Supplementary Information for

Efficient agronomic practices narrow yield gaps and alleviate climate change impacts on winter wheat production in China

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Supplementary Tables

Supplementary Table 1. Fundamental information about the 3-year field experiments conducted at 22 different sites in the three main winter wheat producing regions (the Huang-Huai-Hai, South China, and Xinjing) of China.

Main region	Experimental sites	Longitude (°)	Latitude (°)	Elevation (m)	Wheat cultivar	Sowing time (mm/dd)	Seeding density (plant·m^2)	Irrigation		Fertilizer	
								Times	Depth (mm)	Times	Nitrogen rate (kg·ha^{-1})
Huang-Huai-Hai	Laizhou, Shandong,	120.0	37.4	5	*jimai22*	10/08	225-300	2-3	150-225	2	210-349
	Linzi, Shandong,	118.3	37.0	16	*jimai22*	10/18	270-330	2-3	150-247	2	210-349
	Shangshui, Henan,	114.5	33.5	40	*zhoumai27*	11/07	240-450	1-2	90-180	1-2	456-692
	Wuqiao, Hebei,	116.6	37.7	17	*jimai22*	10/15	525	2	150	2	210-789
	Xiangfu, Henan,	114.6	34.7	65	*zhoumai27*	10/15	240-450	1-2	90-180	1-2	456-689
	Shijiazhuang, Hebei,	114.4	37.5	50	*jimai22*	10/05	450	2-3	120-225	2	456-865
	Yuanyang, Henan,	114.0	35.1	73	*jimai22/zhoumai27*	10/15	544-780	1	75	1-2	264-349
	Qihe, Shandong,	116.5	36.7	26	*jimai22*	10/08-11/07	270-330	1-3	75-225	2	210-360
	Yanzhou, Shandong,	116.8	35.6	49	*jimai22*	10/21	300	1-2	90-180	2	375-590
Southern China	Huaiyuan, Anhui,	116.9	33.1	24	*genetype1*	10/22	270	-	-	1-2	210-270
	Changfeng, Anhui,	117.1	32.4	30	*genetype1*	11/14	300	-	-	1-2	273-389
	Guannan,Jiangsu,	119.3	34.2	1	*genetype2*	10/27-10/28	240-451	-	-	1-3	600-870
	Gaoyou, Jiangsu,	119.6	32.9	1	*genetype2*	11/15	150-300	-	-	4	240-300
	Xinghua, Jiangsu,	120.0	33.1	1	*genetype2*	12/11	300-390	-	-	4	240-300
	Yangzhou, Jiangsu,	119.4	32.4	9	*genetype2*	11/16	150-300	-	-	4	240-300
	Jintan, Jiangsu,	119.5	31.7	4	*genetype2*	11/05	153-222	-	-	1-3	90-200
	Jinzhou, Hubei,	112.1	30.4	34	*genetype2*	11/05-11/07	225	-	-	2-3	90-113
	Guanghan, Sichuan,	104.4	31.0	466	*genetype3*	11/01-11/07	262-472	-	-	2	159-233
	Tongling, Anhui,	117.7	30.9	6	*genetype1*	11/05	300	-	-	2	273-389

	Qitai, Xinjiang,	44.0	90.0	766	*xindong36*	9/27	479	6	375	4	189-416
Xinjiang	Zepu, Xinjiang,	38.2	77.3	1256	*xindong60*	10/06	590-631	6	405	3-4	288-541
	Junhu, Xinjiang,	43.6	87.0	715	*xindong41*	9/25	519	6	375	4	156-416

Supplementary Table 2. Locations of the reference weather stations and corresponding experimental sites involved in this study.

NO	**County, Province**	**Longitude (°)**	**Latitude (°)**	**Elevation (m)**	**Main region**	**Reference site**	**Representative wheat cultivar**
1	Xuchang, Henan	113.9	34.0	67	Huang-Huai-Hai	HNSS	*zhoumai27*
2	Shangqiu, Henan	115.7	34.5	50	Huang-Huai-Hai	HNLK	*zhoumai27*
3	Kaifeng, Henan	114.3	34.8	74	Huang-Huai-Hai	HNLK	*zhoumai27*
4	Xingtai, Hebei	114.5	37.1	77	Huang-Huai-Hai	HBLC	*jimai22*
5	Yanzhou, Shandong	116.9	35.6	52	Huang-Huai-Hai	SDYZ	*jimai22*
6	Huimin, Shandong	117.5	37.5	12	Huang-Huai-Hai	SDNJ	*jimai22*
7	Raoyang, Hebei	115.7	38.2	19	Huang-Huai-Hai	SDNJ	*jimai22*
8	Suining, Jiangsu	117.9	33.9	24	Huang-Huai-Hai	SDYZ	*jimai22*
9	Xinxiang, Henan	113.9	35.3	73	Huang-Huai-Hai	HNYY	*zhoumai27*
10	Weifang, Shandong	119.2	36.8	22	Huang-Huai-Hai	SDGR	*jimai22*
11	Mengjin, Henan	112.4	34.8	333	Huang-Huai-Hai	HNYY	*zhoumai27*
12	Pucheng, Shanxi	109.6	35.0	500	Huang-Huai-Hai	HNYY	*zhoumai27*
13	Yiyuan, Shandong	118.2	36.2	305	Huang-Huai-Hai	SDGR	*jimai22*
14	Pingdong, Shandong	119.9	36.8	49	Huang-Huai-Hai	SDLZ	*jimai22*
15	Bazhou, Hebei	116.4	39.1	9	Huang-Huai-Hai	SDNJ	*jimai22*
16	Haiyang, Shandong	121.2	36.8	41	Huang-Huai-Hai	SDLZ	*jimai22*
17	Linfen, Shanxi	111.5	36.1	450	Huang-Huai-Hai	HNYY	*zhoumai27*
18	Changwu, Shanxi	107.8	35.2	1207	Huang-Huai-Hai	HNYY	*zhoumai27*
19	Jinan, Shandong	117.1	36.6	170	Huang-Huai-Hai	SDCP	*jimai22*
20	Miyun, Beijing	116.9	40.4	72	Huang-Huai-Hai	SDNJ	*jimai22*
21	Shangzhou, Shanxi	110.0	33.9	742	Huang-Huai-Hai	HNYY	*zhoumai27*
22	Houma, Shanxi	111.4	35.7	434	Huang-Huai-Hai	HNYY	*zhoumai27*
23	Wugong, Shanxi	108.2	34.3	448	Huang-Huai-Hai	HNYY	*zhoumai27*
24	Tangshan, Hebei	118.2	39.7	28	Huang-Huai-Hai	SDNJ	*jimai22*
25	Juxian, Shandong	118.8	35.6	107	Huang-Huai-Hai	SDGR	*jimai22*
26	Rizhao, Shandong	119.5	35.4	37	Huang-Huai-Hai	SDGR	*jimai22*
27	Kongtong, Gansu	106.7	35.6	1347	Huang-Huai-Hai	HNYY	*zhoumai27*
28	Jixian, Shanxi	110.7	36.1	954	Huang-Huai-Hai	HNYY	*zhoumai27*
29	Wuqi, Shanxi	108.2	36.9	1331	Huang-Huai-Hai	HBLC	*jimai22*
30	Guyuan, Ningxia	106.3	36.0	1753	Huang-Huai-Hai	HNYY	*zhoumai27*
31	Tianjin, Tianjin	117.1	39.1	3	Huang-Huai-Hai	SDNJ	*jimai22*
32	Shenmu, Shanxi	110.4	38.8	941	Huang-Huai-Hai	HBLC	*jimai22*
33	Xiangyuan, Shanxi	113.0	36.5	879	Huang-Huai-Hai	HBLC	*jimai22*
34	Xifengzhen, Gansu	107.6	35.7	1421	Huang-Huai-Hai	HNYY	*zhoumai27*
35	Suide, Shanxi	110.2	37.5	930	Huang-Huai-Hai	HBLC	*jimai22*
36	Taigu, Shanxi	112.5	37.4	783	Huang-Huai-Hai	HBLC	*jimai22*
37	Xixia, Henan	111.5	33.3	250	Huang-Huai-Hai	HNSS	*zhoumai27*
38	Xixian, Shanxi	111.0	36.7	1053	Huang-Huai-Hai	HBLC	*jimai22*
39	Lueyang, Shanxi	106.2	33.3	794	Huang-Huai-Hai	HNSS	*zhoumai27*

40	Nanyang, Henan	112.6	33.0	129	Southern China	HBJZ	*genetype2*
41	Bangbu, Anhui	117.4	33.0	19	Southern China	AHHY	*genetype1*
42	Bozhou, Anhui	115.8	33.9	38	Southern China	AHHY	*genetype1*
43	Guanyun, Jiangsu	119.2	34.3	5	Southern China	JSGN	*genetype2*
44	Shuyang, Jiangsu	118.8	34.1	9	Southern China	JSGN	*genetype2*
45	Dafeng, Jiangsu	120.5	33.2	7	Southern China	JSXH	*genetype2*
46	Suining, Sichuan	105.6	30.5	355	Southern China	SCGH	*genetype3*
47	Nantong, Jiangsu	120.9	32.0	6	Southern China	JSJT	*genetype2*
48	Dingyuan, Anhui	117.7	32.5	77	Southern China	AHCF	*genetype1*
49	Maanshan, Anhui	118.5	31.7	20	Southern China	JSJT	*genetype2*
50	Gushi, Henan	115.6	32.2	43	Southern China	AHCF	*genetype1*
51	Wuxi, Jiangsu	120.3	31.6	11	Southern China	JSJT	*genetype2*
52	Tongbai, Henan	113.4	32.4	149	Southern China	HBJZ	*genetype2*
53	Ningguo, Anhui	119.0	30.6	89	Southern China	JSJT	*genetype2*
54	Jingzhou, Hubei	112.2	30.4	32	Southern China	HBJZ	*genetype2*
55	Xiaogan, Hubei	114.0	30.9	26	Southern China	HBJZ	*genetype2*
56	Suizhou, Hubei	113.4	31.7	98	Southern China	HBJZ	*genetype2*
57	Nanxian, Hunan	112.4	29.4	36	Southern China	HBJZ	*genetype2*
58	Wenjiang, Sichuan	103.8	30.7	539	Southern China	SCGH	*genetype3*
59	Dawu, Hubei	114.1	31.6	72	Southern China	HBJZ	*genetype2*
60	Yibin, Sichuan	104.6	28.8	341	Southern China	SCGH	*genetype3*
61	Xuyong, Sichuan	105.4	28.2	378	Southern China	SCGH	*genetype3*
62	Wanzhou, Zhongqing	108.4	30.8	187	Southern China	HBJZ	*genetype2*
63	Hanzhong, Shanxi	107.0	33.1	510	Southern China	SCGH	*genetype3*
64	Qimen, Anhui	117.7	29.9	139	Southern China	AHTL	*genetype1*
65	Panxian, Guizhou	104.5	25.7	1800	Southern China	SCGH	*genetype3*
66	Ankang, Shanxi	109.0	32.7	291	Southern China	HBJZ	*genetype2*
67	Huoshan, Anhui	116.3	31.4	68	Southern China	AHCF	*genetype1*
68	Hangzhou, Zhejiang	120.2	30.2	42	Southern China	JSJT	*genetype2*
69	Huishui, Guizhou	106.7	26.2	989	Southern China	SCGH	*genetype3*
70	Tongling, Anhui	117.8	31.0	38	Southern China	AHTL	*genetype1*
71	Daxian, Sichuan	107.5	31.2	345	Southern China	SCGH	*genetype3*
72	Zhengan, Guizhou	107.5	28.6	680	Southern China	SCGH	*genetype3*
73	Wanyuan, Sichuan	108.0	32.1	674	Southern China	SCGH	*genetype3*
74	Zhongxiang, Hubei	112.6	31.2	66	Southern China	HBJZ	*genetype2*
75	Qianjiang, Zhongqing	108.8	29.5	609	Southern China	HBJZ	*genetype2*
76	Wuan, Jiangxi	115.1	29.3	77	Southern China	AHTL	*genetype1*
77	Zhenba, Shanxi	107.9	32.5	694	Southern China	SCGH	*genetype3*
78	Atushi, Xinjiang	76.2	39.7	1299	Xinjiang	XJZP	*xindong60*
79	Maigaiti, Xinjiang	77.6	38.9	1179	Xinjiang	XJZP	*xindong60*
80	Hetian, Xinjiang	79.9	37.1	1375	Xinjiang	XJZP	*xindong60*
81	Akesu, Xinjiang	80.2	41.2	1104	Xinjiang	XJZP	*xindong60*
82	Aletai, Xinjiang	88.1	47.7	735	Xinjiang	XJML	*xindong36*

Supplementary Table 3. Definitions and estimated values of the genetic parameters in the DSSAT-CERES-Wheat model for different representative winter wheat varieties involved in this study.

Parameter	Definition	**Different representative wheat varieties**							
		jimai22	*zhoumai27*	*genetype1*	*genetype2*	*genetype3*	*xindong36*	*xindong41*	*xindong60*
P1V	Days, optimum vernalizing temperature, required for vernalization (d)	57.0	57.0	55.0	55.0	55.0	55.0	25.0	55.0
P1D	Photoperiod response (% reduction in rate/10h drop in pp) (%)	120.0	120.0	105.0	109.0	107.0	175.0	25.0	147.0
P5	Grain filling (excluding lag) phase duration (℃·d)	685.0	625.0	785.0	735.0	640.0	640.0	520.0	700.0
G1	Kernel number per unit canopy weight at anthesis (# g^{-1})	27.00	15.00	16.50	31.50	40.00	40.24	49.79	14.88
G2	Standard kernel size under optimum conditions (mg)	42.70	43.50	42.50	26.70	75.73	17.70	80.00	51.00
G3	Standard, non-stressed mature tiller weight (incl grain) (g)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
PHINT	Interval between successive leaf tip appearances (℃·d)	95.0	95.0	95.0	83.0	95.0	95.0	50.0	108.0

Supplementary Table 4. List of the 27 global climate models (GCMs) used in this study to project daily weather data under the future climate emission scenarios of SSP245 and SSP585.

No	Name	Abbreviation	Institute	Country
1	ACCESS-CM2	ACC1	CSIRO-ACCESS	Australia
2	ACCESS-ESM1-5	ACC2	CSIRO-ACCESS	Australia
3	BCC-CSM2-MR	BCCC	BCC	China
4	CanESM5	Can1	CCCma	Canada
5	CanESM5-CanOE	Can2	CCCma	Canada
6	CIESM	CIES	THU	China
7	CMCC-CM2-SR5	CMCS	CMCC	Italy
8	CNRM-CM6-1	CNR2	CNRM-CERFACS	France
9	CNRM-CM6-1-HR	CNR3	CNRM-CERFACS	France
10	CNRM-ESM2-1	CNR1	CNRM-CERFACS	France
11	EC-Earth3	ECE1	EC-EARTH-Consortium	Europe
12	EC-Earth3-Veg	ECE2	EC-EARTH-Consortium	Europe
13	FGOALS-g3	FGOA	CAS	China
14	GFDL-CM4	GFD1	NOAA-GFDL	USA
15	GFDL-ESM4	GFD2	NOAA-GFDL	USA
16	GISS-E2-1-G	GISS	NASA-GISS	USA
17	HadGEM3-GC31-LL	HadG	MOHC	UK
18	INM-CM4-8	INM1	INM	Rusia
19	INM-CM5-0	INM2	INM	Rusia
20	IPSL-CM6A-LR	IPSL	IPSL	France
21	MIROC6	MIR1	MIROC	Japan
22	MIROC-ES2L	MIR2	MIROC	Japan
23	MPI-ESM1-2-HR	MPI1	MPI-M	Germany
24	MPI-ESM1-2-LR	MPI2	MPI-M	Germany
25	MRI-ESM2-0	MTIE	MRI	Japan
26	NESM3	NESM	NUIST	China
27	UKESM1-0-LL	UKES	MOHC	UK

Supplementary Table 5. Average yields and yield gaps during the baseline period of 1961-2020, and under two scenarios of SSP245 and SSP585 in future periods of 2040s and 2080s in the three main winter-wheat producing regions (i.e., Huang-Huai-Hai, Southern China, and Xinjiang) of China.

Main region	Period	Scenarios	Yield ($t{\cdot}ha^{-1}$)					Yield Gap ($t{\cdot}ha^{-1}$)			
			BSF	**FP**	**HEP**	**HYP**	**YP**	**YG-3**	**YG-2**	**YG-1**	**YG-0**
Huang-Huai-Hai	1961-2020		5.3	7.1	7.3	7.9	11.5	1.8	0.2	0.6	3.5
	2021-2060	SSP245	5.9	8.5	8.6	9.3	12.7	2.6	0.0	0.7	3.4
	(2040s)	SSP585	6.0	8.8	8.9	9.7	13.3	2.8	0.1	0.8	3.6
	2061-2100	SSP245	6.1	9.3	9.4	10.2	14.3	3.1	0.1	0.8	4.1
	(2080s)	SSP585	6.4	10.3	10.8	11.6	15.9	3.9	0.5	0.9	4.2
Southern China	1961-2020		3.2	5.7	6.5	6.8	8.6	2.4	0.8	0.3	1.8
	2021-2060	SSP245	3.4	6.2	7.2	7.5	9.3	2.8	1.0	0.3	1.8
	(2040s)	SSP585	3.5	6.3	7.3	7.7	9.7	2.8	1.0	0.4	2.0
	2061-2100	SSP245	3.7	6.5	7.7	8.0	10.5	2.9	1.1	0.4	2.5
	(2080s)	SSP585	3.8	6.8	8.1	8.5	11.7	3.0	1.3	0.4	3.2
Xinjiang	1961-2020		3.0	7.4	7.4	8.1	9.6	4.4	0.0	0.6	1.5
	2021-2060	SSP245	3.2	8.4	8.5	9.3	11.4	5.2	0.1	0.8	2.1
	(2040s)	SSP585	3.2	8.6	8.7	9.6	11.9	5.3	0.2	0.9	2.3
	2061-2100	SSP245	3.2	8.6	8.9	9.9	12.5	5.4	0.2	1.0	2.6
	(2080s)	SSP585	3.2	9.1	9.6	11.2	14.1	5.9	0.5	1.6	2.9

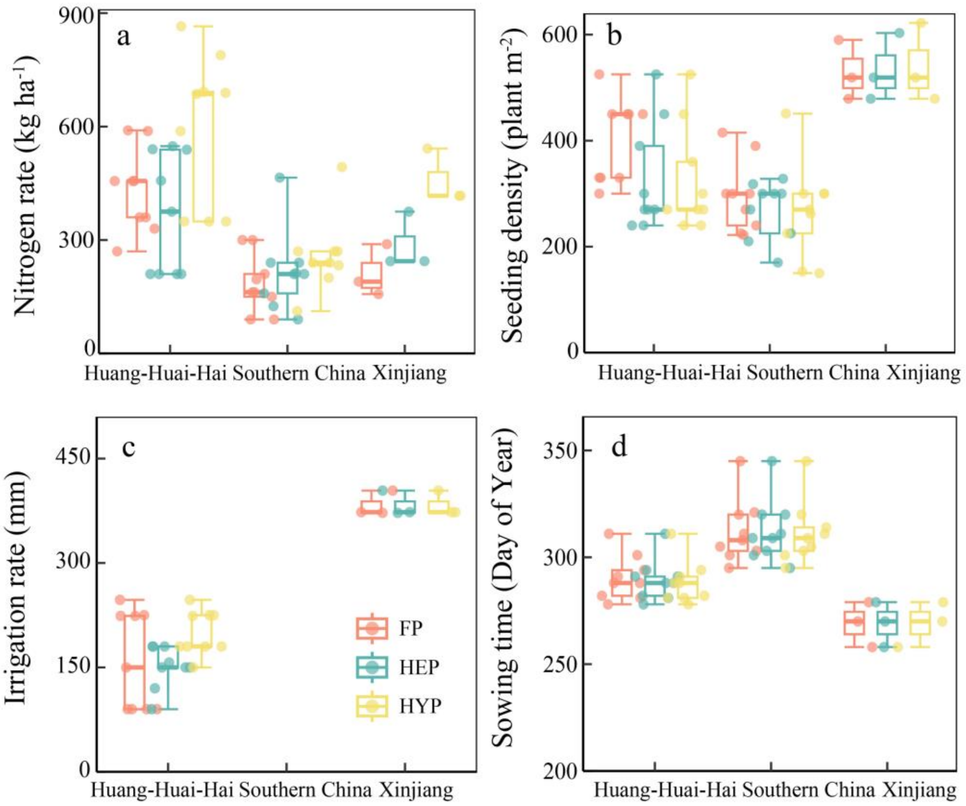
Notes: This study defined five different yield levels (Yield potential, YP; High-yield practice, HYP; High-efficiency practice, HEP; Farmer practice, FP; Basic soil fertility, BSF) and four different yield gaps of YG-0 (yield gap between the ‘YP’ and ‘HYP’ yield levels), YG-1(yield gap between the ‘HYP’ and ‘HEP’ yield levels), YG-2 (yield gap between the ‘HEP’ and ‘FP’ yield levels), and YG-3 (yield gap between the ‘FP’ and ‘BSF’ yield levels).

Supplementary Table 6. Average NAE (Nitrogen agronomic efficiency) and WUE_i (Irrigation water use efficiency) during the baseline period of 1961-2020, and under two scenarios of SSP245 and SSP585 in future periods of 2040s and 2080s in the three main winter-wheat producing regions (i.e., Huang-Huai-Hai, Southern China, and Xinjiang) of China.

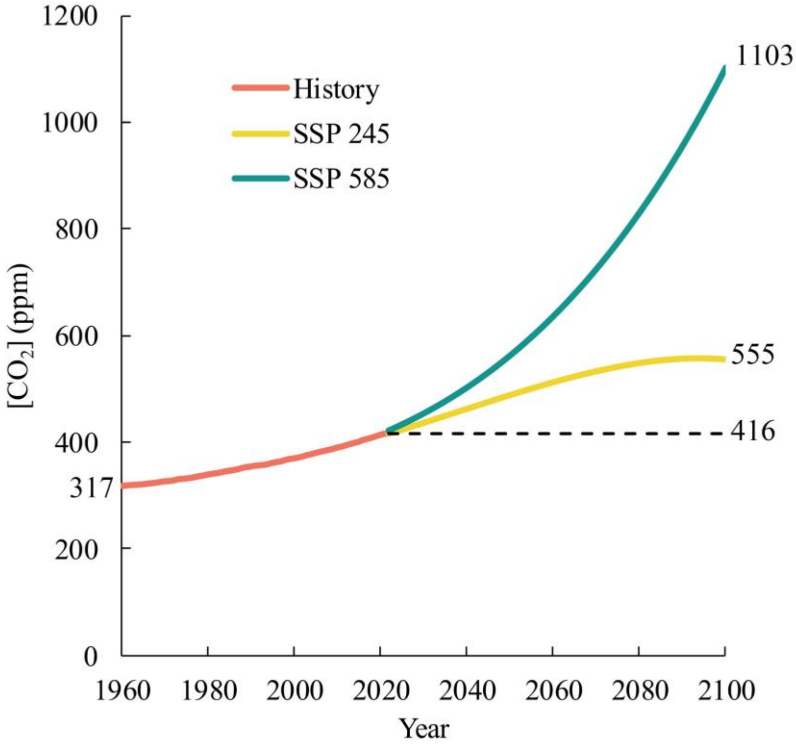
Main region	**Period**	**Scenarios**	**NAE ($kg \cdot kg^{-1}$)**			**WUE_i ($kg \cdot m^{-1}$)**		
			FP	**HEP**	**HYP**	**FP**	**HEP**	**HYP**
Huang-Huai-Hai	1961-2020		4.1	5.1	4.3	5.8	5.2	4.3
	2021-2060	SSP245	6.0	6.7	5.4	7.1	5.9	5.0
	(2040s)	SSP585	6.5	7.3	5.8	7.4	6.2	5.2
	2061-2100	SSP245	7.2	8.3	6.4	7.7	6.5	5.5
	(2080s)	SSP585	8.9	11.3	8.0	8.7	7.5	6.3
Southern China	1961-2020		18.6	23.2	18.6	-	-	-
	2021-2060	SSP245	20.9	25.5	20.4	-	-	-
	(2040s)	SSP585	21.1	25.8	20.7	-	-	-
	2061-2100	SSP245	21.4	26.3	21.2	-	-	-
	(2080s)	SSP585	21.8	26.6	21.5	-	-	-
Xinjiang	1961-2020		15.9	12.3	9.6	1.8	1.8	1.9
	2021-2060	SSP245	18.4	14.6	11.5	2.0	2.0	2.2
	(2040s)	SSP585	19.0	15.2	12.1	2.0	2.1	2.3
	2061-2100	SSP245	19.4	15.7	12.7	2.1	2.1	2.4
	(2080s)	SSP585	20.9	17.6	15.2	2.2	2.3	2.7

Notes: This study included three winter-wheat yield levels of HYP (High-yield practice), HEP (High-efficiency practice), and FP (Farmer practice).

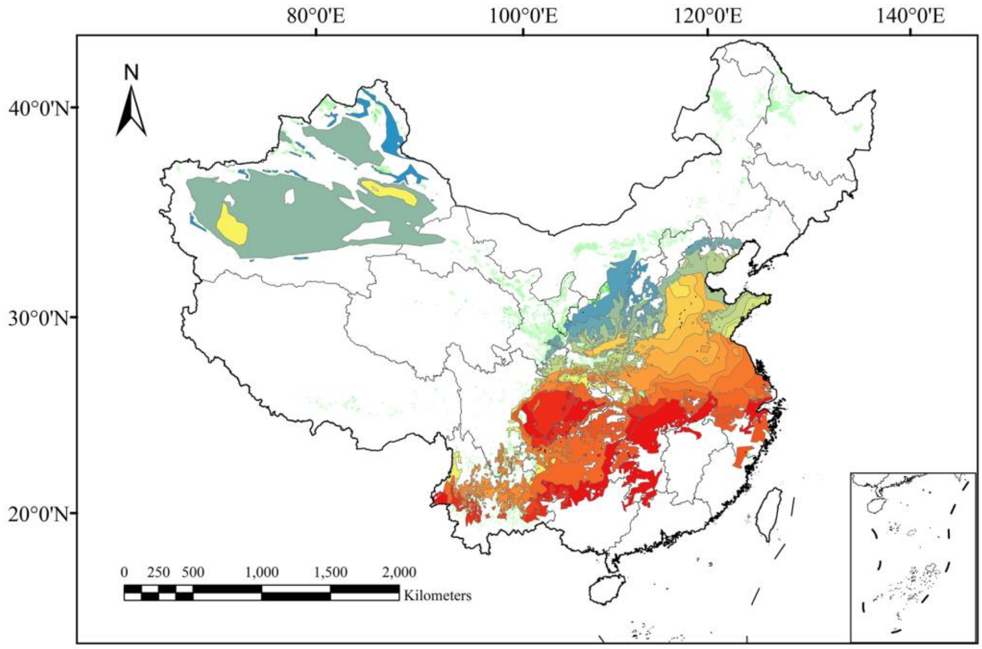
Supplementary Figures



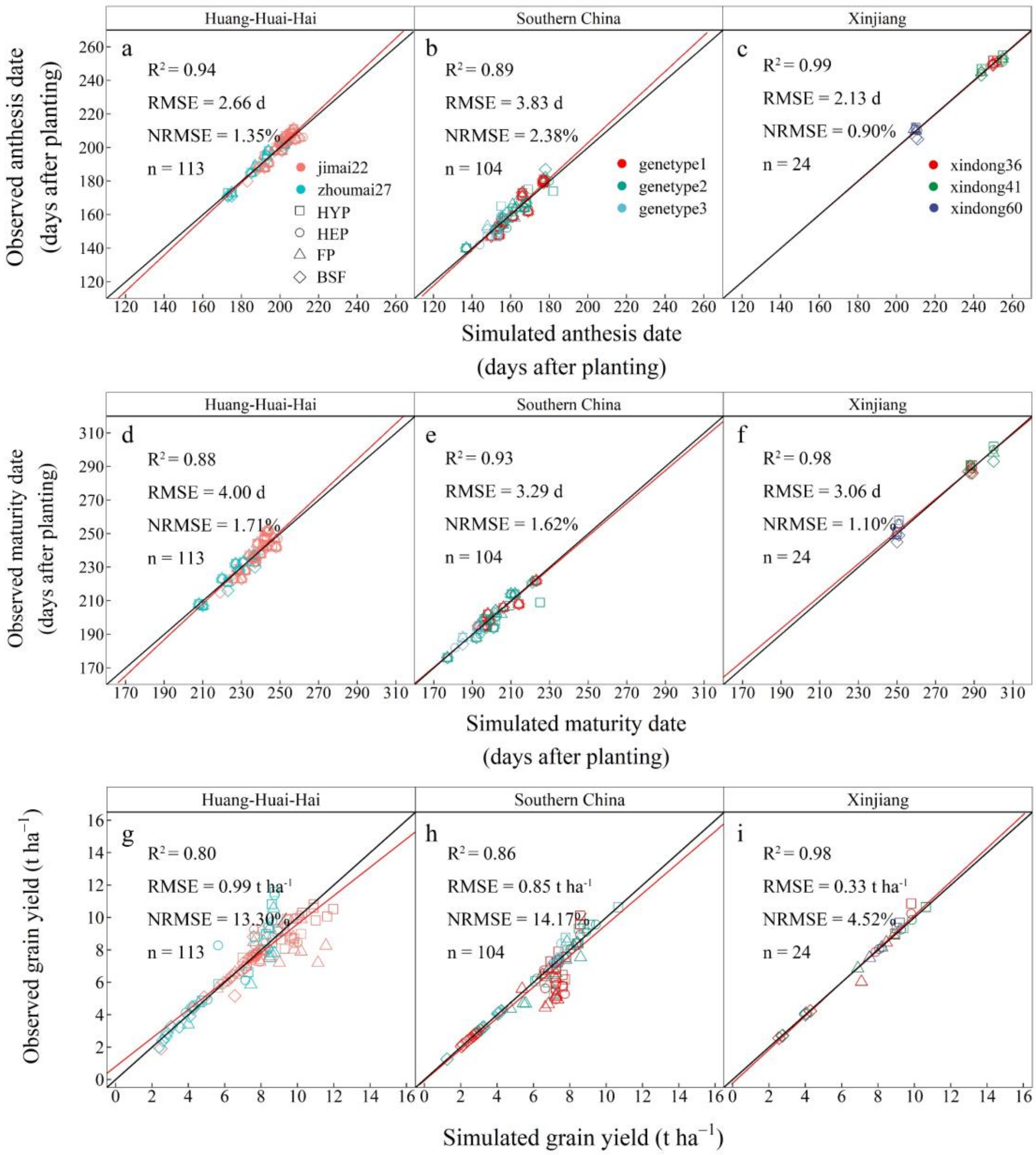
Supplementary Figure 1. Efficient agronomic practices of HYP (High-yield practice) and HEP (High-efficiency practice), and normal agronomic practice level of FP (Farmer practice) in the field experiments for the different winter-wheat cultivation systems of wheat-maize rotation in the Huang-Huai-Hai region, wheat-rice rotation in the Southern region, and drip-irrigated wheat production in the Xinjiang region in China.



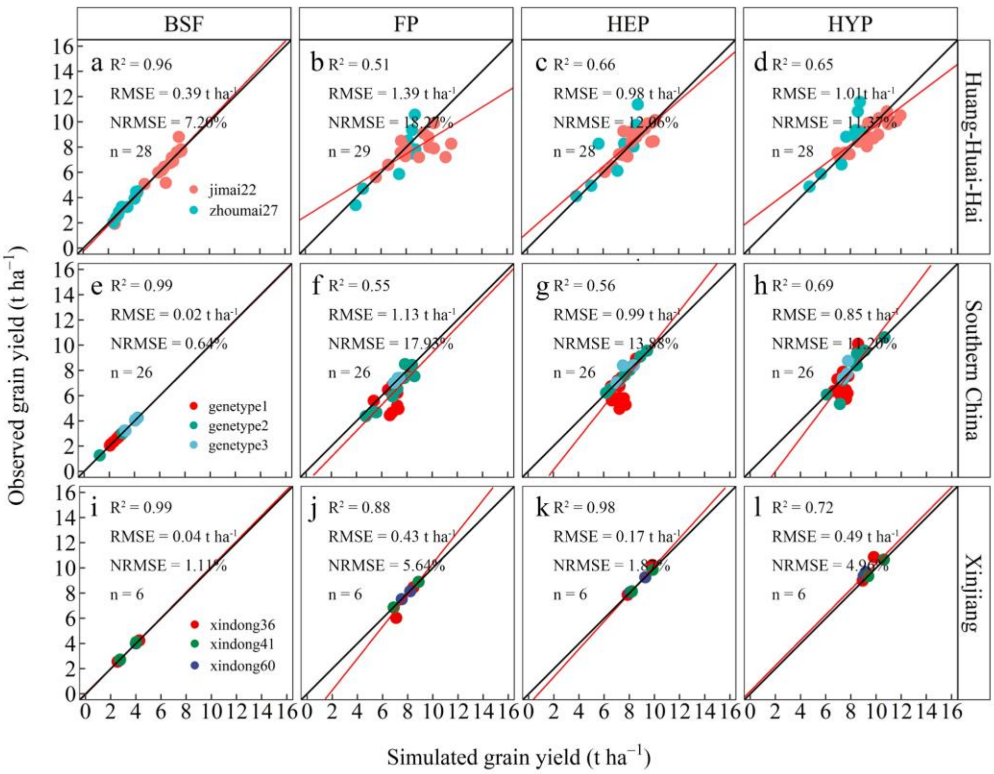
Supplementary Figure 2. [CO_2] pathways for the SSP245 and SSP585 scenarios in the CMIP6 (Coupled Model Intercomparison Project Phase 6).



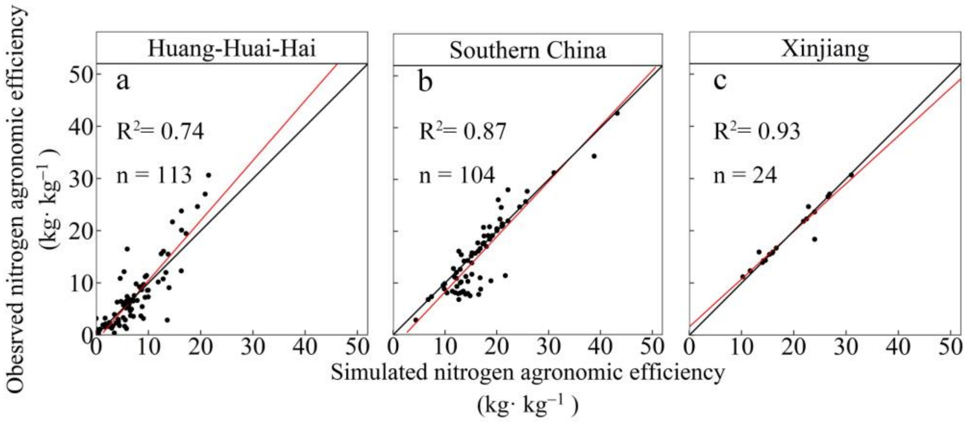
Supplementary Figure 3. Selected climate zones in the three main winter-wheat producing regions (Huang-Huai-Hai, Southern China, and Xinjiang) in China. The colors ranging from red to blue represent the transition from cooler to warmer climate. This study selected a total of 26 different climate zones (CZs) that covered about 89% of the total winter-wheat growing areas in China.



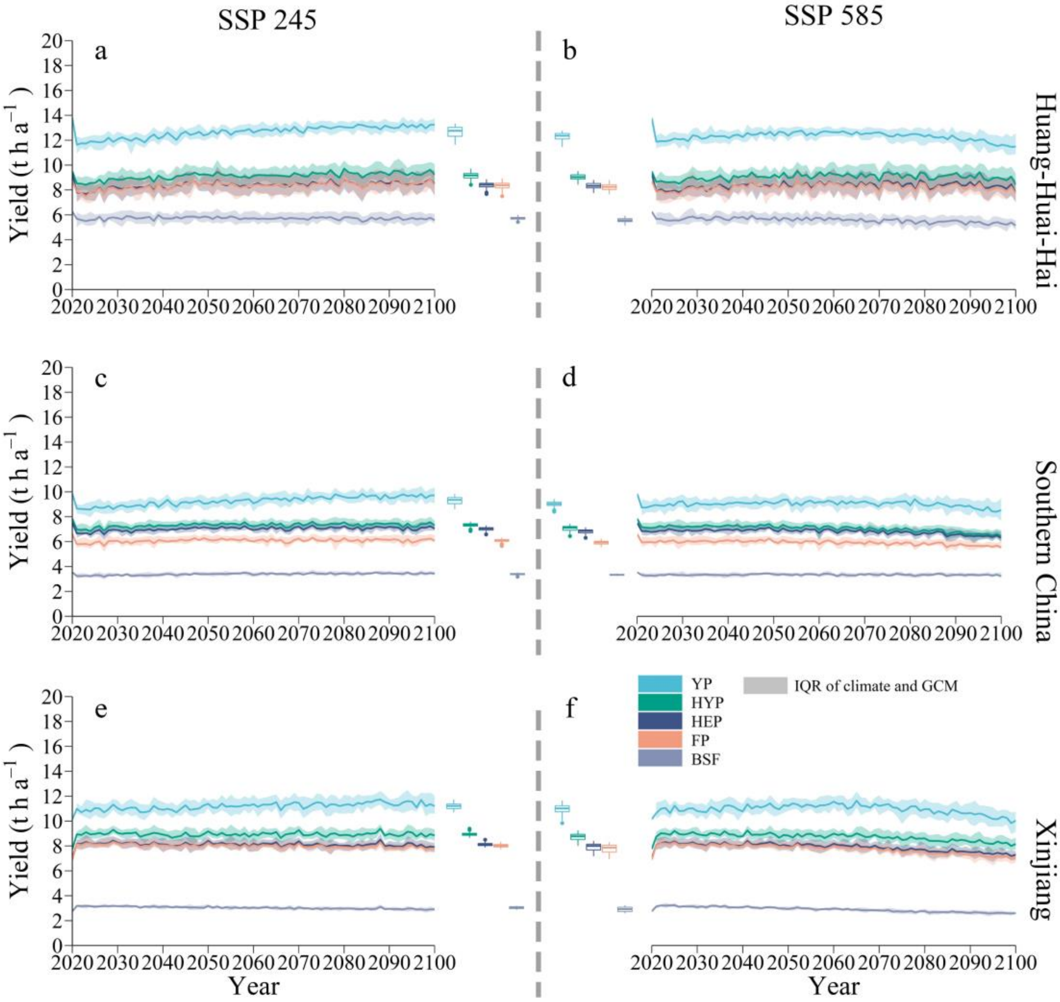
Supplementary Figure 4. Validation results of the DSSAT-CERES-wheat model based on the comparisons between simulated and observed anthesis dates (a-c), maturity dates (d-f), and per-unit grain yields (g-i) in the three main winter wheat producing regions (Huang-Huai-Hai, Southern China and Xinjiang) in China. Observation data were obtained from the field experiments involved in this study. Black and red lines in each subplot are the 1:1 line and the linear regression line, respectively. And the same below.



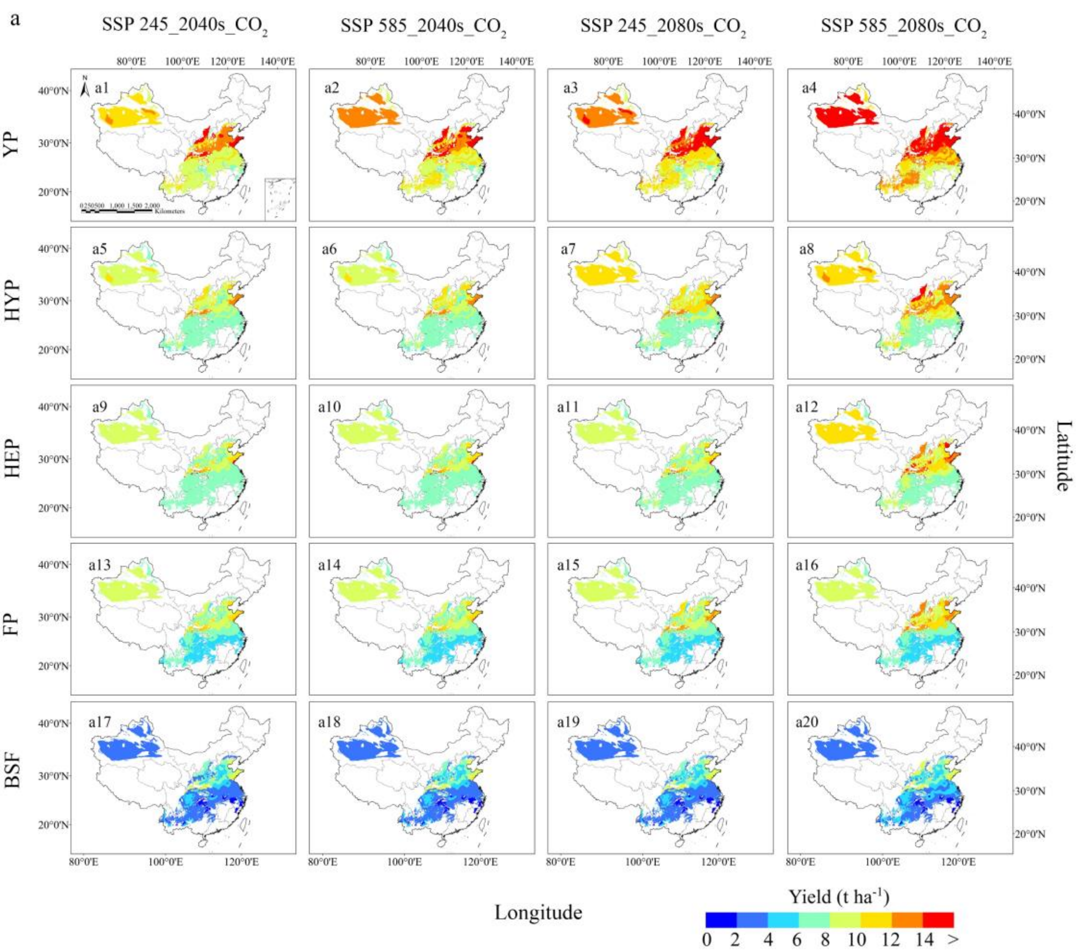
Supplementary Figure 5. Validation results of the DSSAT-CERES-Wheat model for the simulations of per-unit grain yields under different agronomic practices of YP (‘Yield potential’), HYP (‘High-yield practice’), HEP (‘High-efficiency practice’), FP (‘Farmer practice’), and BSF (‘Basic soil fertility’) in the three main winter-wheat producing regions (Huang-Huai-Hai, a-d; Southern China, e-h; and Xinjiang, i-l) in China.

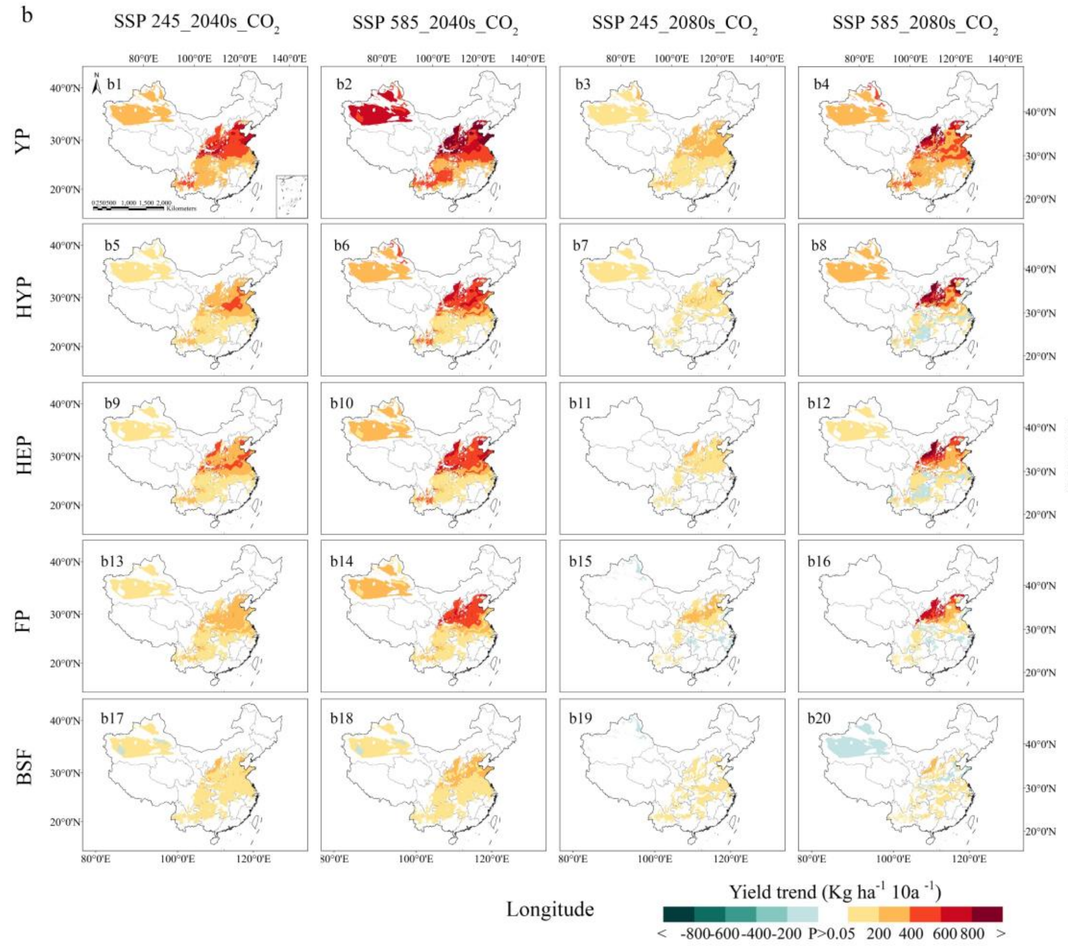


Supplementary Figure 6. Validation results of the DSSAT-CERES-wheat model for the simulations of nitrogen agronomic efficiency (NAE) in the three main winter-wheat producing regions (Huang-Huai-Hai, a; Southern China, b; and Xinjiang, c) in China.

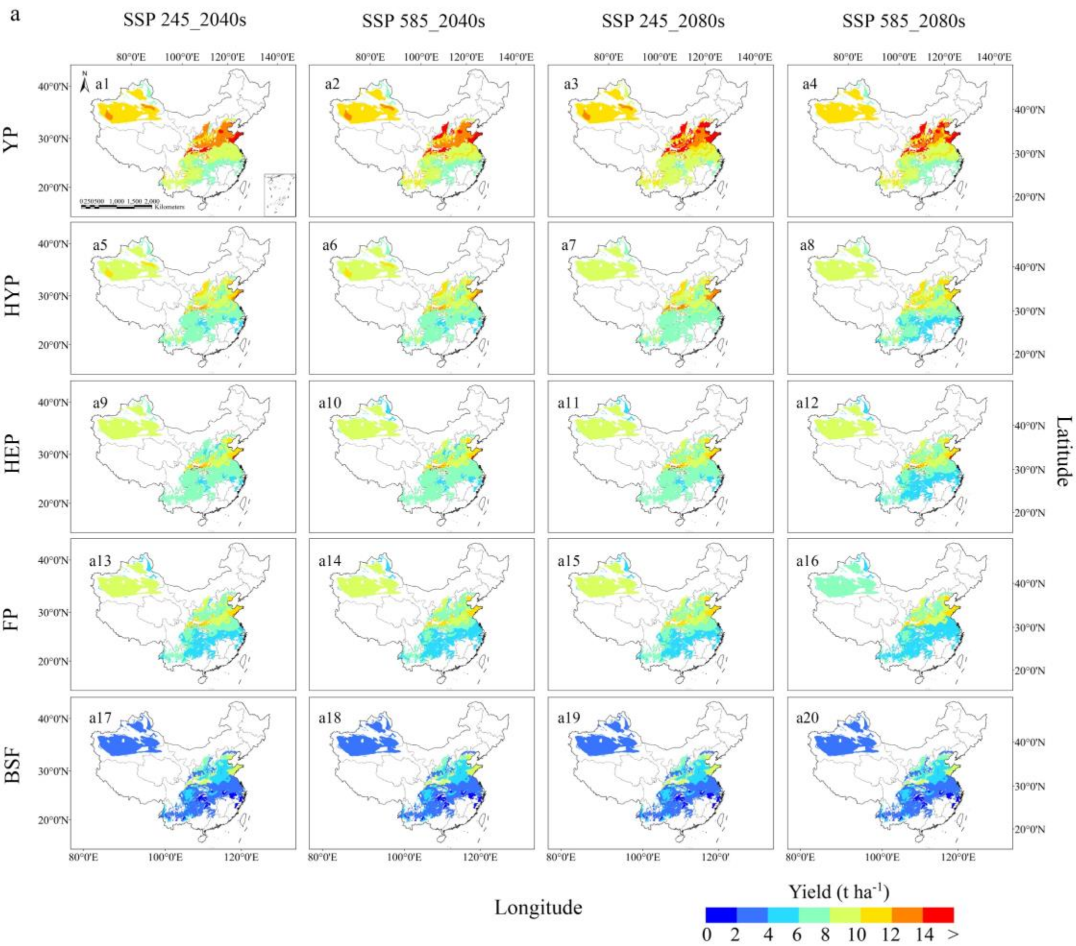


Supplementary Figure 7. Projected trends of winter wheat yiels at different yield levels of YP ('Yield potential'), HYP ('High-yield practice'), HEP ('High-efficiency practice'), FP ('Farmer practice'), and BSF ('Basic soil fertility') with stable [CO_2] (416 ppm) in the three main winter wheat producing regions (Huang-Huai-Hai, a-b; Southern China, c-d; and Xinjiang, e-f) in China in period of 2021-2100 under the SSP245 (a, c, e) and SSP585 (b, d, f) scenarios. Shaded ranges illustrate the interquartile range (IQR) of the winter wheat yields simulated based on projected future climatic data derived from all of the 27 GCMs (global climate models). The solid lines show the mean response curves. Box boundaries indicate the 25th and 75th percentiles; the line within the box marks the median; whiskers below and above the box indicate the 10th and 90th percentiles, respectively. And the same below.


a
SSP 245_2040s_CO2
SSP 585_2040s_CO2
SSP 245_2080s_CO2
SSP 585_2080s_CO2
YP
HYP
HEP
FP
BSF
a1
a2
a3
a4
a5
a6
a7
a8
a9
a10
a11
a12
a13
a14
a15
a16
a17
a18
a19
a20
80°0'E
100°0'E
120°0'E
140°0'E
40°0'N
30°0'N
20°0'N
Latitude
Longitude
Yield (t ha-1)
0 2 4 6 8 10 12 14 >



Supplementary Figure 8. Projected per-unit yields (a) and yield trends (b) of winter wheat in the periods of 2040s (2021-2060) and 2080s (2061-2100) under the SSP245 and SSP585 scenarios in China. The data were the mean projection values based on the future climatic data derived from the 27 selected global climate models (GCMs). All values were reported on a per-harvest basis and were then mapped at the spatial scale of climate zone. Note that there may be several climate zones within areas showing the similar current farm yield, and thus having the same color in these figures.


a
SSP 245_2040s
SSP 585_2040s
SSP 245_2080s
SSP 585_2080s
YP
HYP
HEP
FP
BSF
a1
a2
a3
a4
a5
a6
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a9
a10
a11
a12
a13
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a15
a16
a17
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a19
a20
Latitude
Longitude
Yield (t ha-1)
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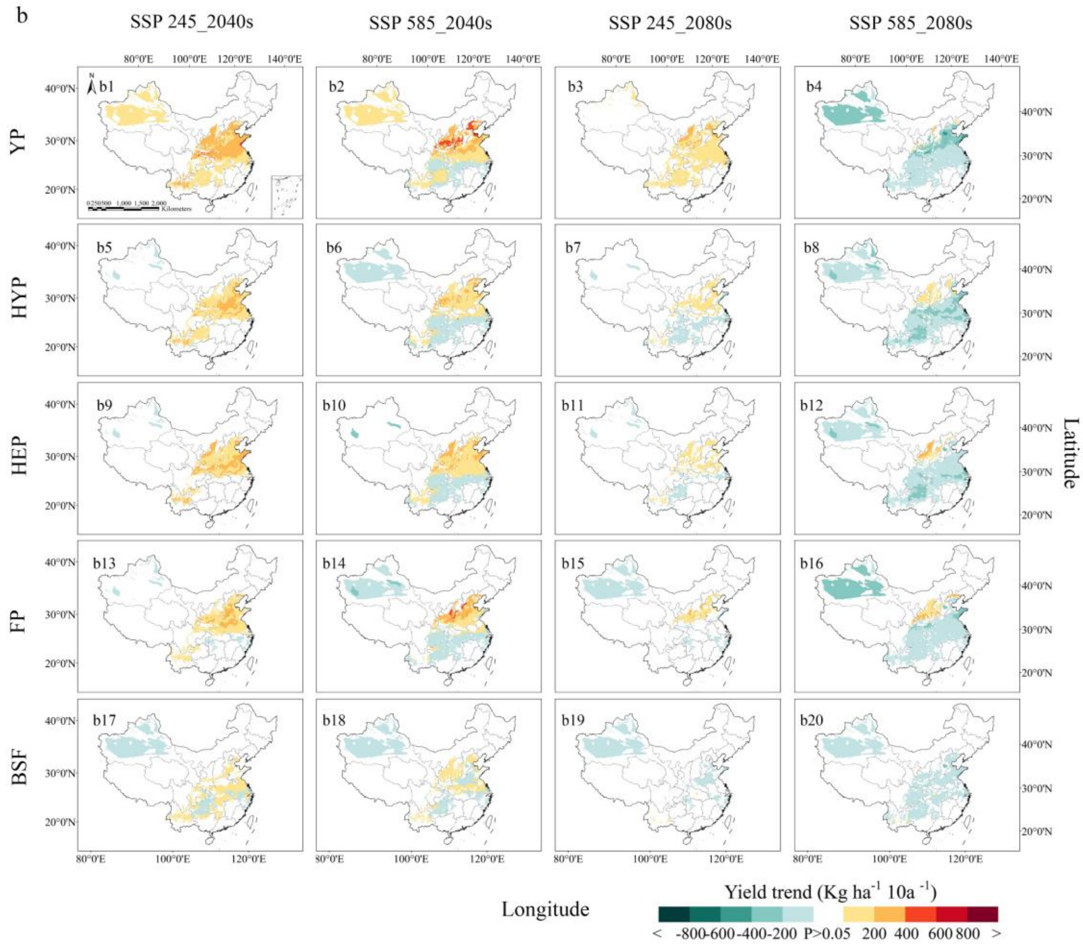
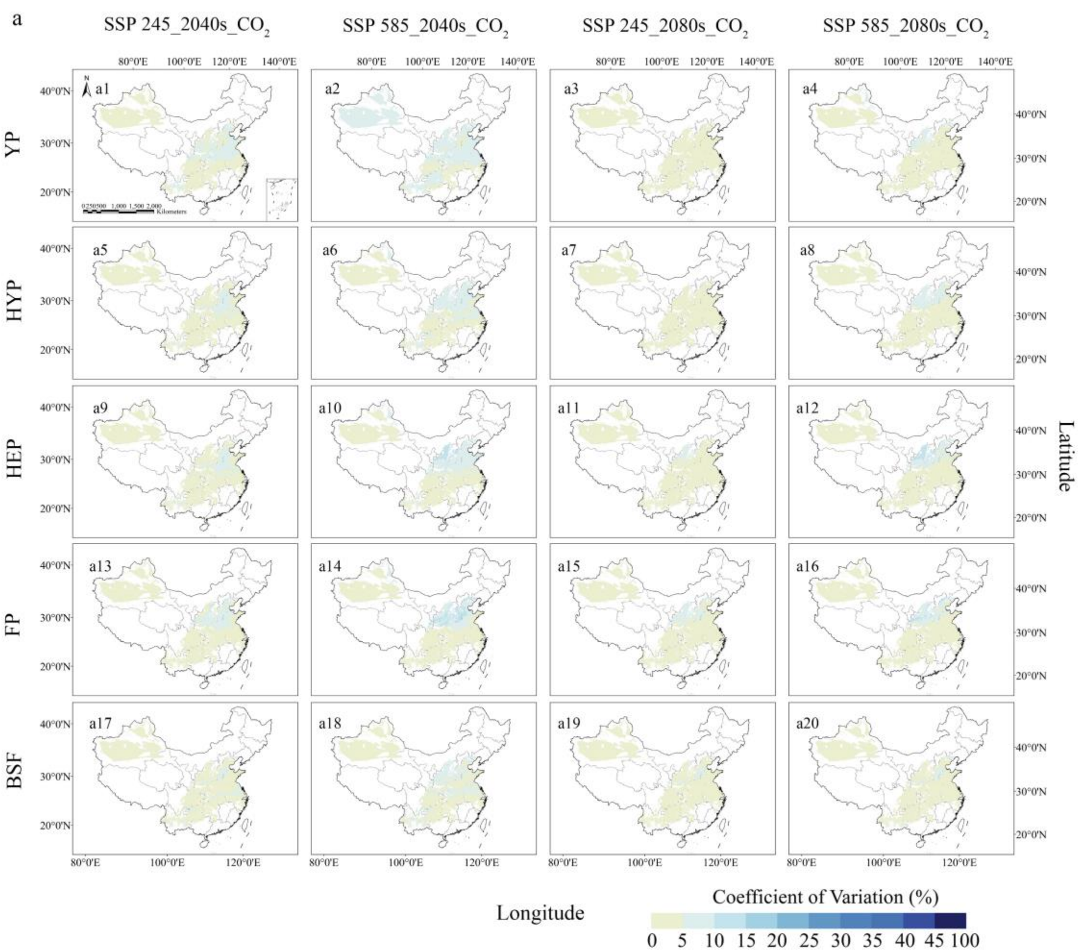
80°0'E
100°0'E
120°0'E
140°0'E
20°0'N
30°0'N
40°0'N



Supplementary Figure 9. Projected per-unit yields (a) and yield trends (b) of winter wheat in the periods of 2040s (2021-2060) and 2080s (2061-2100) under the SSP245 and SSP585 scenarios with stable [CO_2] (416 ppm) in China. The data were the mean projection values based on the future climatic data derived from the 27 selected global climate models (GCMs). All values were reported on a per-harvest basis and then were mapped at the spatial scale of climate zone. Note that there may be several climate zones within areas showing the similar current farm yield, and thus having the same color in these figures.


a
SSP 245_2040s_CO2
SSP 585_2040s_CO2
SSP 245_2080s_CO2
SSP 585_2080s_CO2
YP
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BSF
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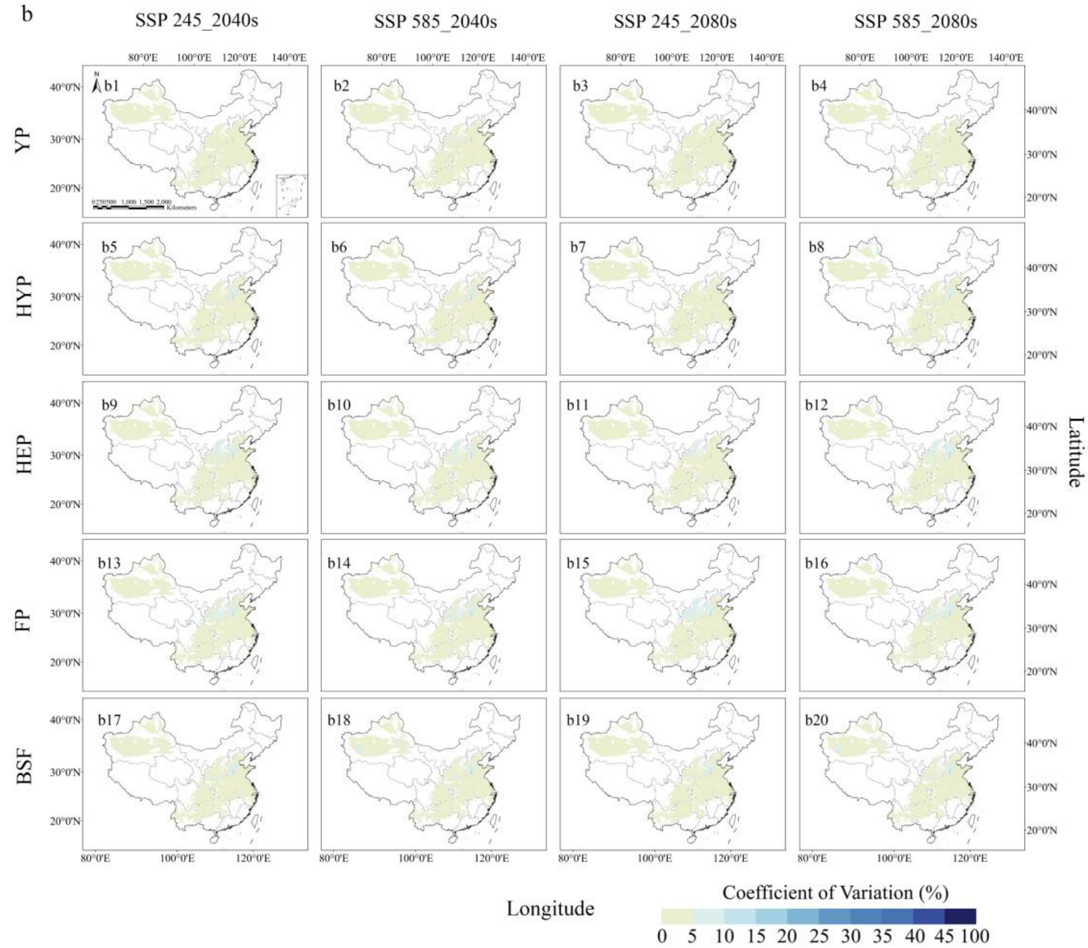
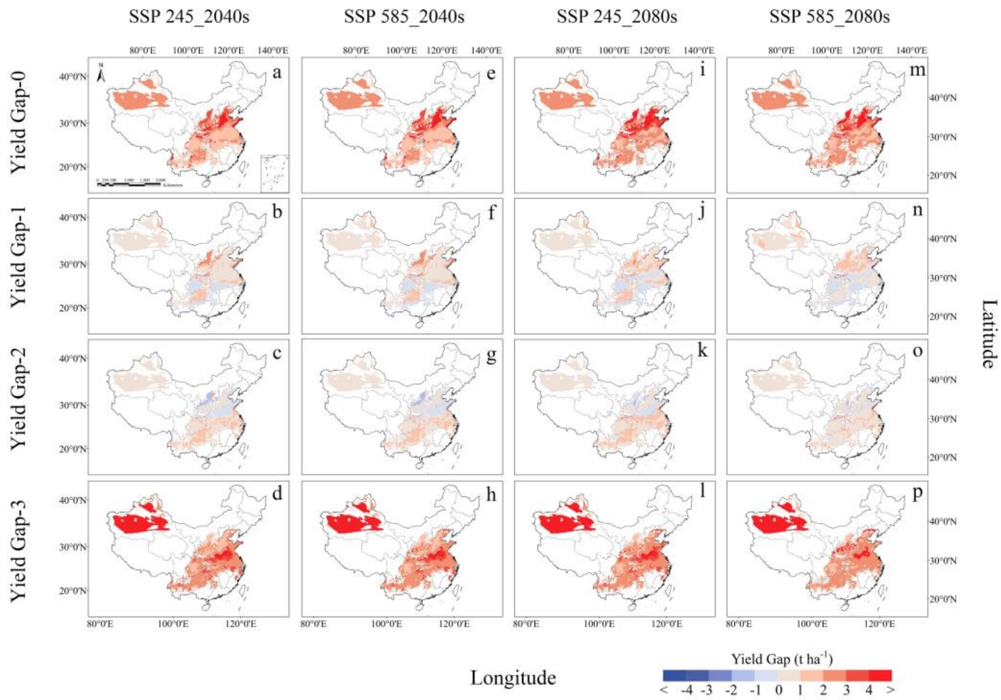
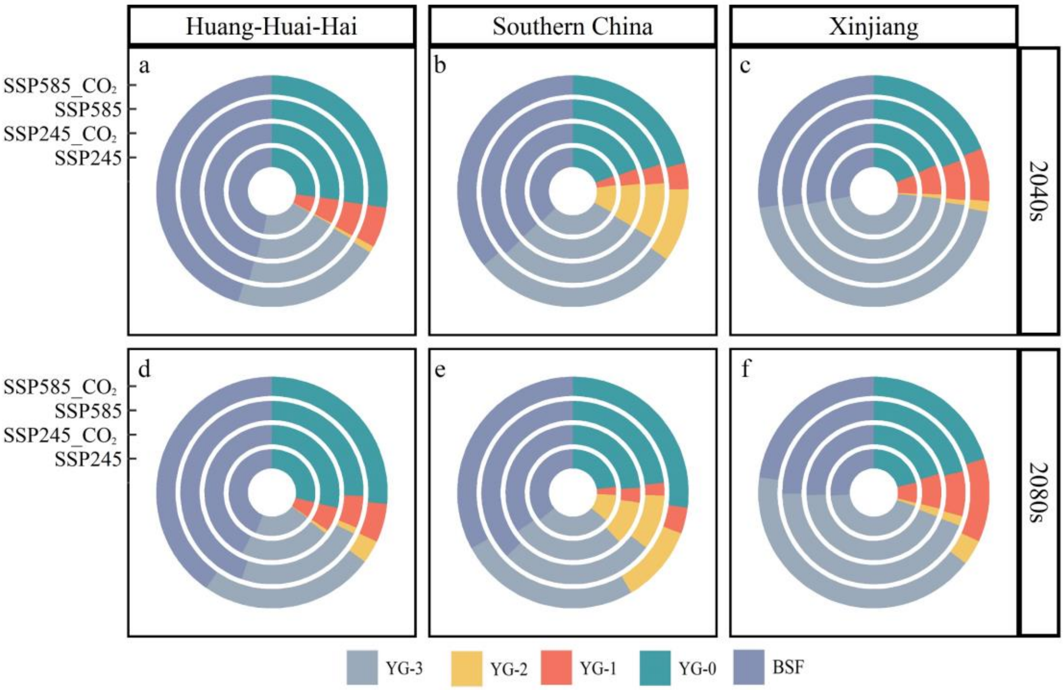
a18
a19
a20
80°0'E
100°0'E
120°0'E
140°0'E
40°0'N
30°0'N
20°0'N
Latitude
Longitude
Coefficient of Variation (%)
0 5 10 15 20 25 30 35 40 45 100



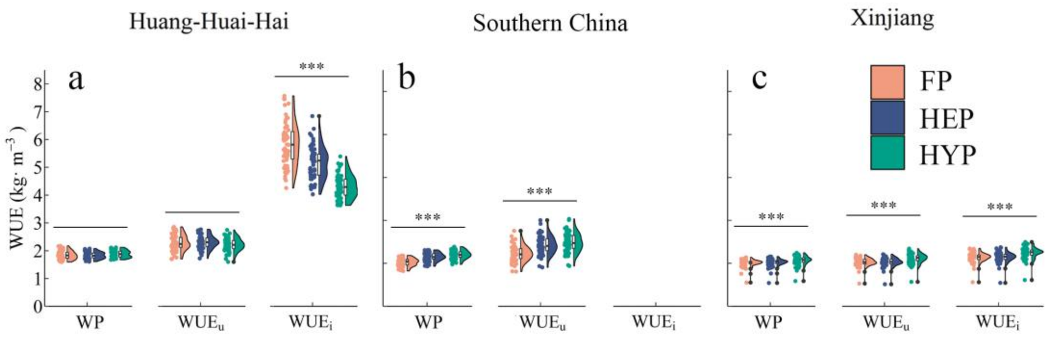
Supplementary Figure 10. Projected values of coefficient of variation (CV) at different yield levels of YP (‘Yield potential’), HYP (‘High-yield practice’), HEP (‘High-efficiency practice’), FP (‘Farmer practice’), and BSF (‘Basic soil fertility’) in periods of 2040s (2021-2060) and 2080s (2061-2100) under the SSP245 and SSP585 scenarios with stable (a) and changing [CO_2] (b) concentrations in China.



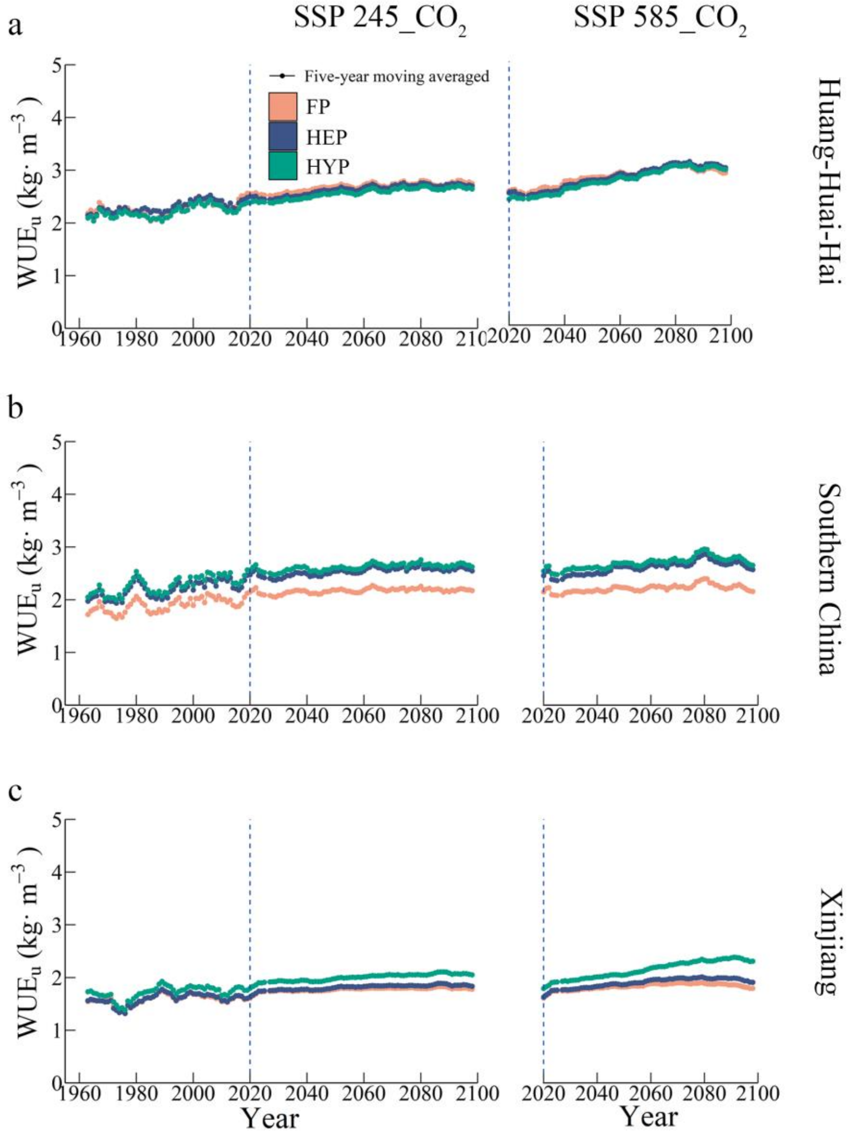
Supplementary Figure 11. Projected yield gaps in the periods of 2040s (2021-2060; a-h) and 2080s (2061-2100; i-p) under the SSP245 and SSP585 scenarios with stable [CO_2] in China. YG-0 (Yield gap between the 'YP' and 'HYP' yield levels), YG-1(Yield gap between the 'HYP' and 'HEP' yield levels), YG-2(Yield gap between the 'HEP' and 'FP' yield levels) and YG-3 (Yield gap between the 'FP' and 'BSF' yield levels) are the different yield gaps defined in this study. Negative values of YG-1 and YG-2 indicated that the winter wheat yield at the HEP ('High efficiency practice') level was higher than that at the HYP ('High-yield practice') level or lower than that at the 'FP' level.



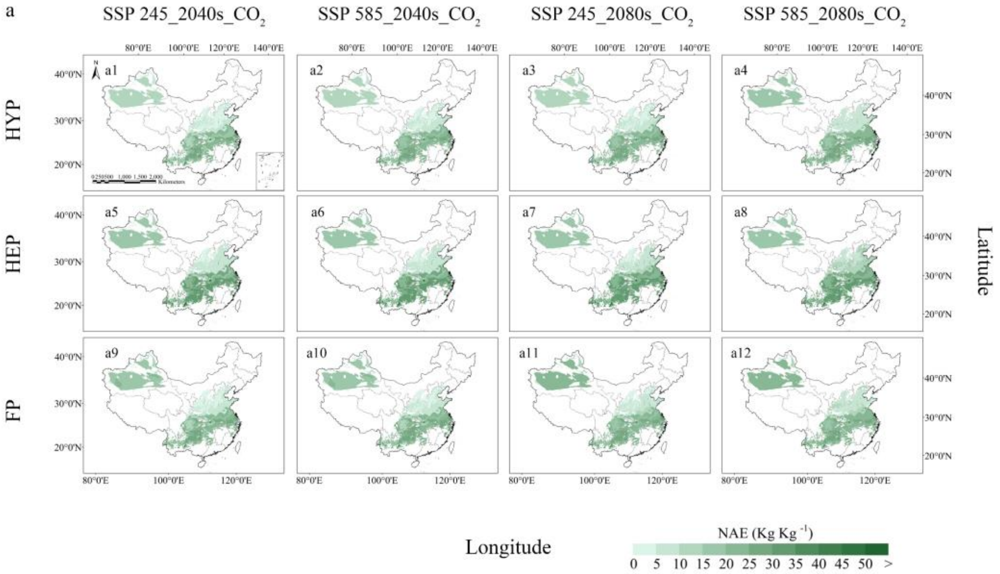
Supplementary Figure 12. Projected yield gaps (represented as the percentages of yield potential) of winter wheat in the periods of 2040s (2021-2060; a-c) and 2080s (2061-2100; d-f) under the SSP245 and SSP585 scenarios with stable and changing [CO_2] concentrations based on the future climatic data derived from 27 different GCMs (global climate models) in the three main winter-wheat producing regions (Huang-Huai-Hai, a, d; Southern China, b, e; Xinjiang, c, f) in China.

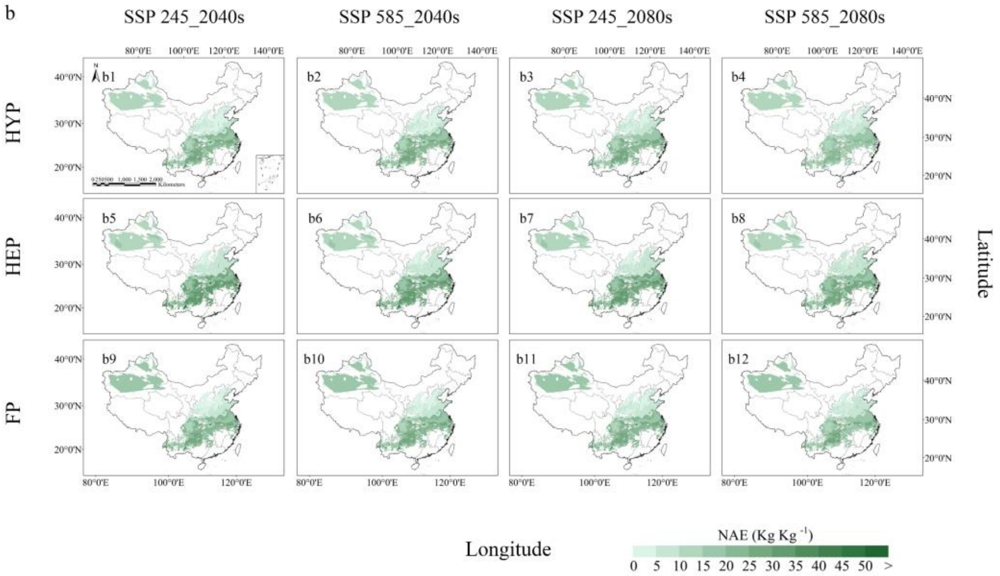


Supplementary Figure 13. Simulated values of water use efficiency (WUE) for different levels of agronomic practices in the three main winter wheat producing regions (Huang-Huai-Hai, a; Southern China, b; Xinjiang, c) in China during the baseline period of 1961-2020. The plots present the correct horizontally jittered mean values, a boxplot, and a split half violin plot of the densities of the WP (water productivity; kg m^{-3}), WUE_u (broad water use efficiency; kg m^{-3}), and WUE_i (irrigation water use efficiency; kg m^{-3}), respectively. Due to the absence of irrigation in winter wheat cultivation in Southern China, there were no WUE_i (kg m^{-1}) values available in this region. The WUE values annotated with *, ** or *** are significantly different at $P < 0.1$, $P < 0.05$, or $P < 0.01$, respectively.

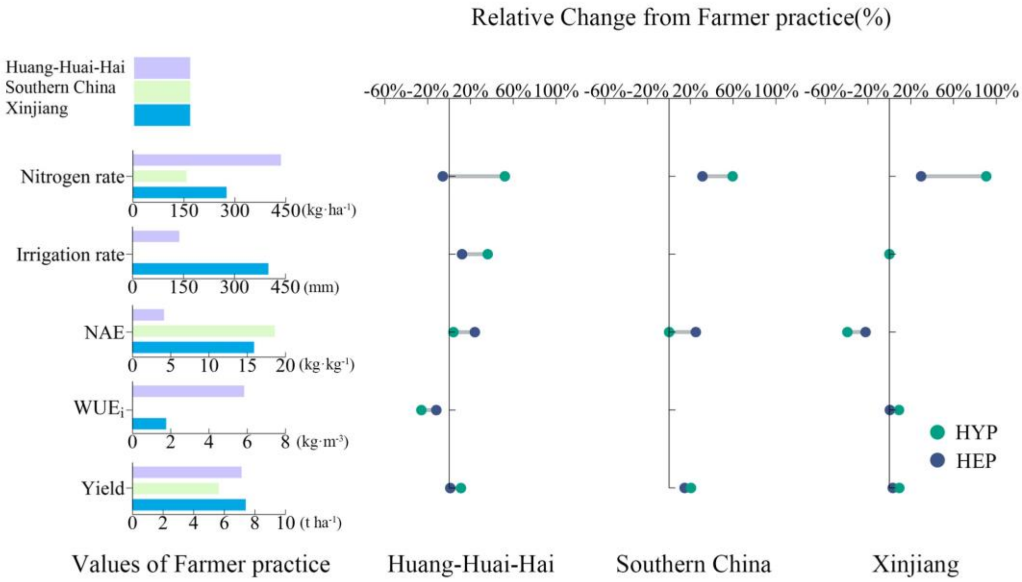


Supplementary Figure 14. Trends of WUE_u (broad water use efficiency; kg m^{-3}) of winter wheat production at different yield levels of YP ('Yield potential'), HYP ('High-yield practice'), HEP ('High-efficiency practice'), FP ('Farmer practice'), and BSF ('Basic soil fertility') in the future period of 2021-2100 under the SSP245 and SSP585 scenarios in the three main winter wheat producing regions (Huang-Huai-Hai, a; Southern China, b; Xinjiang, c;) in China. The solid lines are the mean response curves based on 5-year moving average.

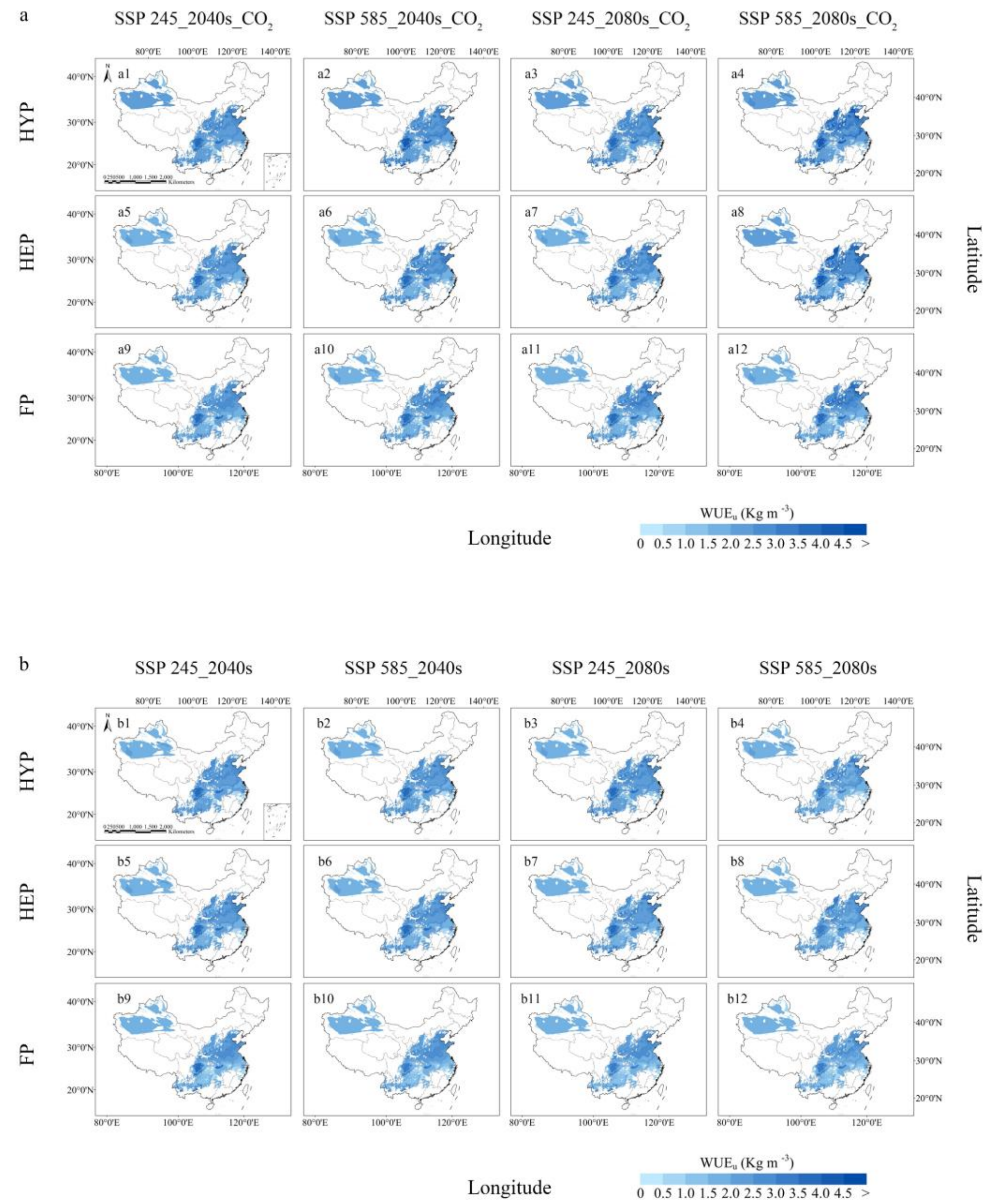




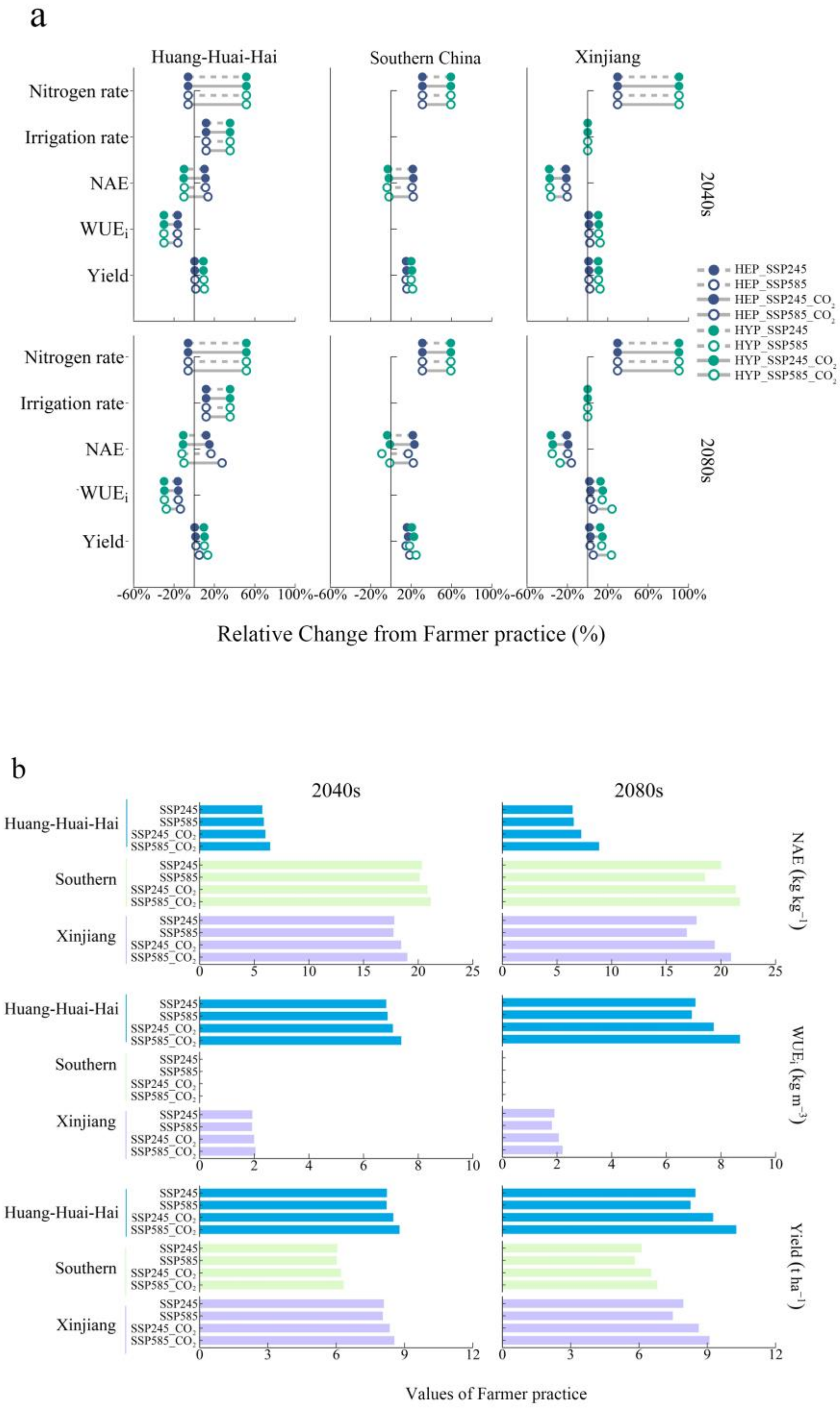
Supplementary Figure 15. Projected values of NAE (nitrogen agronomic efficiency; kg wheat grain per kg fertilizer applied) of winter wheat at different yield levels of YP ('Yield potential'), HYP ('High-yield practice'), HEP ('High-efficiency practice'), FP ('Farmer practice'), and BSF ('Basic soil fertility') in the periods of 2040s (2021-2060) and 2080s (2061-2100) under the SSP245 and SSP585 scenarios with changing (a) and stable (b) [CO_2] concentrations in China.



Supplementary Figure 16. Relative changes of nitrogen use efficiency (NUE), water use efficiency (WUE), and yield in winter wheat production at the HEP ('High-efficiency practice') and HYP ('High-yield practice') levels compared to the FP ('Farmer practice') level in the baseline period (1961-2020) in the three main winter wheat producing regions (Huang-Huai-Hai, Southern China, and Xinjiang) in China.



Supplementary Figure 17. Projected values of WUE_u (broad water use efficiency; kg m^{-3}) of winter wheat at different yield levels of YP ('Yield potential'), HYP ('High-yield practice'), HEP ('High-efficiency practice'), FP ('Farmer practice'), and BSF ('Basic soil fertility') in periods of 2040s (2021-2060) and 2080s (2061-2100) under the SSP245 and SSP585 scenarios with changing (a) and stable (b) [CO_2] concentrations in China.



Supplementary Figure 18. Relative changes (a) of nitrogen rate, irrigation rate, NAE (nitrogen agronomic efficiency; kg wheat grain per kg fertilizer applied), WUE_i (irrigation water use efficiency; kg m^{-3}), and per-unit yield of winter wheat at the yield levels of HEP ('High-efficiency practice') and HYP ('High-yield practice'), and the comparisons (b) with the NAE, WUE_i, and per-unit yield at the FM ('Farm management') level in periods of 2040s (2021-2060) and 2080s (2061-2100) under the SSP245 and SSP585 scenarios with changing and stable [CO_2] concentrations in the three main winter wheat producing regions (Huang-Huai-Hai; Southern China, and Xinjiang) in China.