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Supplementary information

Sources of uncertainty for wheat yield projections under future climate are site-specific

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Sources of uncertainty for wheat yield projections under future climate are site-specific

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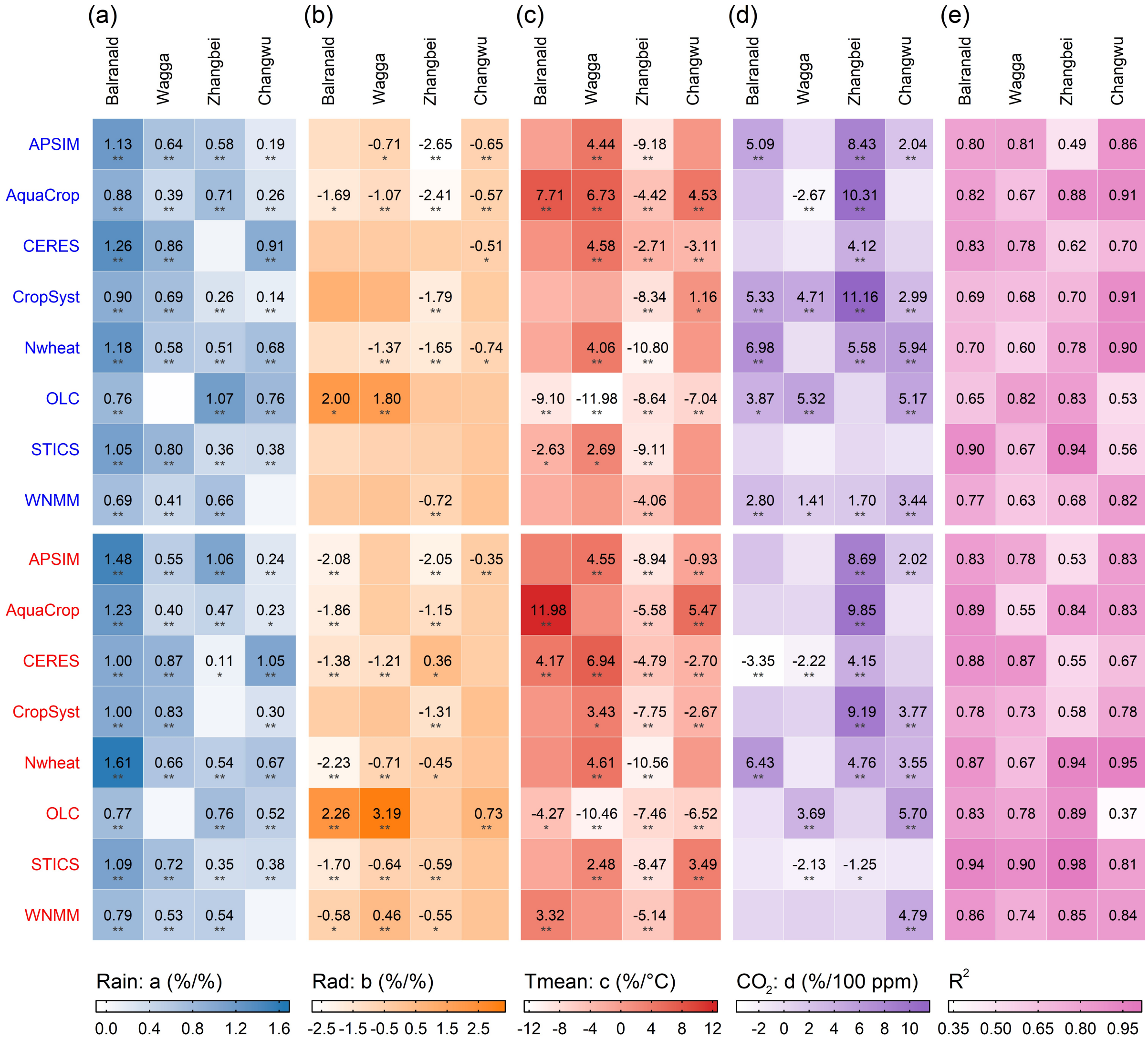
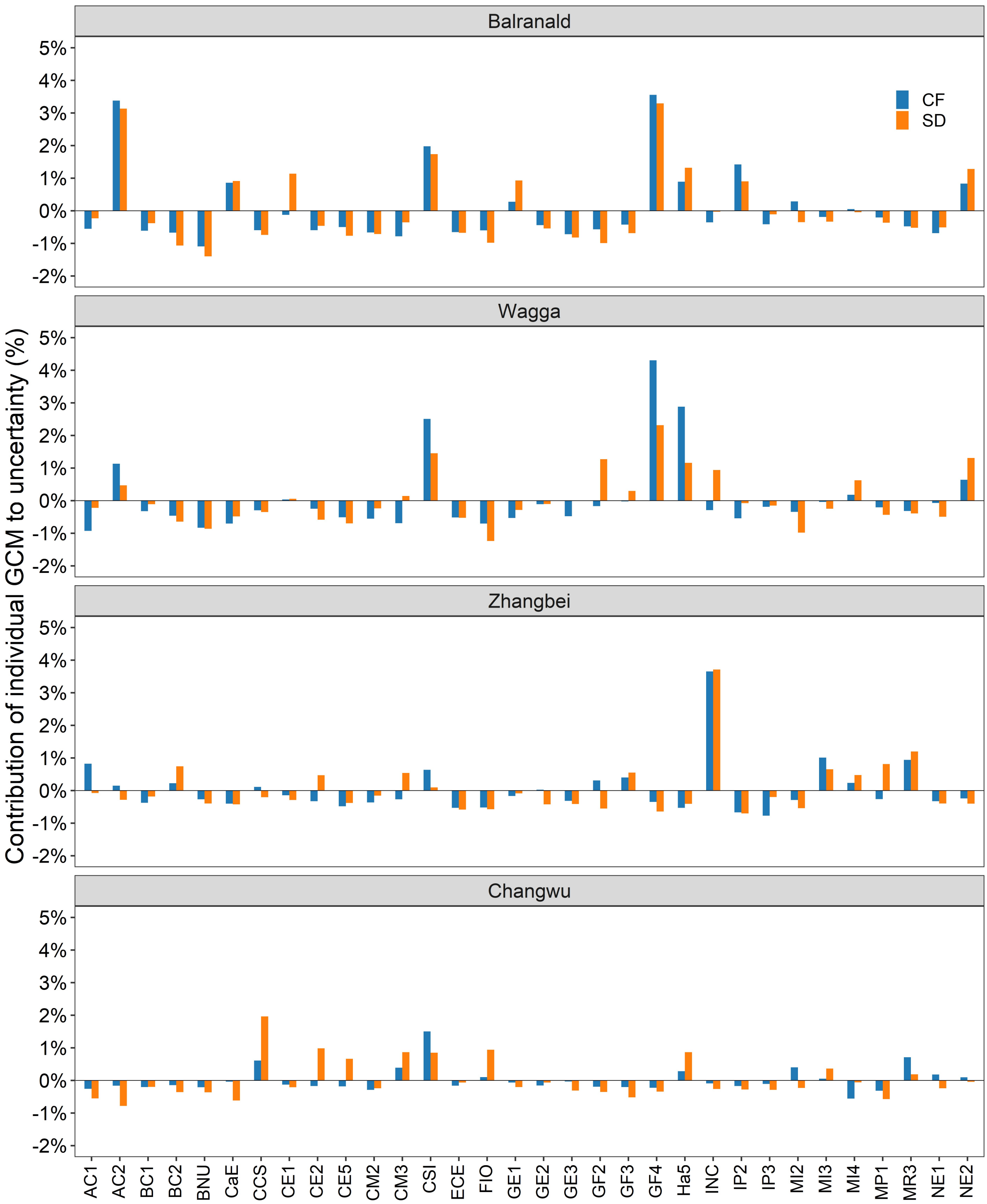
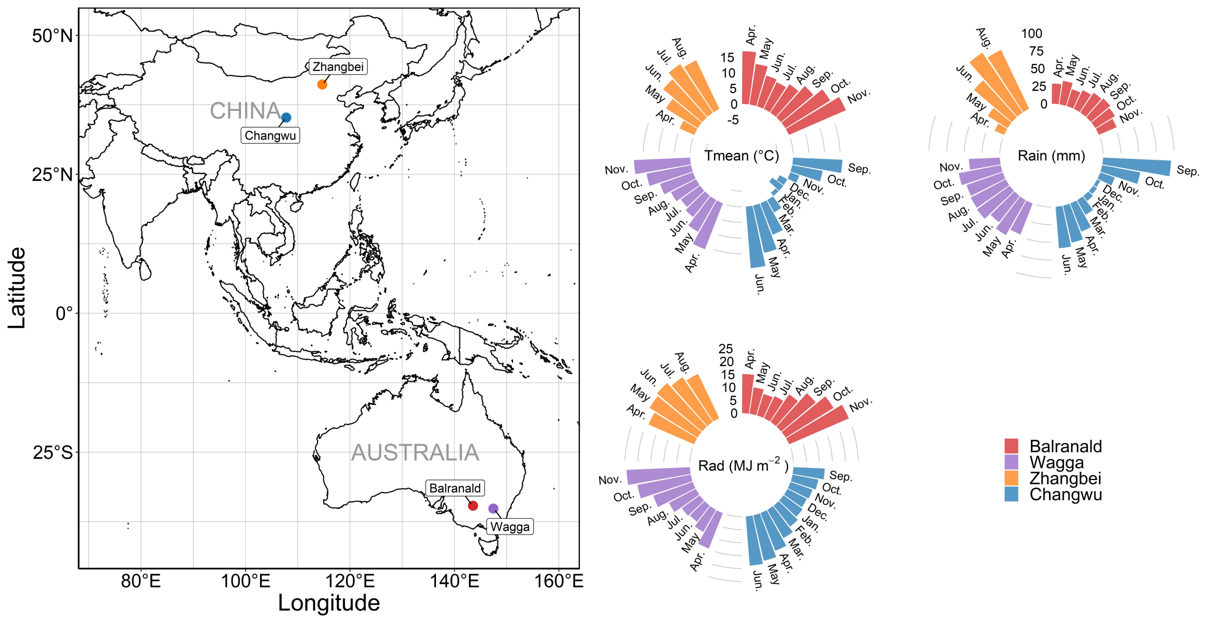
1 Supplementary Figures



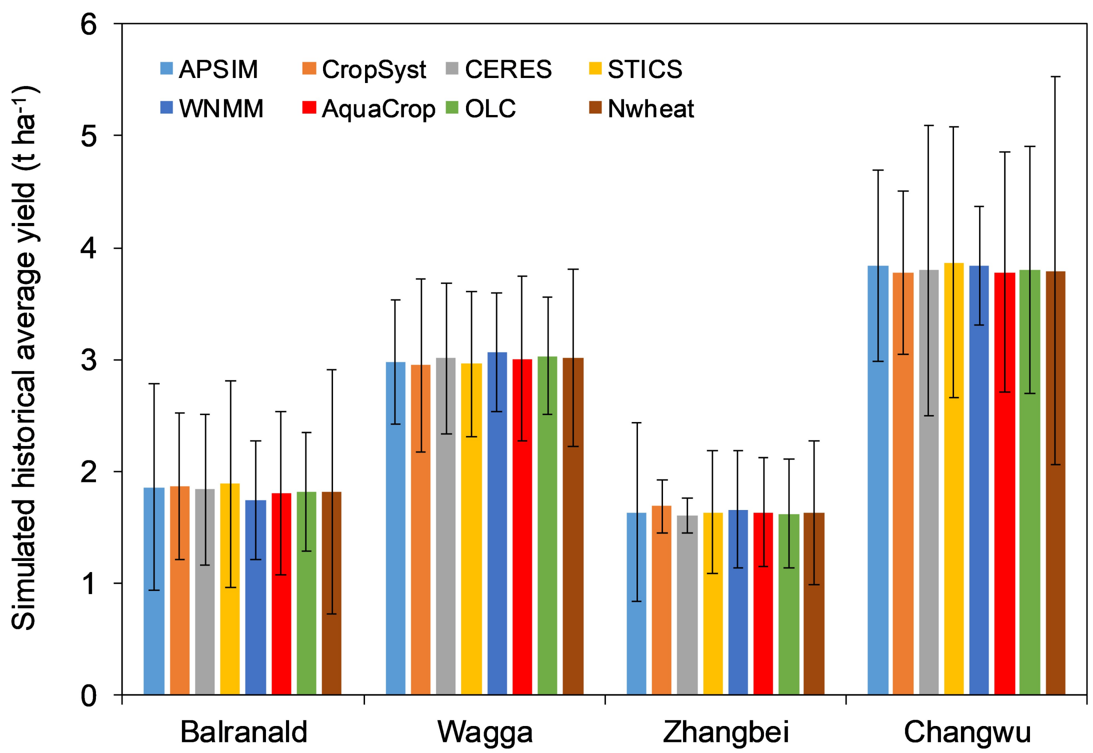
Supplementary Figure 1 Results of multiple linear regression of future yield change for each crop model, site and downscaling method (i.e. 32 GCMs × 4 climate scenarios = 128 data points for each analysis) against changes in growing season rainfall (ΔRain, %), solar radiation (ΔRad, %), mean temperature (ΔTmean, °C) and CO_2 concentration (ΔCO_2, per 100 ppm). Regression coefficients for R^2 values are shown for $\Delta Yield = a\Delta Rain + b\Delta Rad + c\Delta Tmean + d\Delta CO_2$. * denotes $p < 0.05$, ** denotes $p < 0.01$. The blue text shows results for ***SD*** and the red text results for ***CF***.



Supplementary Figure 2 The contribution of uncertainty made by individual global climate models (GCMs) by removing each of 32 GCMs from the ensemble of GCMs at four sites for both statistical downscaling (***SD***) and change factor (***CF***) methods. If the difference is positive, it means that a single GCM presents a positive contribution to the total uncertainty otherwise it has a negative contribution to the total uncertainty.



Supplementary Figure 3 Locations of the four study sites in northern China and south-eastern Australia and their corresponding growing season monthly mean temperature (Tmean, °C), rainfall (Rain, mm) and solar radiation (Rad, MJ m^{-2}).



Supplementary Figure 4 Mean average (column) and inter-annual variation (error bar) of wheat yield simulated for 1961-2000 from eight crop models at four sites.

2 Supplementary Tables

Supplementary Table 1 Pearson correlation coefficients between ***CF*** and ***SD*** downscaling methods for projected future growing season mean temperature, rainfall and radiation change at four study sites. Correlations are between 128 pairs of data (i.e. 32 GCMs × 4 climate scenarios). All correlation coefficients are significant ($p < 0.001$). The location "Wagga Wagga" is abbreviated here as "Wagga".

	Australia		China	
	Balranald	Wagga	Zhangbei	Changwu
Temperature	0.94	0.93	0.92	0.93
Rainfall	0.98	0.98	0.96	0.96
Radiation	0.77	0.83	0.98	0.86

Supplementary Table 2 The eight crop models used in this study.

ID	Model	Full name	Version	References	
1	APSIM	Agricultural Production Systems sIMulator	V7.7	Keating, et al. [1]	https://www.apsim.info/
2	AquaCrop	Aqua Crop	V6.1	Steduto, et al. [2]	http://www.fao.org/aquacrop
3	CropSyst	Cropping Systems Simulation Model	V4	Stockle, et al. [3]	http://modeling.bsyse.wsu.edu/CS_Suite_4/CropSyst/index.ht
4	DSSAT-CERES	Crop Environment Resource Synthesis (CERES) wheat model was integrated into the Decision Support System for Agro-technology (DSSAT)	V4.7	Jones, et al. [4]	http://dssat.net
5	DSSAT-Nwheat	Nitrogen wheat (Nwheat) model was integrated into the Decision Support System for Agro-technology (DSSAT)	V4.7	Kassie, et al. [5]	https://dssat.net/
6	OLC	OLEARY-CONNOR	V9	O'Leary, et al. [6]	gjoleary@yahoo.com
7	STICS	Multidisciplinary simulator for standard crops	V1.31	Brisson, et al. [7]	https://www6.paca.inra.fr/stics_eng/
8	WNMM	Water and Nitrogen Management Model	NSW DPI version	Li, et al. [8]	de.li.liu@dpi.nsw.gov.au or yli@isa.ac.cn

Supplementary Table 3 Collinearity diagnostics of input variables for regression analysis based on variance inflation factor. Generally, a VIF value of < 10 is the acceptable threshold for predictor independence in climate related studies.

Site	***SD***				***CF***			
	ΔRain	ΔRad	ΔTmean	ΔCO_2	ΔRain	ΔRad	ΔTmean	ΔCO_2
Balranald	1.88	8.49	27.30	19.40	1.58	4.10	44.75	33.63
Wagga	1.79	6.92	26.28	20.61	1.85	4.02	50.13	37.86
Zhangbei	2.73	1.11	12.51	13.58	2.93	1.29	19.14	17.62
Changwu	3.34	1.11	15.08	12.79	3.37	1.05	16.40	14.63

Supplementary Table 4 Pearson correlation coefficients between yield change projected by ***CF*** and ***SD*** for each crop model at four study sites. Correlations are between 128 pairs of data (i.e. 32 GCMs × 4 climate scenarios). All correlation coefficients are significant ($p < 0.001$).

	Australia		China	
	Balranald	Wagga	Zhangbei	Changwu
APSIM	0.96	0.83	0.81	0.79
AquaCrop	0.87	0.62	0.75	0.59
CERES	0.86	0.89	0.59	0.76
CropSyst	0.91	0.85	0.76	0.69
Nwheat	0.86	0.68	0.77	0.82
OLC	0.83	0.56	0.85	0.53
STICS	0.94	0.86	0.85	0.72
WNMM	0.89	0.76	0.72	0.47

Supplementary Table 5 A brief description of four locations used in our study. Growing season mean temperature, rainfall and solar radiation were calculated from observed data for 1961-2000. See main text for datasets used.

Site	Cultivar	Country	Latitude	Longitude	Elevation (m)	Wheat type	Average yield (t ha^{-1})	Growing season	Flowering time	Temperature (°C)	Rainfall (mm)	Radiation (MJ m^{-2})
Balranald	Axe	Australia	-34.64	143.56	65	Spring	1.8	Apr-Nov	Sep-Oct	13.8	245	15.0
Wagga	Yitpi	Australia	-35.16	147.46	212	Spring	3.0	Apr-Nov	October	12.0	421	14.2
Zhangbei	Yulan	China	41.15	114.70	1393	Spring	1.6	Apr-Aug	July	13.9	311	20.7
Changwu	Changhan-521	China	35.20	107.80	1186	Winter	3.8	Sep-Jun	May	7.1	371	12.4

Supplementary Table 6 Summary of various component processes of each crop model used in the study.

Model	Leaf area/light interception[a]	Light utilization[b]	Yield formation[c]	Phenology[d]	Root distribution over depth[e]	Environmental constraints involved[f]	Type of water stress[g]	Type of heat stress[h]	Water dynamics[i]	Evapotranspiration[j]	Soil CN-model[k]	Process modified by elevated CO2[l]
APSIM	S	RUE	Prt/Gn/B	T/DL/V/O	O	W/N/A	E	-	C/R	PT/PM	CN/P(3)/B	RUE/TE/CLN
AquaCrop	S	TE	HI/B	T/DL/V/O	EXP	W/N/H	E/S	V/R	C	PM	-	TE
CropCyst	S	TE/RUE	HI/B	T/DL/V	EXP	W/N/H	E	R	C/R	PM	N/P(4)	TE/RUE
DSSAT-CERES	S	RUE	B/Gn	T/DL/V	EXP	W/N	E/S	-	C	PT	CN/P(4)/B	RUE/TE
DSSAT-Nwheat	S	RUE	Prt	T/DL/V	EXP	W/N/A	S	V	C	PT	CN/P(3)/B	RUE/TE
OLC	S	TE/RUE	Gn/Prt	T/DL/O	O	W/N/A/H	E/S	V/R	C	P	CN/P(3)/B	TE/RUE/CLN
STICS	D	RUE	Gn/B	T/DL/V/O	SIG	W/N/H	E/S	V/R	C	P/PT/SW	CN/P(3)/B(2)	RUE/TE
WNMM	S	RUE	HI_mw	T/O	EXP	W/N/H	E/S	V/R	C	PM	CN/P(3)/B(2)	RUE

[a] S, simple approach (e.g. LAI); D, detailed approach (e.g. canopy layers).
[b] RUE, radiation use efficiency approach; TE, transpiration efficiency biomass growth.
[c] HI, fixed harvest index; B, total (above-ground) biomass; Gn, number of grains; Prt, partitioning during reproductive stages; HI_mw, harvest index modified by water stress.
[d] T, temperature; DL, photoperiod (day length); V, vernalization; O, other water/nutrient stress effects considered.
[e] LIN, linear, EXP, exponential, SIG, sigmoidal, Call, carbon allocation; O, other approaches.
[f] W, water limitation; N, N limitation; A, aeration deficit stress; H, heat stress.
[g] E, actual to potential evapotranspiration ratio; S, soil available water in root zone.
[h] V, vegetative organ (source); R, reproductive organ (sink).
[i] C, capacity approach; R, Richards approach (https://www.apsim.info/documentation/model-documentation/soil-modules-documentation/swim3/).
[j] P, Penman; PM, Penman-Monteith; PT, Priestley –Taylor; SW, Shuttleworth and Wallace (resistive model) [9].
[k] CN, CN model; N, N model; P(x), x number of organic matter pools; B, microbial biomass pool.
[l] RUE, radiation use efficiency; TE, transpiration efficiency; CLN, critical leaf N concentration.

Supplementary Table 7 The soil properties used for simulations at the four sites in our study.

Balranald					
Soil depth	Bulk density	Saturated water content	Drained upper limit	Permanent wilting point	Organic C
cm	g cm^{-3}		mm mm^{-1}		g kg^{-1}
0-15	1.50	0.38	0.23	0.12	10.0
15-30	1.50	0.39	0.29	0.12	5.0
30-60	1.40	0.44	0.35	0.25	2.5
60-90	1.45	0.43	0.35	0.25	1.0
90-120	1.50	0.41	0.35	0.25	1.0
120-150	1.55	0.40	0.35	0.25	1.0
Wagga					
Soil depth	Bulk density	Saturated water content	Drained upper limit	Permanent wilting point	Organic C
cm	g cm^{-3}		mm mm^{-1}		g kg^{-1}
0-10	1.55	0.38	0.24	0.12	12.3
10-20	1.55	0.39	0.22	0.10	6.2
20-40	1.50	0.40	0.24	0.12	3.1
40-60	1.50	0.40	0.34	0.12	1.5
60-90	1.55	0.40	0.34	0.12	0.8
90-120	1.55	0.40	0.34	0.12	0.8
120-150	1.55	0.40	0.34	0.12	0.8
Zhangbei					
Soil depth	Bulk density	Saturated water content	Drained upper limit	Permanent wilting point	Organic C
cm	g cm^{-3}		mm mm^{-1}		g kg^{-1}
0-30	1.38	0.40	0.31	0.11	6.4
30-60	1.36	0.41	0.33	0.12	4.9
60-80	1.36	0.39	0.30	0.11	4.9
80-100	1.39	0.41	0.34	0.13	3.9
100-150	1.39	0.43	0.35	0.14	2.7
Changwu					
Soil depth	Bulk density	Saturated water content	Drained upper limit	Permanent wilting point	Organic C
cm	g cm^{-3}		mm mm^{-1}		g kg^{-1}
0–10	1.27	0.51	0.28	0.11	8.5
10–20	1.27	0.52	0.28	0.10	7.3
20–30	1.35	0.47	0.28	0.07	6.3
30–40	1.35	0.49	0.29	0.12	6.3
40–50	1.30	0.48	0.29	0.11	5.5
50–60	1.30	0.48	0.29	0.11	5.5
60–80	1.25	0.47	0.29	0.11	5.8
80–100	1.25	0.54	0.27	0.09	5.8

Supplementary Table 8 Model settings for all crop models at four sites used in this study.

Study sites	Base cultivar	Sowing window	Sowing criteria[a]	Sowing fertiliser[b] (kg ha^{-1})	Reset date[c]	soil profile initial nitrogen[d] (kg ha^{-1})	Soil initial water[e]
Balranald	Axe	1 May–30 Jun	≥ 25 mm	60	1 Jan	20; 5	30%
Wagga	Yitpi	1 May–30 Jun	≥ 25 mm	60	1 Jan	20; 5	30%
Zhangbei	Yulan	20 Apr–10 May	≥ 10 mm	100	1 Jan	40; 15	55%
Changwu	Changhan-521	1 Sep–30 Sep	≥ 50 mm	120	1 Aug	60; 25	40%

[a] Cumulative rainfall in ten consecutive days. If the crop was not sown before the end of the sowing window, it was sown at the end of sowing window.
[b] Amount of nitrogen in fertiliser.
[c] Each simulation was reset on a specific date to exclude the "carry-over" effects from previous seasons and to provide typical starting conditions,
[d] Initial nitrate-N and ammonium-N on reset date.
[e] Percentage of maximum available water relative to lower limit of the soil on reset date.

Supplementary Table 9 Definition and values of adjusted parameter for four wheat cultivars at four locations used in the simulations with the APSIM model.

Cultivar parameters	Definition	Unit	Cultivar (Location)			
			Axe-1 (Balranald)	Yitpi-1 (Wagga)	Changhan-521-1 (Changwu)	Yulan-1 (Zhangbei)
tt_end_of_juvenile	Thermal time from sowing to end of juvenile	°C·day	400	400	400	450
tt_floral_initiation	Thermal time from floral initiation to flowering	°C·day	555	555	577	490
tt_start_grain_fill	Thermal time from start grain filling to maturity	°C·day	560	545	600	580
Grains_per_gram_stem	Kernel number per stem weight at the beginning of grain filling	g	25	25	25	23
Potential_grain_filling_rate	Potential daily grain filling rate	$g \cdot grain^{-1} \cdot day^{-1}$	0.0030	0.0020	0.0019	0.0020
Max_grain_size	Maximum grain size	g	0.041	0.041	0.041	0.043
Vern_sens	sensitivity to vernalization		2.0	1.5	2.8	0
Photop_sens	sensitivity to photoperiod		3.0	3.0	3.0	2.0

Supplementary Table 10 Definition and values of adjusted parameter for four wheat cultivars at four locations used in the simulations with the AquaCrop model.

Cultivar parameters and definition	Unit	Cultivar (Location)			
		Axe-1 (Balranald)	Yitpi-1 (Wagga)	Changhan-521-1 (Changwu)	Yulan-1 (Zhangbei)
GDDays: from sowing to maturity (length of crop cycle)	°C·day	1750	1950	2050	1950
GDDays: from sowing to flowering	°C·day	930	1100	1600	1130
GDDays: building-up of Harvest Index during yield formation	°C·day	880	1100	700	750
Water Productivity normalized for ETo and CO_2 (WP*)	g/m^2	31.0	38.5	40.5	18.5
Reference Harvest Index (HIo)	%	28	23	32	24

Supplementary Table 11 Definition and values of adjusted parameter for four wheat cultivars at four locations used in the simulations with the CropSyst model.

Cultivar parameters	Definition	Unit	Cultivar (Location)			
			Axe-1 (Balranald)	Yitpi-1 (Wagga)	Changhan-521-1 (Changwu)	Yulan-1 (Zhangbei)
flowering	Begin flowering	°C·day	830	900	1220	900
senescence	Begin senescence	°C·day	1030	1080	1450	1080
unstressed	Unstressed harvest index		0.24	0.28	0.40	0.35
translocation_max	Biomass translocation to grain faction		0.20	0.19	0.20	0.25
Kc	Canopy extinction coefficient for total (global) solar radiation		0.40	0.40	0.48	0.50
ET_crop_coef	Evapotranspiration crop coefficient at full canopy		1.4	1.4	1.4	1.05
water_productivity_veg	Water productivity during vegetative growth	BM/kg H_2O	15	15	17	13.5

Supplementary Table 12 Definition and values of adjusted parameter for four wheat cultivars at four locations used in the simulations with the DSSAT-CERES model.

Cultivar parameters	Definition	Unit	Cultivar (Location)			
			Axe-1 (Balranald)	Yitpi-1 (Wagga)	Changhan-521-1 (Changwu)	Yulan-1 (Zhangbei)
P1V	Days,optimum vernalizing temperature,required for vernalization	days	5.0	5.0	25.0	5.0
P1D	Photoperiod response	%	69.95	71.94	58.36	53.67
P5	Grain filling (excluding lag) phase duration	°C·day	337.1	671.1	379.0	438.3
G1	Kernel number per unit canopy weight at anthesis	$no.g^{-1}$	17.63	45.21	23.50	15.00
G2	Standard kernel size under optimum conditions	mg	28.84	65.79	45.93	57.03
G3	Standard,non-stressed mature tiller wt (incl grain)	g	1.486	1.987	1.640	2.100
PHINT	Interval between successive leaf tip appearances	°C·day	120	95	130	120
P1	Duration of phase end juvenile to terminal spikelet	°C·day	460	400	350	460
P2	Duration of phase terminal spikelet to end leaf growth	°C·day	380	300	400	380
P3	Duration of phase end leaf growth to end spike growth	°C·day	300	300	400	300
VEFF	Vernalization effect (Rate reduction when unvernalized		0.1	0.1	0.4	0.05
PARUE	PAR conversion to dm ratio, before last leaf stage	$g\ MJ^{-1}$	2.5	2.5	2.5	2.7
PARU2	PAR conversion to dm ratio, after last leaf	$g\ MJ^{-1}$	2.5	2.5	2.5	2.7
LAFR	Increase in potential area of leaves, reproductive phase		0.5	0.5	0.3	0.3
LSPHS	Final leaf senescence starts		5.3	5.3	5.5	5.7

Supplementary Table 13 Definition and values of adjusted parameter for four wheat cultivars at four locations used in the simulations with the DSSAT-Nwheat model.

Cultivar parameters	Definition	Unit	Cultivar (Location)			
			Axe-1 (Balranald)	Yitpi-1 (Wagga)	Changhan-521-1 (Changwu)	Yulan-1 (Zhangbei)
VSEN	Sensitivity to vernalization		1.5	1.5	3.5	1.5
PPSEN	Sensitivity to photoperiod		1.9	2.1	1.9	1.9
P5	Thermal time from beginning of grain filling to maturity	°C·day	600	630	670	600
PHINT	Phyllochron interval		95	95	95	90
GRNO	Coefficient of kernel number per stem weight at the beginning of grain filling		21	22	22	21
MXFIL	Potential kernel growth rate	mg $kernel^{-1}$ day^{-1}	2.0	2.0	2.3	2.0

Supplementary Table 14 Definition and values of adjusted parameter for four wheat cultivars at four locations used in the simulations with the OLC model.

Cultivar parameters	Definition	Unit	Cultivar (Location)			
			Axe-1 (Balranald)	Yitpi-1 (Wagga Wagga)	Changhan-521-1 (Changwu)	Yulan-1 (Zhangbei)
TH	critical water content below which emergence does not advance	g cm^{-3}	0.2	0.20	0.3	0.3
TL	relative available content below which LAI growth is reduced	(g cm^{-3}) (g $cm^{-3})^{-1}$	0.8	0.8	0.4	0.4
SL	optimal specific leaf nitrogen of canopy	g m^{-2}	2.7	2.5	2.3	3.1
T1	base temperature for emergence	ºC	3	3	0	0
T2	base temperature for stem extension	ºC	4	4	4	4

T3	base temperature for booting	ºC	4	4	4	4
T4	base temperature for anthesis	ºC	2	2	2	2
T5	base temperature for maturity – phase 1	ºC	8	8	4	4
T6	base temperature for maturity – phase 2	ºC	8	8	8	8
O1	optimum temperature for emergence	ºC	28	28	33	33
O2	optimum temperature for stem extension	ºC	28	28	33	33
O3	optimum temperature for booting	ºC	28	28	33	33
O4	optimum temperature for anthesis	ºC	28	28	33	33
O5	optimum temperature for maturity – phase 1	ºC	35	35	40	40
Z1	maximum temperature for emergence	ºC	35	35	40	40
D1	base daylength for booting photothermal time	h	0	0	0	0
D2	base daylength for anthesis photothermal time	h	6	6	6	6
TE	thermal time for emergence	ºCd	78	78	78	78
TA	thermal time for stem extension	ºCd	315	315	315	315
PB	photothermal time for booting	ºCdh	5500	5300	6800	6300
PA	photothermal time for anthesis	ºCdh	6700	6000	8100	9200
M1	thermal time for maturity phase 1	ºCd	550	480	680	500
M2	thermal time for maturity – phase 2	ºCd	550	480	680	500
FT	frost threshold temperature	ºC	0	0	-4	0
FD	frost damage to grain number	%	7.2	7.2	3.1	7.2
HT	heat threshold temperature	ºC	32	32	32	32
HD	heat damage to grain number	%	0.96	0.96	0.96	0.96
G1	grain number coefficient	# m^{-2}	2700	2200	6500	800
G2	grain number coefficient	# g^{-1}	1.051	1.051	1.93	1
GR	maximum grain growth rate	g d^{-1}	2	2	3.9	1.5
GS	maximum grain size	mg	50	50	60	40
GN	target maturity grain N concentration	g g^{-1}	0.0202	0.0192	0.03	0.015
GT	duration of grain N transfer to grain	ºCd	400	500	650	300
PR	maximum pre-anthesis biomass transfer to grain – proportion of biomass at anthesis	g g^{-1}	0.3	0.2	0.4	0.1

Supplementary Table 15 Definition and values of adjusted parameter for four wheat cultivars at four locations used in the simulations with the STICS model.

Cultivar parameters	Definition	Unit	Cultivar (Location)			
			Axe-1 (Balranald)	Yitpi-1 (Wagga)	Changhan-521-1 (Changwu)	Yulan-1 (Zhangbei)
stamflax	Cumulative thermal time between end of juvenile stage and end leaf growth	°C·day	375	375	475	375
stlevdrp	Cumulative thermal time between emergence and starting date of filling of harvested organs	°C·day	500	590	510	590
stdrpmat	Cumulative thermal time between starting date of filling of harvested organs and maturity	°C·day	500	500	590	550
kmax	Maximum crop coefficient for water requirements		2.7	2.7	2.5	2.7
pgrainmaxi	Maximum grain weight	g	0.027	0.015	0.040	0.020
vitircarb	Rate of increase of the C harvest index vs time	g grain·g^{-1}·d^{-1}	0.01050	0.01070	0.01070	0.00870
jvcmini	Minimum number of vernalising days	d	-	-	7.0	-
tfroid	Optimal temperature for vernalisation	°C	-	-	2.0	-
ampfroid	Semi thermal amplitude for vernalising effect	°C	-	-	10.0	-

Supplementary Table 16 The definition and values of adjusted parameter for four wheat cultivars at four locations used in the simulations with the WNMM model.

Cultivar parameters and definition	Unit	Cultivar (Location)			
		Axe-1 (Balranald)	Yitpi-1 (Wagga)	Changhan-521-1 (Changwu)	Yulan-1 (Zhangbei)
RUE (Radiation use efficiency, based on PAR)	G $MJ^{-1}m^{-2}$	0.75	0.9	1.225	0.6
HI (Harvest index)	%	40	42	45	40
BLAI (Maximum leaf area index (m^2 leaf area m^{-2} unit of land)	m^2 m^{-2}	5.21	6	5	5
CNyld (N fraction in grains)	%	2.25	2.25	2.5	2.25
WAVP (Declining rate in RUE /vapor pressure deficit)	%	4	6	4	4

Supplementary Table 17 List of 32 global climate models (https://pcmdi.llnl.gov/mips/cmip5/availability.html) used in this study.

Name of GCM	Abbr	Institute ID	Country
ACCESS1-0	AC1	CSIRO and BoM	Australia
ACCESS1-3	AC2	CSIRO and BoM	Australia
BCC-CSM1-1	BC1	BCC	China
BCC-CSM1-1-m	BC2	BCC	China
BNU-ESM	BNU	GCESS	China
CanESM2	CaE	CCCMA	Canada
CCSM4	CCS	NCAR	USA
CESM1-BGC	CE1	NSF-DOE-NCAR	USA
CESM1-CAM5	CE2	NSF-DOE-NCAR	USA
CESM1-WACCM	CE5	NSF-DOE-NCAR	USA
CMCC-CM	CM2	INGV CMCC	Italy
CMCC-CMS	CM3	INGV CMCC	Italy
CSIRO-Mk3-6-0	CSI	CSIRO-QCCCE	Australia
EC-EARTH	ECE	EC-EARTH	Europe
FIO-ESM	FIO	FIO	China
GISS-E2-H	GE1	NASA GISS	USA
GISS-E2-H-CC	GE2	NASA GISS	USA
GISS-E2-R	GE3	NASA GISS	USA
GFDL-CM3	GF2	NOAA GFDL	USA
GFDL-ESM2G	GF3	NOAA GFDL	USA
GFDL-ESM2M	GF4	NOAA GFDL	USA
HadGEM2-AO	Ha5	NIMR/KMA	Korea
INM-CM4	INC	INM	Russia
IPSL-CM5A-MR	IP2	IPSL	France
IPSL-CM5B-LR	IP3	IPSL	France
MIROC5	MI2	MIROC	Japan
MIROC-ESM	MI3	MIROC	Japan
MIROC-ESM-CHEM	MI4	MIROC	Japan
MPI-ESM-LR	MP1	MPI-M	Germany
MRI-CGCM3	MR3	MRI	Japan
NorESM1-M	NE1	NCC	Norway
NorESM1-ME	NE2	NCC	Norway

3 Supplementary Methods

Crop model settings

Cultivar selection was site-specific. “Base” wheat cultivars were chosen based on local climate conditions and experiment records (Yitpi, Axe, Changhan-521 and Yulan for Wagga, Balranald, Changwu and Zhangbei respectively). The cultivar parameters for all crop models were adjusted so the baseline yields achieved a mean yield (1961-2000) with an accuracy of 0.1 t ha^{-1} compared to the observed yields for the cultivars grown at the respective locations.

The conditions under which wheat was sown in the simulations are summarised in Supplementary Table 8. A sowing window was defined at each site. Wheat was sown every year the first time after the start of the sowing window that rainfall accumulated over ten consecutive days exceeded a site-specific threshold, or when the end of the sowing window was reached. Sowing density was 120 plants m^{-2}, at a depth of 3 cm with row spacing being 250 mm for all four sites. A site-specific amount of nitrogen fertiliser was applied at sowing (Supplementary Table 8). To exclude “carry-over” effects from previous seasons and to provide typical starting conditions, in all simulations, soil profile mineral nitrogen (nitrate and ammonium) content and soil water content were reset on 1st of January for spring wheat at Balranald, Wagga and Zhangbei. As winter wheat was harvested in June or July next year at Changwu, simulations were reset on 1st of August. At all four sites, wheat residues were set each year to 1 t/ha with a carbon : nitrogen ratio of 80.

The adjusted parameter values for the resultant variants of the base cultivars are given in Supplementary Tables 9-16.

Atmospheric CO_2 concentrations

For the baseline 1961-2000 simulations, the atmospheric CO_2 concentration was set to 350 ppm. For RCP4.5, the atmospheric CO_2 concentration was calculated after Wang, et al. [10] by

$$[CO_2]_{year} = 650.18 + \frac{0.000075326*y-0.16276}{0.00022299 \ \frac{727.97}{y^2}} - 0.00018747 * (y-2045)^3 \qquad (1)$$

For RCP8.5, it was fitted by:

$$[CO_2]_{year} = 1034.3 + \frac{267.78-1.6188*y}{4.0143+\frac{53.342}{y^{5.2822}}} + 21.746 * \left(\frac{y-2010}{100}\right)^3 + 100.65 * \left(\frac{y-191}{100}\right)^3 \qquad (2)$$

Collinearity test

The VIF (variance inflation factor) is a frequently used index for collinearity detection [11-13] in regression analyses. It measures the inflation in the variance of estimates of a parameter due to collinearities that exist among the predictors. Small VIF values indicate high independence of the predictors. In general, a VIF value of < 10 is an acceptable threshold to regard predictors as being independent in climate related studies [14-16]. In our study, growing season mean temperature and CO_2 concentration for both ***CF*** and ***SD*** showed significant collinearity (i.e. VIF > 10) (Supplementary Table 2).

4 Supplementary References

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