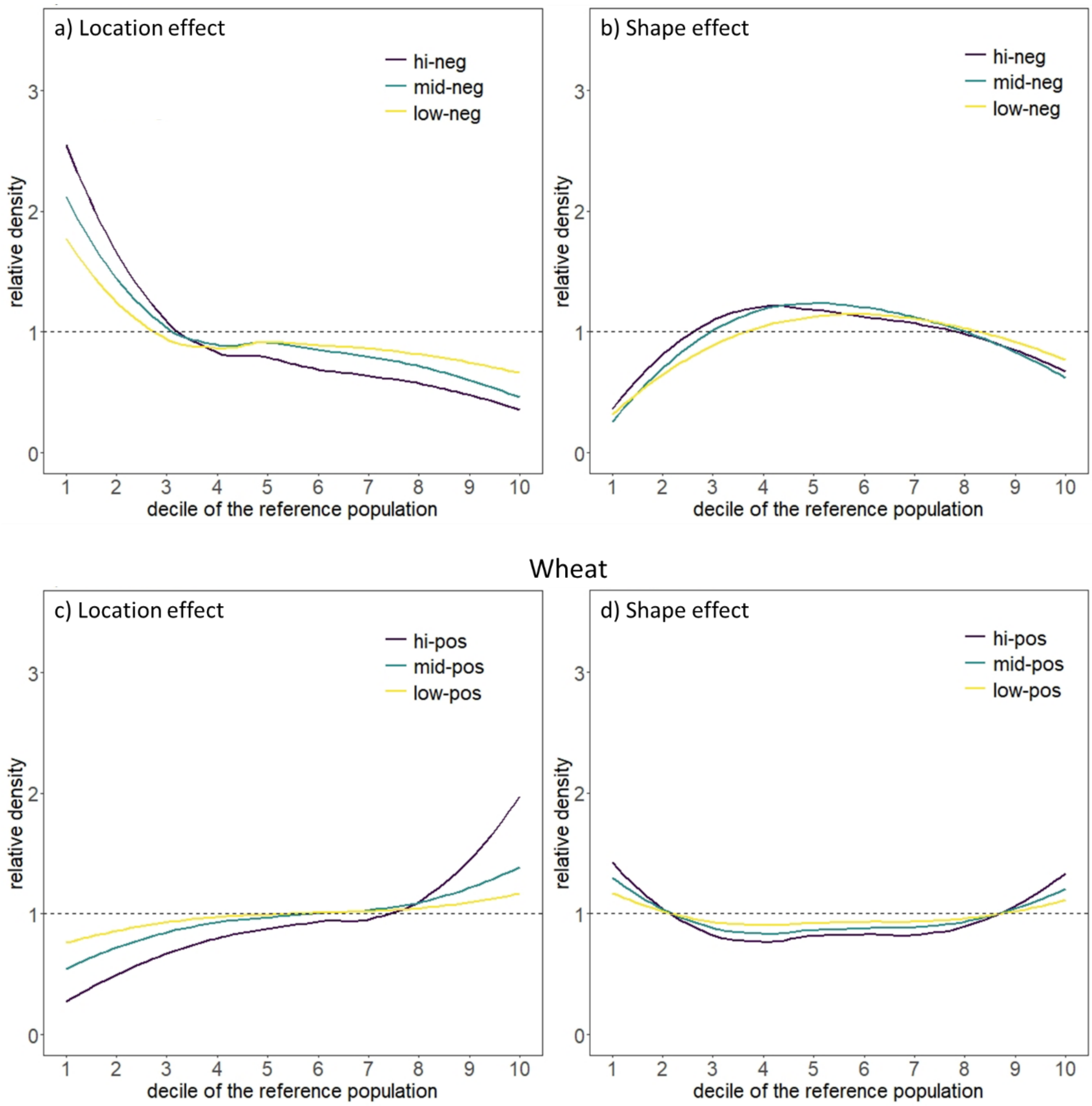

Figure S5. Decomposition of relative distribution into location and shape components for maize (a, b) and wheat (c, d) for the types of relative distributions identified. The labels identify the magnitude and direction of the impact of climate change. For maize, the impact is increasingly negative for types “low-neg”, “mid-neg” and “hi-neg”. For wheat, the impact is increasingly positive for types “low-pos”, “mid-pos” and “hi-pos”.

Supplementary S6

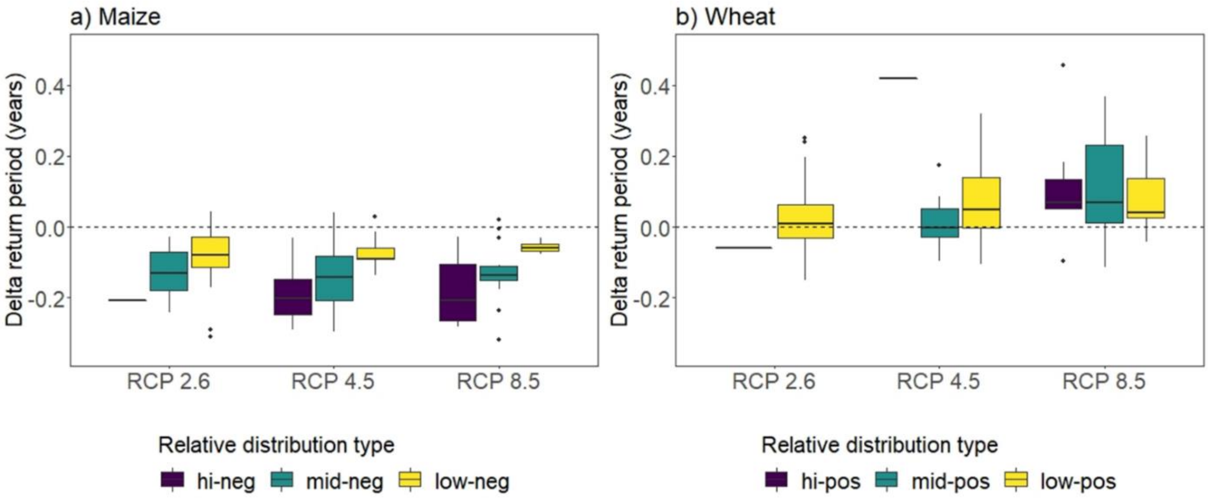

Figure S6. Changes in return period of a failure for maize (a) and wheat (b) under different climate change scenarios and types of relative distribution. Delta return period is the difference between return period of yield failure under climate change and baseline scenarios in each cluster. The delta is calculated based on the ensemble of all crop and climate models.

Supplementary S7

Table S7. Evaluation of model ensemble skills in simulating the frequency of yield failures (i.e., yield anomalies falling below 15% of the 5-year average) in the study area for the period 1982-2010. For each NUTS2 district, the frequency of yield failure was calculated as the number of failures detected in the time period divided by the length of the period (years) where data were available. The Pearson correlation coefficient (r) and percent bias (pbias) were calculated comparing yield failure frequencies from observed data and simulations (ensemble median aggregated at the NUTS2 level). Positive bias highlights an overestimation of the frequency of yield failures by the model ensemble. Time series of NUTS2 level production amounts were from the CAPRI (Comparative Analysis of PRotein-protein Interaction) database (Webber et al., 2018).

Crop	**r**	**pbias**
maize	0.288	367
wheat	0.479	226