

Supplementary Text

Determination of area cultivated for *indica* and *japonica* rice

Based on the available data, we classified India, Bangladesh, Vietnam, Thailand, the Philippines and Cambodia as countries that only grow *indica* rice; and Japan and South Korea were classified as countries that only grow *japonica* rice^{1, 2, 3, 4, 5, 6, 7, 8}, and China, Pakistan, United States, Indonesia, Myanmar and Brazil as countries that grow both *indica* and *japonica* subspecies. A more detailed analysis of countries that grow both subspecies is provided below.

China

Based on the studies by Chen and Pan⁹ and Fang¹⁰, we identified 14 provinces in northern China (Beijing, Tianjin, Hebei, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shanghai, Shandong, Ningxia, Shanxi, Gansu, Tibet, and Xinjiang) as regions where only *japonica* rice is grown and 11 provinces in the south (Fujian, Jiangxi, Hubei, Hunan, Guangdong, Taiwan, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Shaanxi) where only *indica* rice is cultivated. Both *japonica* and *indica* rice are planted in Jiangsu, Zhejiang, Anhui, Henan, and Yunnan provinces. In these five provinces, we determined the rice variety cultivated down to an area of more than 667 hectares from China's seed industry big data platform¹¹ to obtain the proportions of *indica* and *japonica* rice grown in each of these five provinces. Due to the lack of data, we assumed that the yield of *indica* and *japonica* rice is the same in these five provinces for the calculation.

Pakistan

Pakistan is a typical *indica* rice area. But for basmati rice, an aromatic rice variety widely grown in Pakistan¹², phylogenetic analysis demonstrates a close evolutionary relationship between the aromatic, temperate *japonica*, and tropical *japonica* subpopulations, which comprise the *japonica* varietal group¹³. A recent study confirms that basmati rice is more closely related to *japonica* rice genetically¹⁴. Therefore, basmati is considered as *japonica* rice.

United States of America

Rice produced in the United States includes long-grained rice, which is usually considered as *indica* rice, and medium- and short-grained rice, which are often classified as the *japonica* type¹⁵.

Indonesia

Rice production in Indonesia is mainly in the lowland¹⁶, with upland rice only accounting for 10% of the rice-planting area and about 5% of the total production in which traditional varieties are grown and cultivated without or with a low rate of fertilizer application¹⁷. Almost all lowland varieties planted in the country belong to the *indica* subspecies, and tropical *japonica* is cultivated in upland sites⁴. We therefore regarded lowland rice as *indica* and dryland rice as *japonica*.

Myanmar

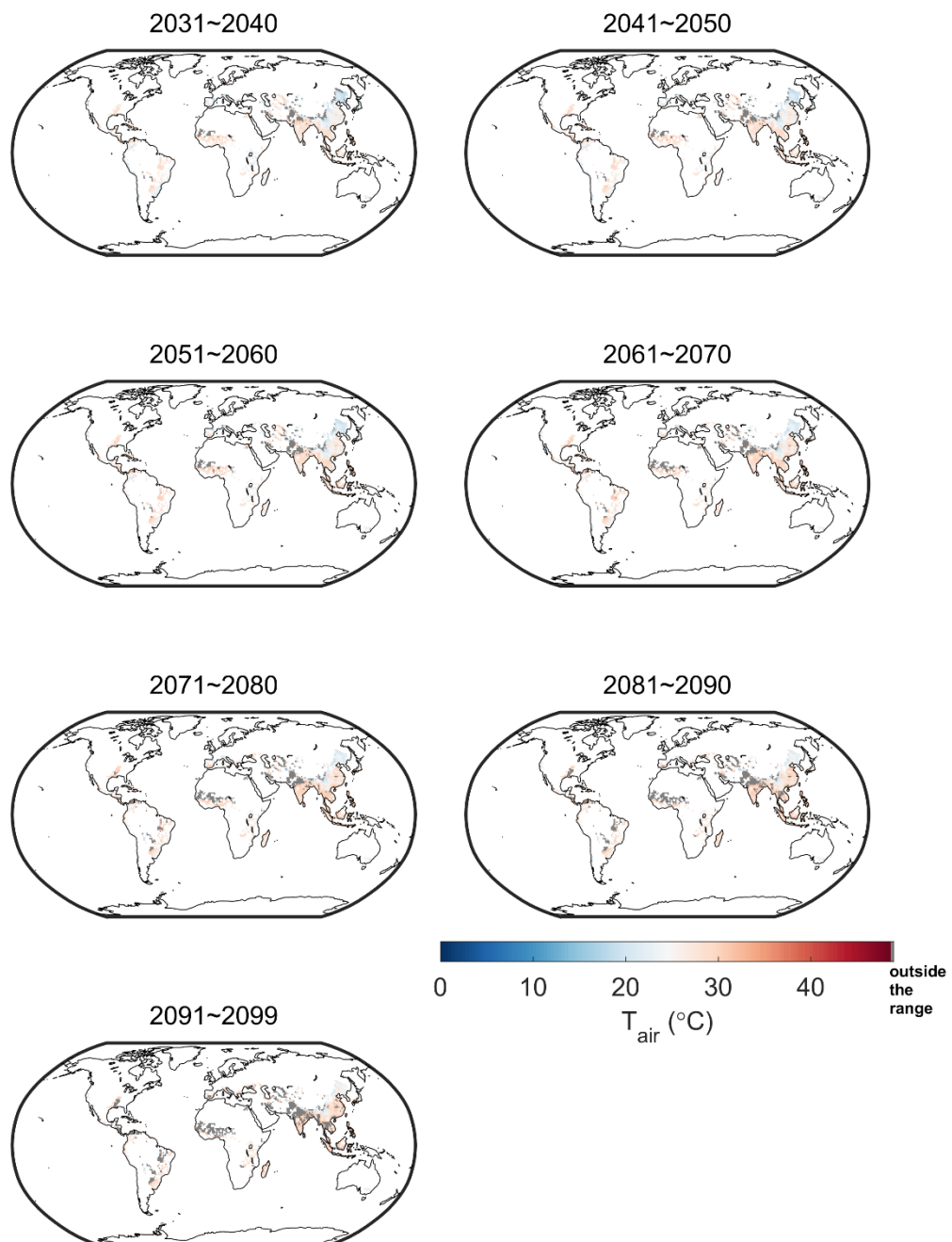
Accessions of *indica* are generally grown in upland areas in Myanmar, and accessions of *japonica* are grown in lowlands ¹⁸. We therefore based the areas of *indica* and *japonica* rice subspecies in Myanmar on rice planting areas of upland and lowland, respectively. Due to the lack of data and low yield levels, we assumed that the yields of *indica* and *japonica* rice were the same.

Brazil

Brazilian landraces of upland rice belong to the tropical *japonica* subspecies, and almost all of rice varieties planted in lowland systems belong to the *indica* type ^{19, 20}. We therefore regard lowland rice as *indica* and upland rice as *japonica*. The ratio of lowland-to-upland rice in Brazil is based on Fageria et al. ²¹.

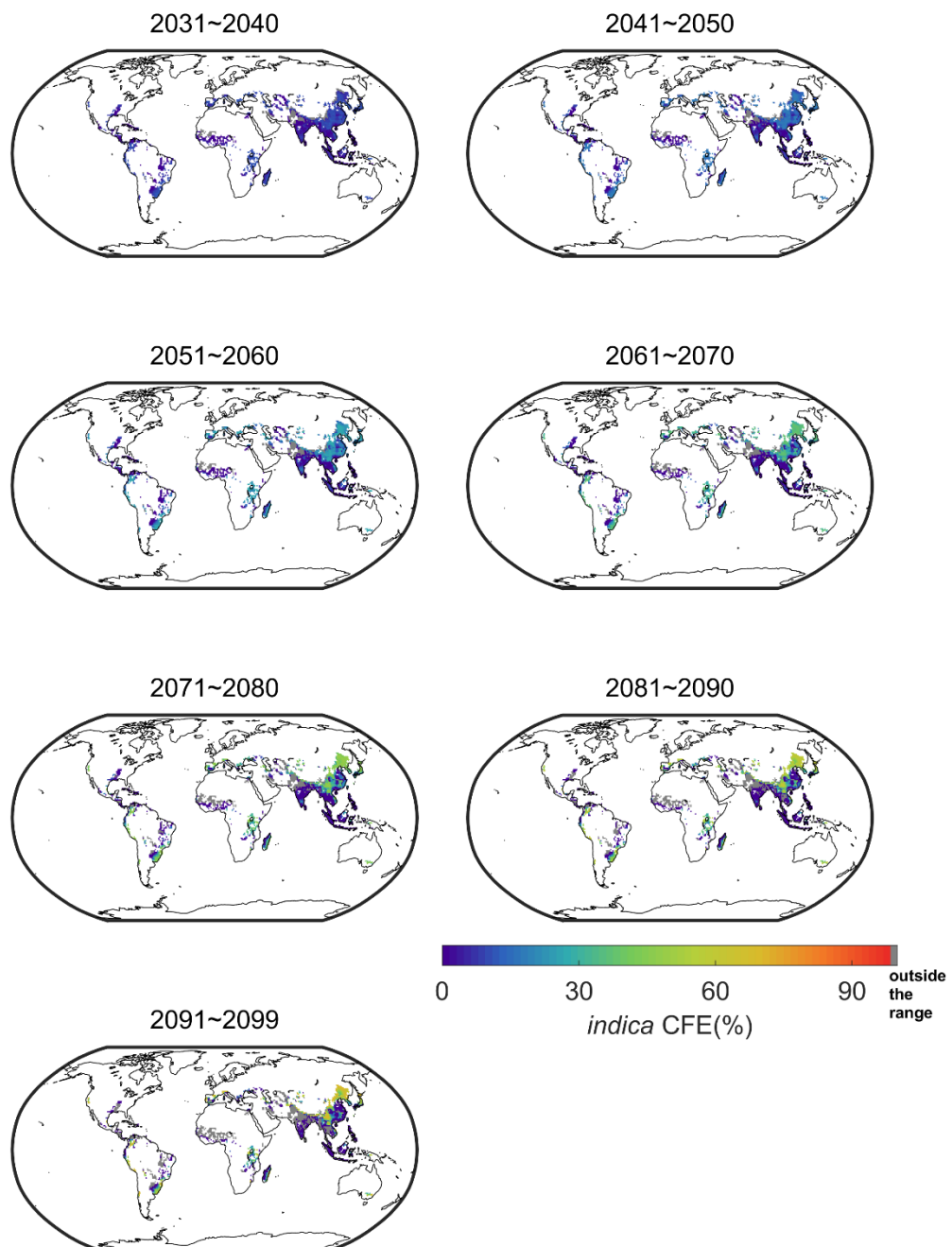
Supplementary Figure 1

Global distribution of predicted average daily air temperature (T_{air}) during the growing season for main rice-planting regions under the “high-end forcing pathway” scenario (SSP5-85) scenario during 2031-2040, 2041-2050, 2051-2060, 2061-2070, 2071-2080, 2081-2090 and 2091-2099. The grey areas fall outside the T_{air} limits of this analysis.



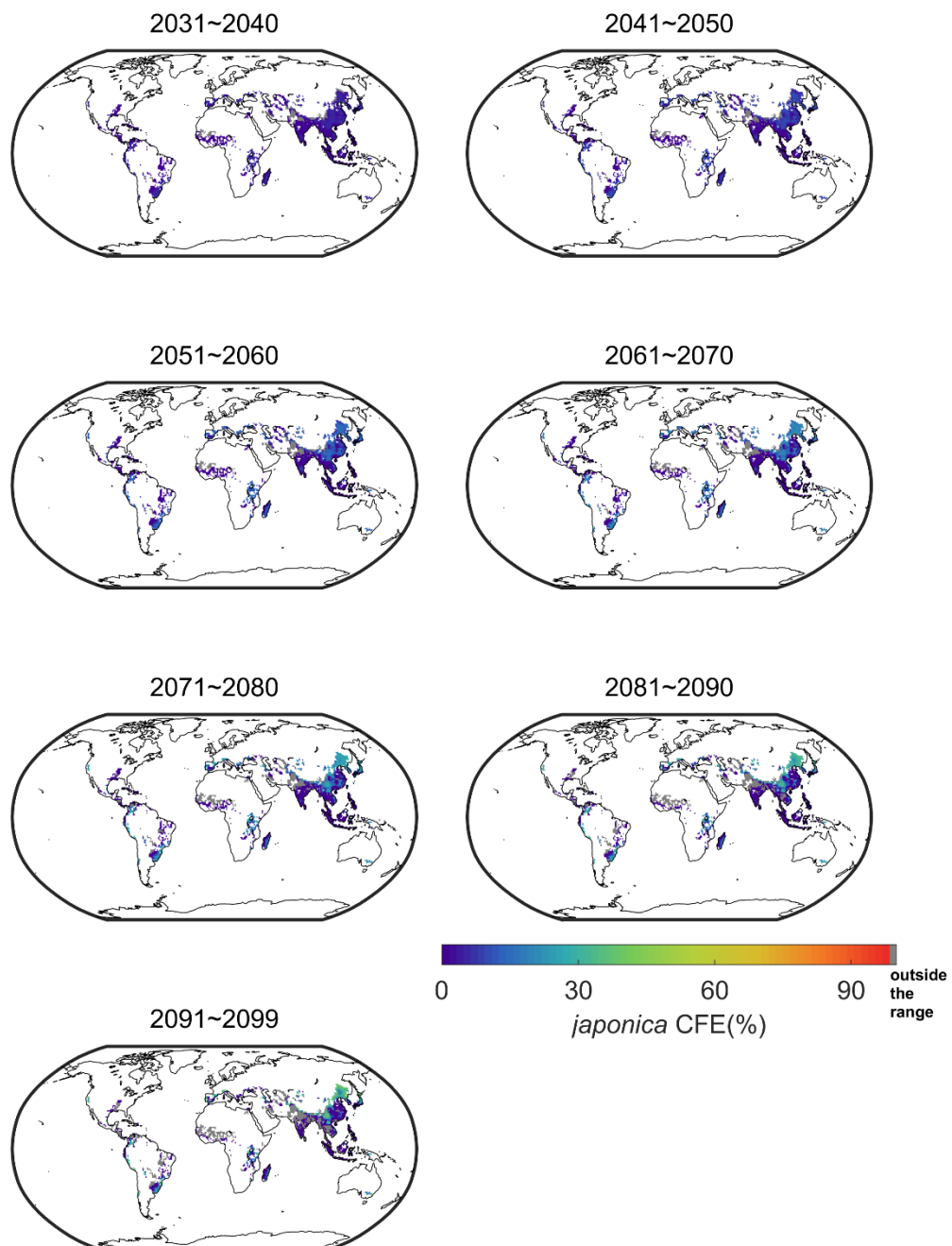
Supplementary Figure 2

Global distribution of projected *indica* CFE (Carbon dioxide Fertilization Effect) for the main rice-planting regions under the “high-end forcing pathway” scenario (SSP5-85) scenario during 2031-2040, 2041-2050, 2051-2060, 2061-2070, 2071-2080, 2081-2090 and 2091-2099. The grey areas fall outside the T_{air} limits of this analysis, and the value '0' in the legend indicates value ' ≤ 0 '.



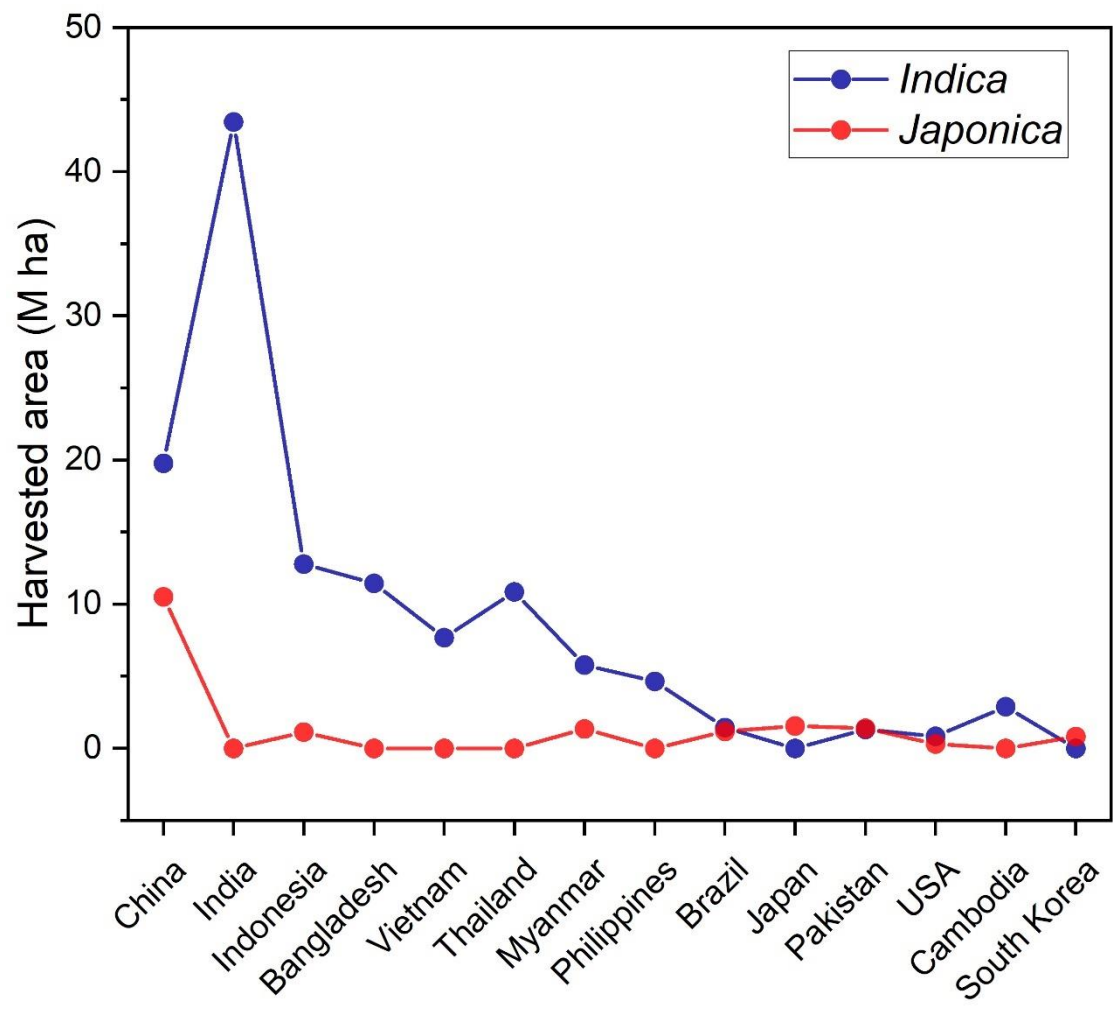
Supplementary Figure 3

Global distribution of projected *japonica* CFE (Carbon dioxide Fertilization Effect) for the main rice-planting regions under the “high-end forcing pathway” scenario (SSP5-85) scenario during 2031-2040, 2041-2050, 2051-2060, 2061-2070, 2071-2080, 2081-2090 and 2091-2099. The grey areas fall outside the T_{air} limits of this analysis, and the value '0' in the legend indicates value ' ≤ 0 '.



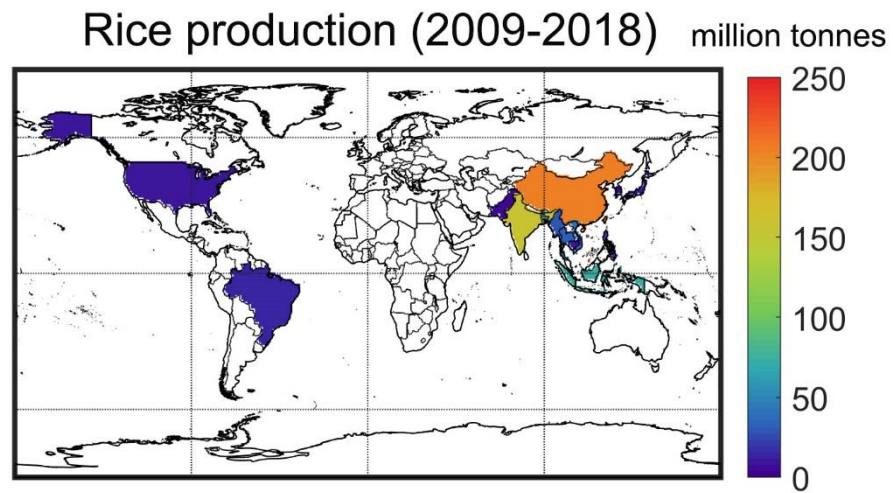
Supplementary Figure 4

Average harvested area for *indica* and *japonica* subspecies in the 14 top rice-producing countries during 2009-2018.



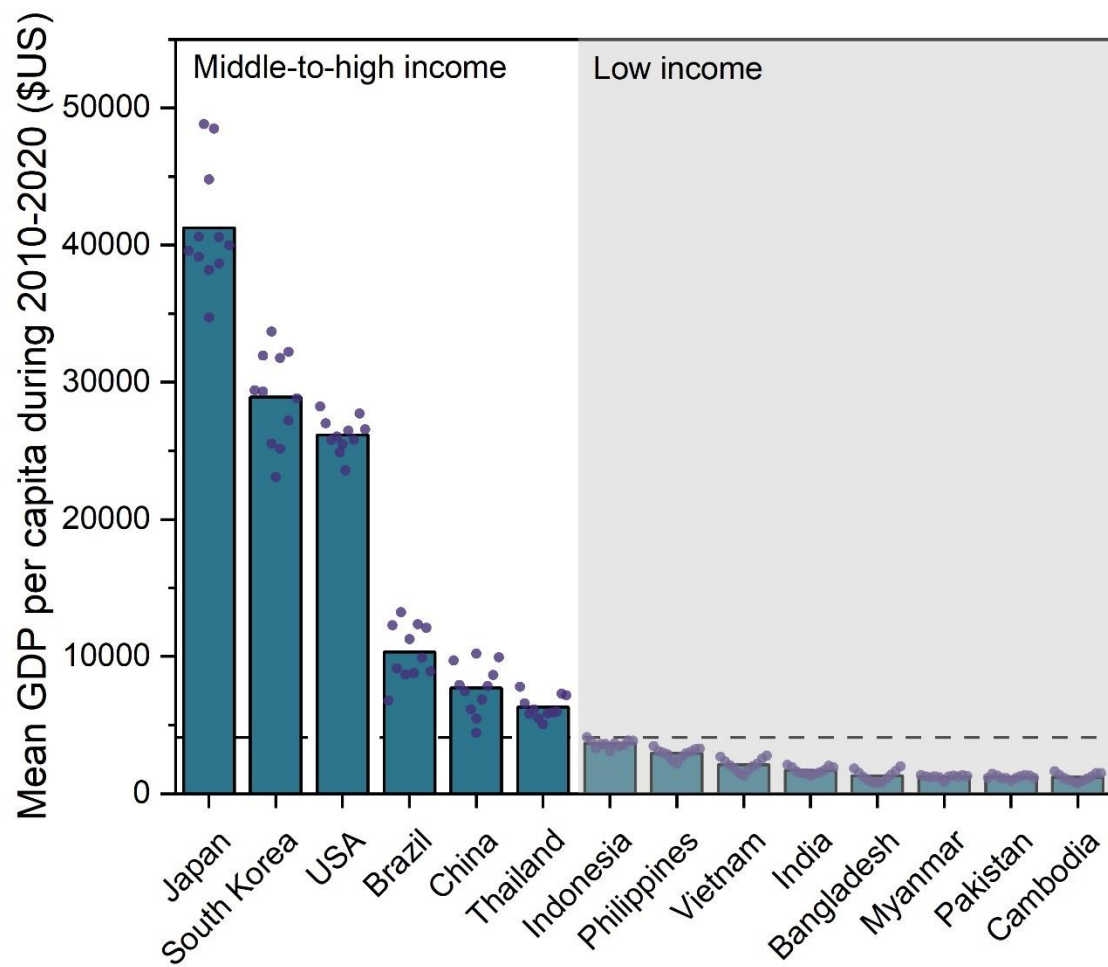
Supplementary Figure 5

Global distribution of historical rice production (2009-2018) in the 14 top rice-producing countries, including China, India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, the Philippines, Brazil, Japan, Pakistan, USA, Cambodia, and South Korea.



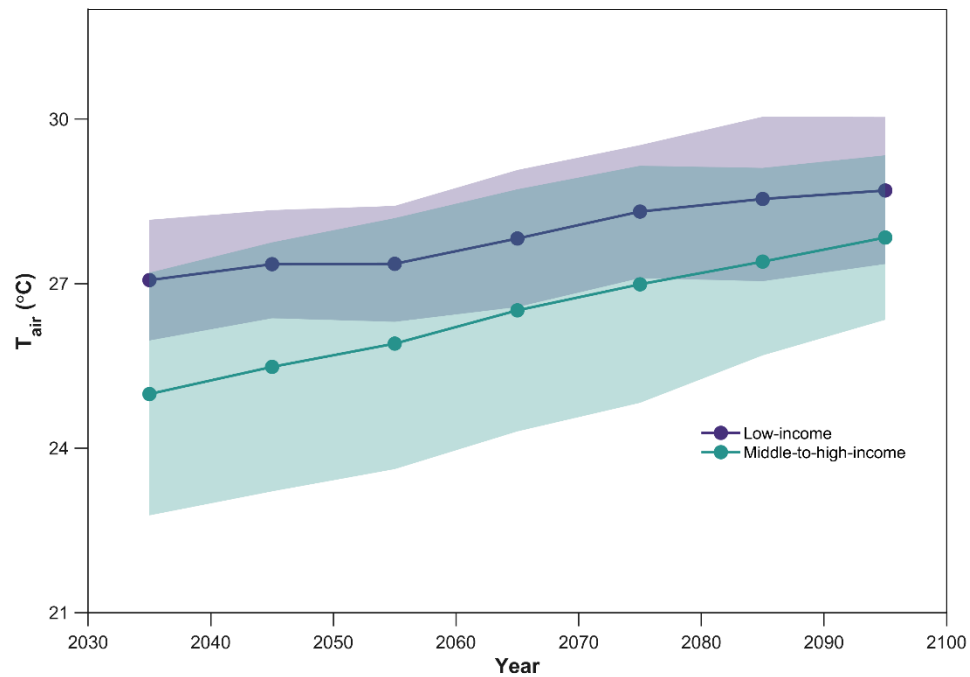
Supplementary Figure 6

Variations of mean GDP (Gross Domestic Product) per capita for 14 main rice-planting countries during 2010-2020. The horizontal dashed line indicates the GDP per capita threshold value from the World Bank between low- and middle-to-high-income countries (\$US 4096 in 2021, <https://blogs.worldbank.org/opendata/new-world-bank-country-classifications-income-level-2021-2022>), and the shaded area indicates low-income countries.



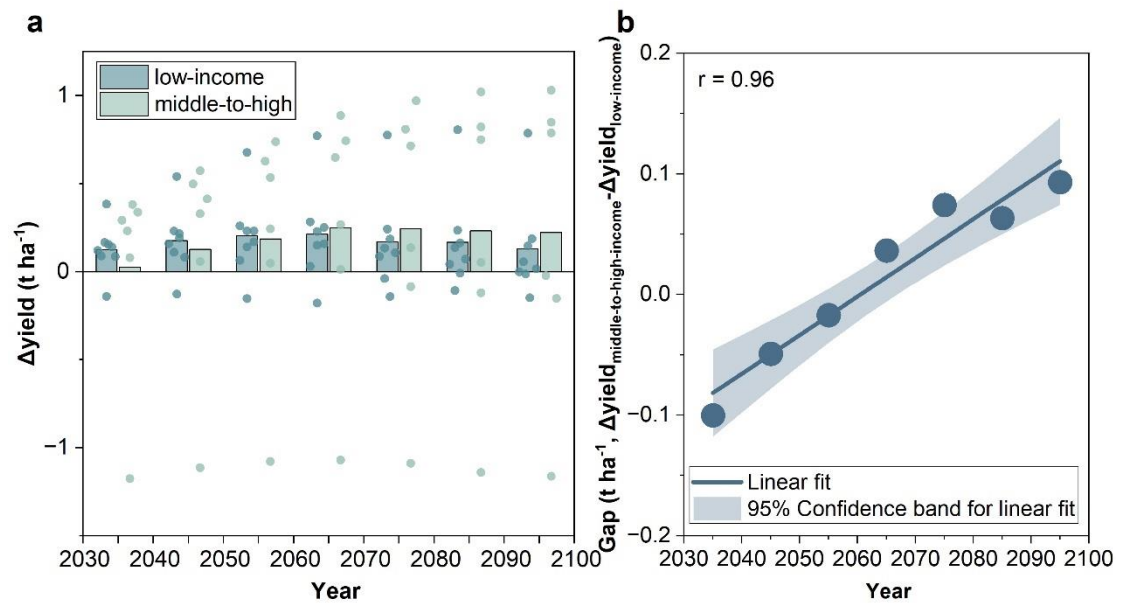
Supplementary Figure 7

Predicted future average daily air temperature (T_{air}) during 2031-2099 for low-income (including Cambodia, Pakistan, Myanmar, Bangladesh, India, Vietnam, the Philippines and Indonesia) and middle-to-high-income (Thailand, China, Brazil, USA, South Korea and Japan) countries under the “high-end forcing pathway” (SSP5-85 scenario). The shaded error bands represent the standard deviation (SD) of T_{air} within rice planting regions for low-income and middle-to-high income countries, and the solid curves are the mean values.



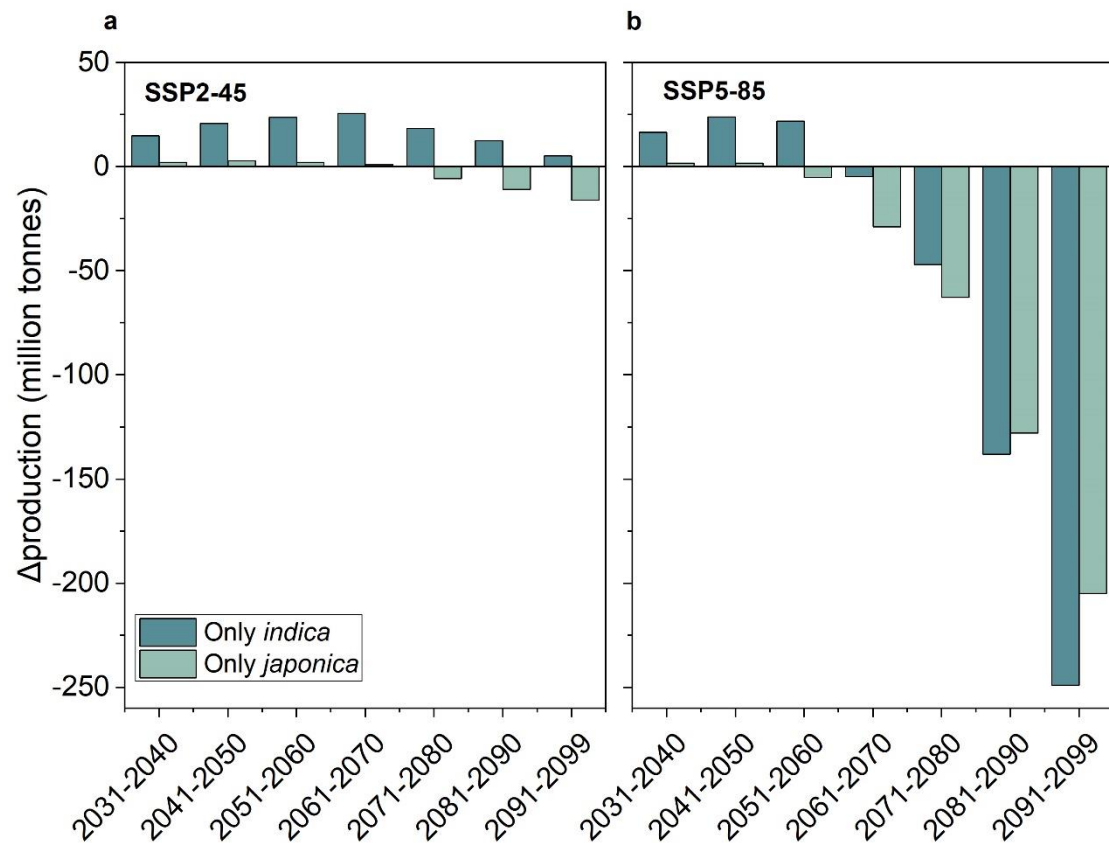
Supplementary Figure 8

Projected changes in rice yield under e[CO₂] for low- and middle-to-high-income rice-planting countries under the SSP2-45 scenario. **a**, Potential future changes in rice yield compared with historical rice yield (means for 2009-2018) during 2030-2099 for low-income (n=8) and middle-to-high-income (n=6) rice-producing countries; and the dots represent each individual sample of Δyield for low-income and middle-to-high income countries. **b**, Gaps (difference of Δyield) between middle-to-high-income and low-income rice-producing countries. The solid line indicates the linear regression of the gap, and shaded area represents the 95% confidence band for the linear fit.



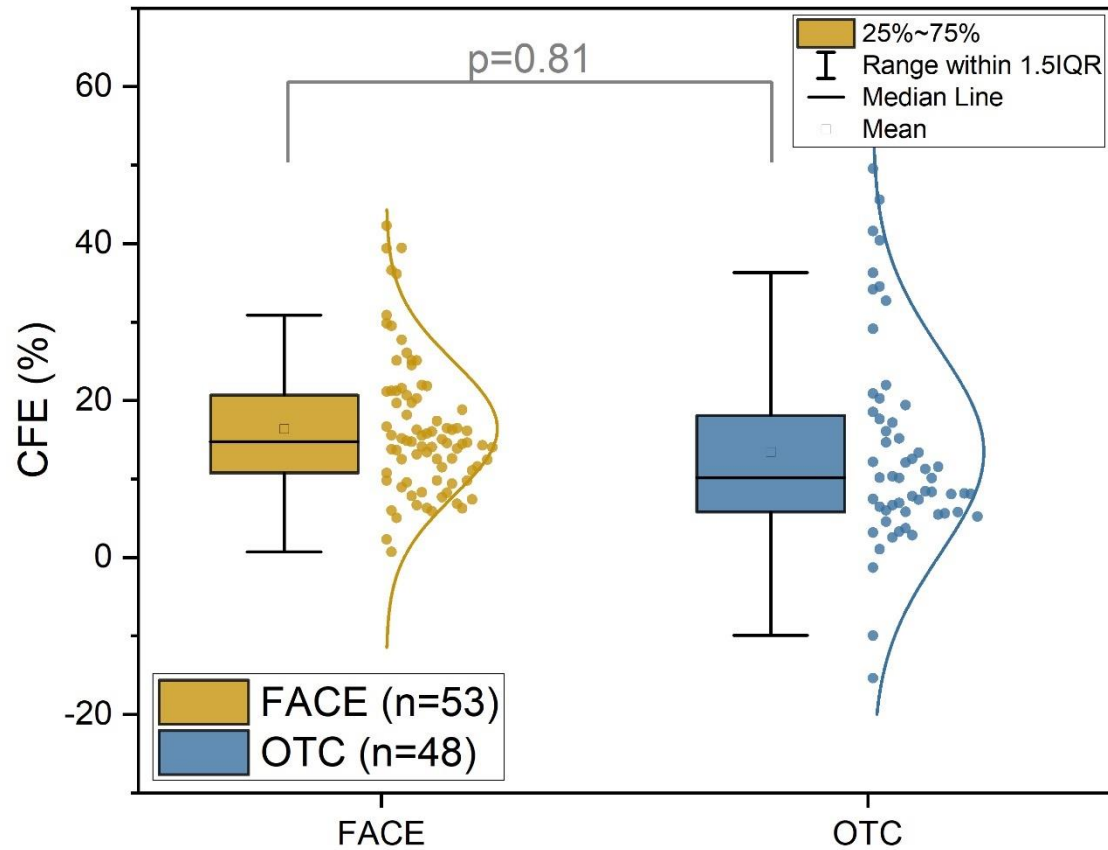
Supplementary Figure 9

Comparison of future changes in global rice production predicted by a model of CO₂ fertilization effect (CFE) considering only *indica* or *japonica* subspecies under a “high-end forcing pathway” scenario (SSP5-85) and a “medium forcing middle-of-the-road pathway” scenario (SSP2-45).



Supplementary Figure 10

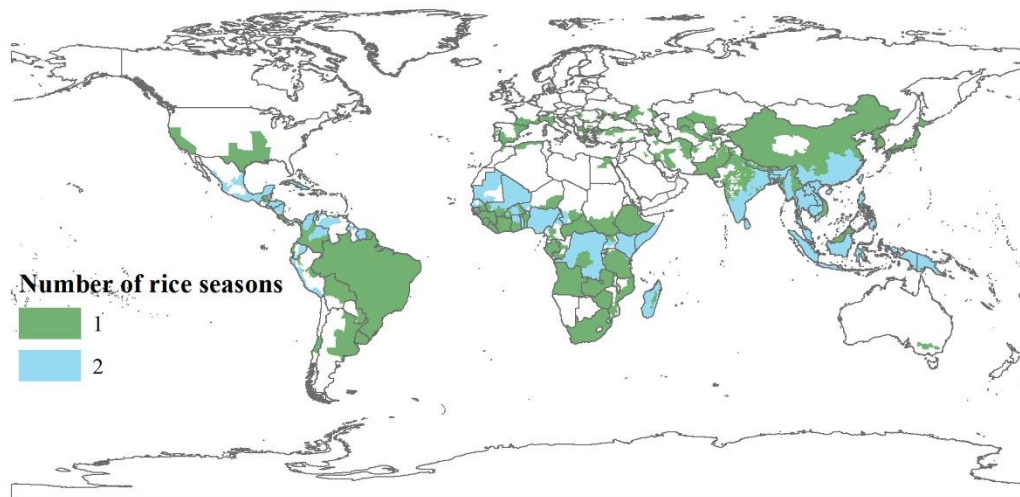
Box plots of CFE (Carbon dioxide Fertilization Effect) of FACE (Free-air CO₂ enrichment) and OTC (Open-top chamber). Horizontal lines are medians, empty squares are means, boxes show the 25%-75% interquartile range (IQR), error bars show the full range excluding outliers defined as being more than ± 1.5 IQR outside the box. The difference between CFE of FACE and OTC with p value uses a two-sided two-sample Kolmogorov-Smirnov test.



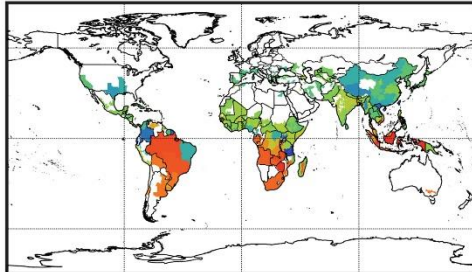
Supplementary Figure 11

Global distribution of rice phenology. **a**, distribution of the number of rice growing seasons per year and phenology. **b** and **c**, global distributions of rice planting of seasons 1 & 2. **d** and **e**, global distributions of rice harvesting dates of season 1 and 2. The DOY represents day of the year.

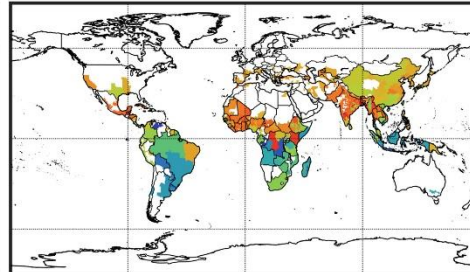
a



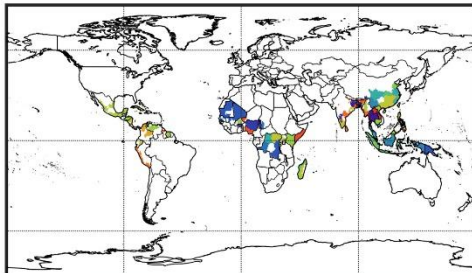
b Planting dates (season 1)



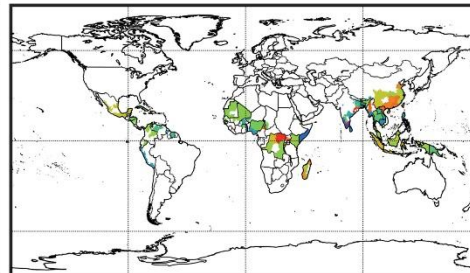
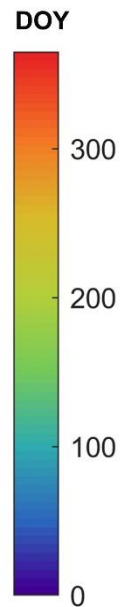
d Harvesting dates (season 1)



c Planting dates (season 2)

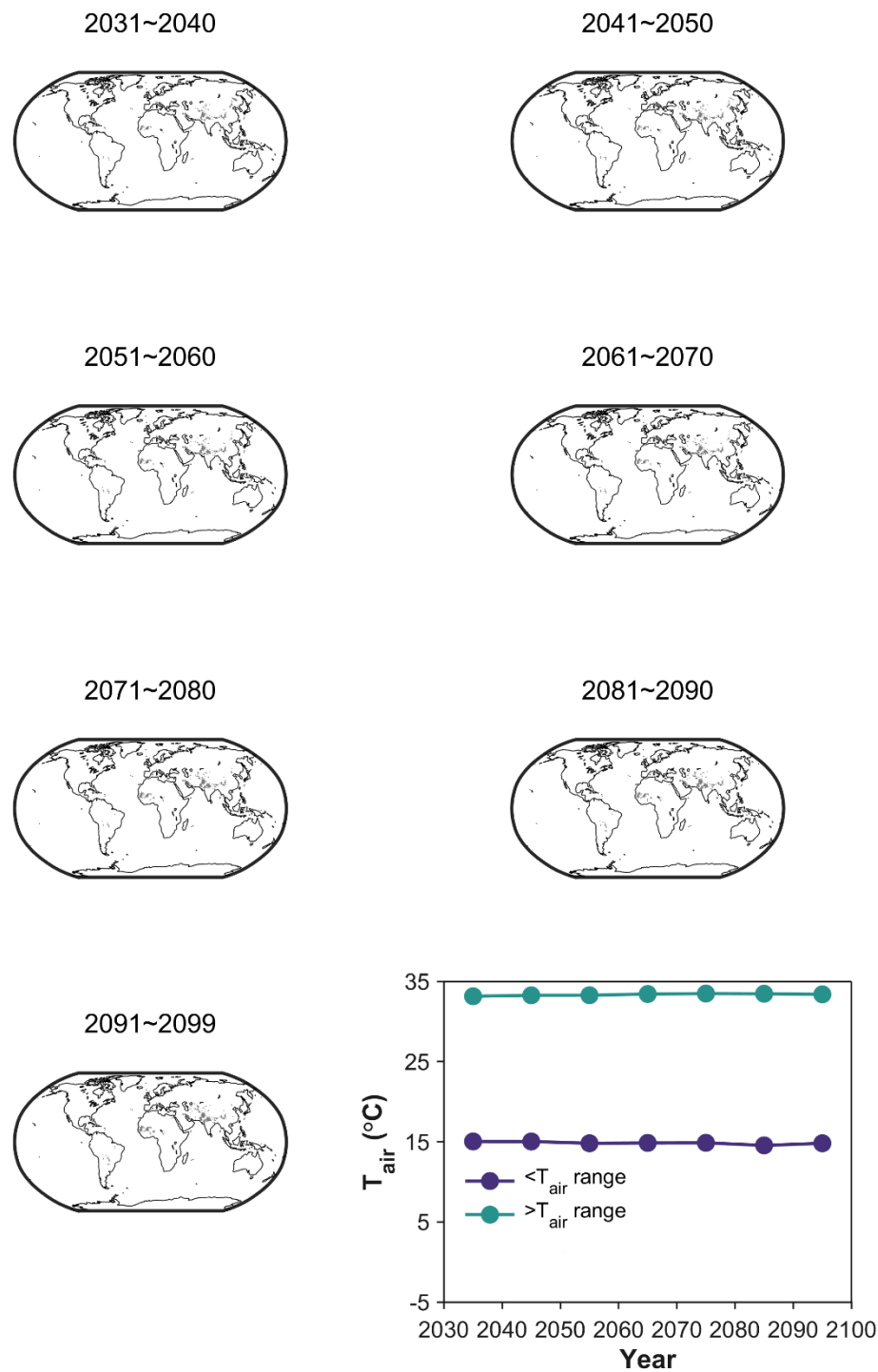


e Harvesting dates (season 2)



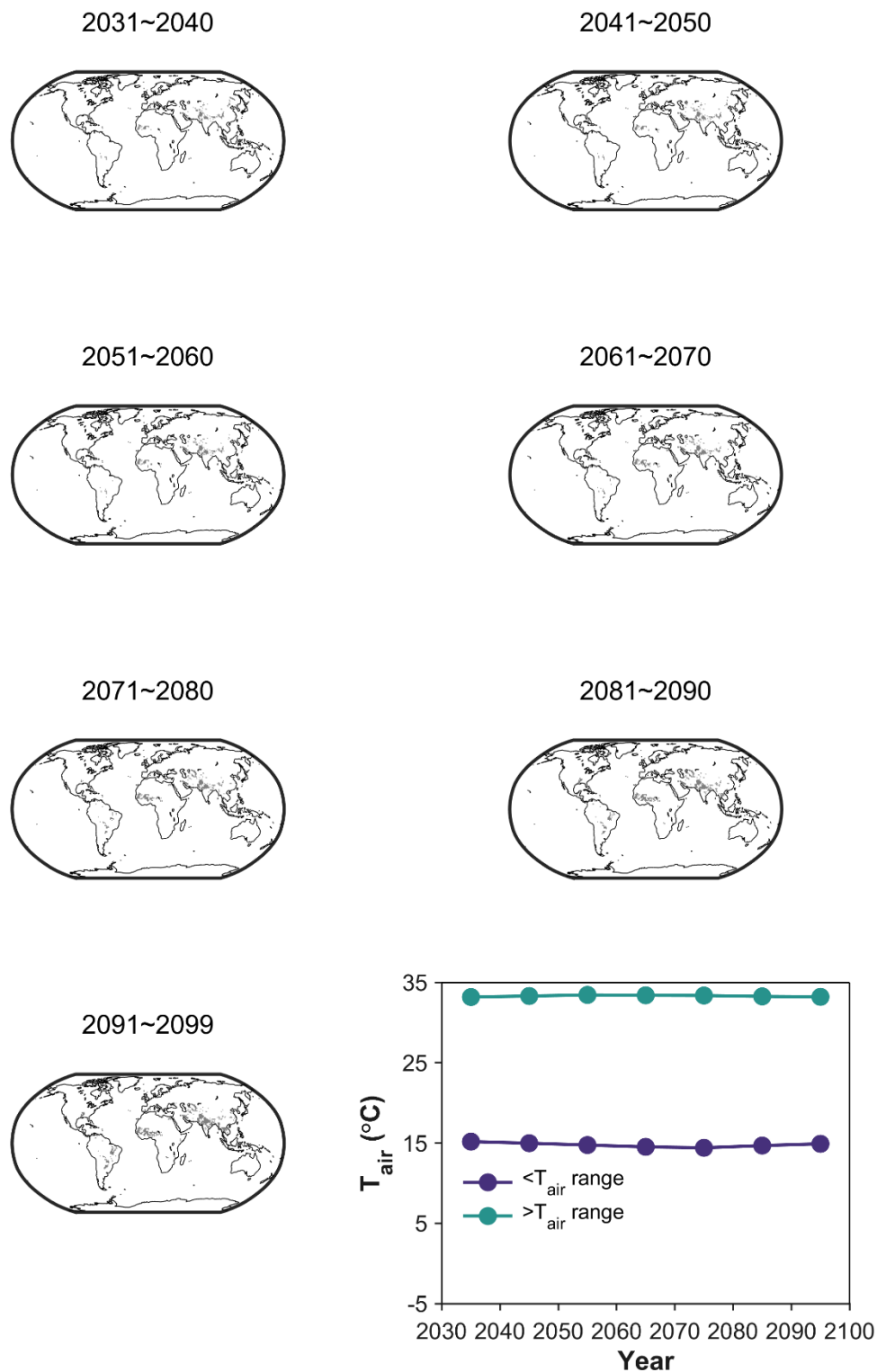
Supplementary Figure 12

Global distributions of areas that fall outside the T_{air} limits of this analysis under the SSP2-45 scenario during 2031-2099, and the variations of average T_{air} of these areas. The value of “ $<T_{\text{air range}}$ ” indicates the average T_{air} lower than the $T_{\text{air range}}$, and value of “ $>T_{\text{air range}}$ ” indicates the average T_{air} higher than the $T_{\text{air range}}$.



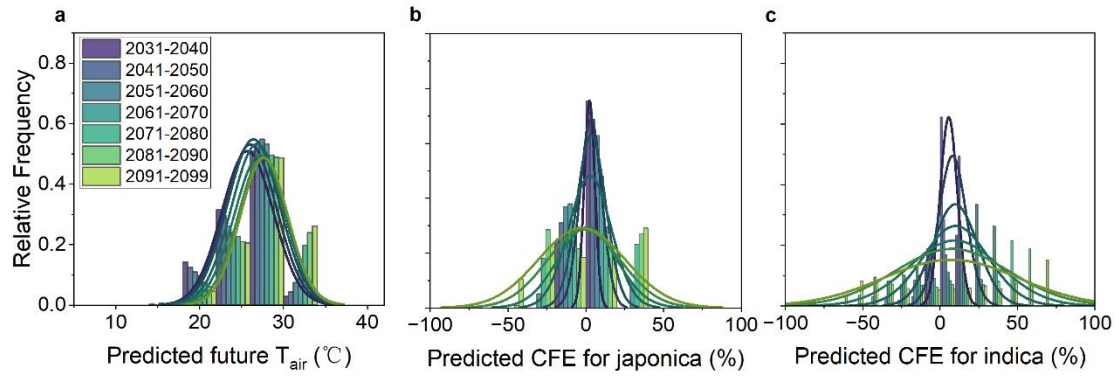
Supplementary Figure 13

Global distributions of areas that fall outside the T_{air} limits of this analysis under the SSP5-85 scenario during 2031-2099, and the variations of average T_{air} of these areas. The value of “ $<T_{\text{air}}$ range” indicates the average T_{air} lower than the T_{air} range, and value of “ $>T_{\text{air}}$ range” indicates the average T_{air} higher than the T_{air} range.



Supplementary Figure 14

Histogram of **a**, predicted future T_{air} (average daily air temperature), **b**, CFE (CO_2 Fertilization Effect) for *japonica*, and **c**, CFE for *indica* (**c**) in global main rice-producing regions during 2031-2099. The solid lines indicate the normal distribution curves of T_{air} , CFE for *japonica* and *indica*.



Supplementary Table 1.

Overview of FACE (Free-Air CO₂ enrichment) and OTC (Open-Top Chamber) CO₂ enrichment experiments included in the main analysis.

Study name	Country	Rice cultivar	Facility type	Period	Latitude	Longitude	Reference
Wuxi FACE	China	<i>Japonica</i>	FACE	2001-2003	31.58°N	120.5°E	22, 23
Yangzhou FACE	China	<i>Japonica</i> & <i>Indica</i>	FACE	2004-2006, 2010-2018	32.58°N	119.7°E	24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34
Changshu FACE	China	<i>Japonica</i>	FACE	2013-2014	31.5°N	120.55°E	35
Tsukuba FACE	Japan	<i>Japonica</i> & <i>Indica</i>	FACE	2010-2014	35.97°N	140.0°E	36, 37, 38
Shizukuishi FACE	Japan	<i>Japonica</i> & <i>Indica</i>	FACE	1998, 2003-2004, 2008	39.63°N	140.95°E	36, 39, 40
Cuttack OTC	India	<i>Indica</i>	OTC	2009-2011	20.45°N	85.0°E	41
Los Banos OTC	Philippines	<i>Indica</i>	OTC	1994-1996	14.22°N	121.25°E	42, 43
Haerbin OTC	China	<i>Japonica</i>	OTC	2016	45.75°N	126.63°E	44
Jingzhou OTC	China	<i>Indica</i>	OTC	2013-2016	30.21°N	112.09°E	45, 46
Gwangju OTC	Korea	<i>Japonica</i>	OTC	2007-2008	35.17°N	126.88°E	47
Kyoto OTC	Japan	<i>Japonica</i>	OTC	1991	35.03°N	135.77°E	48
Sanming OTC	China	<i>Indica</i>	OTC	2019	26.32°N	116.6°E	49
Nanjing OTC	China	<i>Japonica</i>	OTC	2018-2019	32°N	118.83°E	50

Supplementary Table 2.

Summary table of relative change in rice yield at ambient and elevated [CO₂] for FACE (Free-Air CO₂ Enrichment) and OTC (Open-Top Chamber) observations.

Site	Reference	Rice subspecies	ΔCO ₂ (μmol mol ⁻¹)	Average daily air temperature in rice growing season (T _{air} , °C)	Yield change percent (%)	Plant Density (NO. m ⁻²)	Nitrogen fertilization rate (g N m ⁻²)	Phosphorus fertilization rate (g P ₂ O ₅ m ⁻²)	Potassium fertilization rate (g K ₂ O m ⁻²)
Wuxi FACE	22, 23	<i>japonica</i>	200	24.5	10.77	72	25	3.5	3.5
		<i>japonica</i>	200	24.61	13.82	72	25	3.5	7
		<i>japonica</i>	200	25.21	13.68	72	25	3.5	7
		<i>indica</i>	200	24.51	42.31	24	25	3.1	5.8
		<i>indica</i>	200	24.87	16.70	24	25	3.1	5.8
		<i>indica</i>	200	25.34	39.40	24	25	3.1	5.8
		<i>japonica</i>	200	25.28	12.52	72	25	3.3	7
		<i>japonica</i>	200	24.51	21.15	72	25	3.3	7
		<i>indica</i>	200	24.55	30.90	24	25	3.1	5.8
Yangzhou FACE	24-34	<i>japonica</i>	200	24.54	14.89	24	25	3.1	5.8
		<i>indica</i>	200	23.36	29.85	24	25	3.1	5.8
		<i>japonica</i>	200	24.23	15.60	72	22.5	3.9	7.5
		<i>indica</i>	200	24.23	19.69	72	22.5	3.9	7.5
		<i>indica</i>	200	25.14	36.64	72	22.5	3.9	7.5
		<i>indica</i>	200	24.23	36.15	24	22.5	3.9	7.5
		<i>indica</i>	200	23.13	29.53	24	22.5	3.9	7.5
		<i>japonica</i>	200	23.13	9.80	48	22.5	3.9	7.5
		<i>japonica</i>	200	23.13	9.80	48	22.5	3.9	7.5

		<i>japonica</i>	200	25.14	6.00	48	22.5	3.9	7.5
		<i>japonica</i>	200	23.36	14.76	24	22.5	3.9	7.5
		<i>japonica</i>	200	24.90	13.9	48	22.5	3.9	7.5
		<i>japonica</i>	200	24.74	13.16	24	22.5	3.9	7.5
		<i>japonica</i>	200	26.14	8.97	24	22.5	3.9	7.5
		<i>japonica</i>	200	25.00	14.15	24	22.5	3.9	7.5
		<i>japonica</i>	200	27.90	7.68	48	22.5	3.9	7.5
		<i>japonica</i>	200	25.90	8.26	48	22.5	3.9	7.5
		<i>japonica</i>	200	27.50	14.32	48	22.5	3.9	7.5
		<i>japonica</i>	200	25.50	12.47	48	22.5	3.9	7.5
		<i>japonica</i>	200	25.50	14.07	48	22.5	3.9	7.5
		<i>japonica</i>	200	25.77	9.82	48	22.5	3.9	7.5
		<i>japonica</i>	200	25.77	7.40	48	22.5	3.9	7.5
Changshu	35	<i>japonica</i>	100	27.00	9.58	77.1	18.9	2.5	4.7
FACE		<i>japonica</i>	100	24.29	14.08	77.1	18.9	2.5	4.7
		<i>japonica</i>	200	25.10	18.20	66.6	8	4.36	8.3
		<i>indica</i>	200	25.10	21.23	66.6	8	4.36	8.3
		<i>japonica</i>	200	25.00	19.76	66.6	8	4.36	8.3
		<i>japonica</i>	200	25.00	16.30	66.6	8	4.36	8.3
		<i>Indica</i>	200	25.00	21.23	66.6	8	4.36	8.3
		<i>japonica</i>	200	24.10	7.85	66.6	8	4.36	8.3
		<i>japonica</i>	200	24.10	15.56	66.6	8	4.36	8.3
		<i>indica</i>	200	24.10	6.66	66.6	8	4.36	8.3
Tsukuba	36-38	<i>indica</i>	200	23.80	12.57	66.6	8	4.36	8.3
FACE		<i>indica</i>	200	24.20	8.32	66.6	8	4.36	8.3
		<i>indica</i>	200	23.90	2.33	66.6	8	4.36	8.3

		<i>japonica</i>	200	25.10	4.14	57.3	9	13.1	12.5
		<i>japonica</i>	200	25.10	19.76	57.3	9	13.1	12.5
		<i>japonica</i>	200	25.10	16.30	57.3	9	13.1	12.5
		<i>indica</i>	200	25.10	21.23	57.3	9	13.1	12.5
		<i>japonica</i>	200	19.70	15.80	57.15	8	4.36	8.3
		<i>japonica</i>	200	21.40	14.60	57.15	8	4.36	8.3
		<i>japonica</i>	200	19.90	21.57	57.15	8	4.36	8.3
Shizukuis	36, 39, 40	<i>japonica</i>	200	20.00	0.74	57.3	9	13.1	12.5
hi FACE		<i>japonica</i>	200	19.30	9.80	57.3	9	13.1	12.5
		<i>indica</i>	200	19.30	16.06	57.3	9	13.1	12.5
Cuttack	41	<i>indica</i>	150	23.30	18.55	45	10	1.7	3.3
OTC		<i>indica</i>	150	22.40	29.18	45	10	1.7	3.3
		<i>indica</i>	150	24.20	34.18	45	10	1.7	3.3
		<i>indica</i>	202	29.50	7.46	75	11	2	0
		<i>indica</i>	202	29.50	3.20	75	11	2	0
		<i>indica</i>	295	25.80	20.92	75	11	2	0
Los Banos	42, 43	<i>indica</i>	201	25.80	20.27	75	22	4	0
OTC		<i>indica</i>	295	25.80	17.66	75	22	4	0
		<i>indica</i>	201	29.50	16.09	75	22	4	0
		<i>indica</i>	201	29.50	-15.44	75	22	4	0
		<i>indica</i>	330	24.67	6.33	75	22	4	0
		<i>japonica</i>	60	19.80	12.20	42	16.88	6.75	13.5
		<i>japonica</i>	60	19.80	10.19	42	16.88	6.75	13.5
		<i>japonica</i>	60	19.80	14.68	42	16.88	6.75	13.5
		<i>japonica</i>	60	20.80	4.57	42	16.88	6.75	13.5
		<i>japonica</i>	60	20.80	10.35	42	16.88	6.75	13.5

Harbin OTC	44	<i>japonica</i>	60	21.80	17.20	42	16.88	6.75	13.5
		<i>japonica</i>	60	21.80	15.18	42	16.88	6.75	13.5
		<i>japonica</i>	160	19.80	8.46	42	16.88	6.75	13.5
		<i>japonica</i>	160	19.80	8.36	42	16.88	6.75	13.5
		<i>japonica</i>	160	19.80	10.15	42	16.88	6.75	13.5
		<i>japonica</i>	160	20.80	5.48	42	16.88	6.75	13.5
		<i>japonica</i>	160	20.80	12.11	42	16.88	6.75	13.5
		<i>japonica</i>	160	20.80	5.61	42	16.88	6.75	13.5
		<i>japonica</i>	160	21.80	21.98	42	16.88	6.75	13.5
		<i>japonica</i>	160	21.80	12.59	42	16.88	6.75	13.5
		<i>japonica</i>	160	21.80	8.09	42	16.88	6.75	13.5
Jinzhou OTC	45, 46	<i>indica</i>	53.10	26.70	49.56	46	18	2.62	7.47
		<i>indica</i>	54.80	28.10	5.79	46	18	2.62	7.47
		<i>indica</i>	59.30	24.40	34.56	46	18	2.62	7.47
		<i>indica</i>	58.70	23.60	36.29	46	18	2.62	7.47
		<i>indica</i>	58.50	24.90	45.62	46	18	2.62	7.47
		<i>indica</i>	58.50	25.00	37.72	46	18	2.62	7.47
		<i>indica</i>	58.50	27.10	8.18	46	18	2.62	7.47
		<i>indica</i>	57.60	25.90	41.61	46	18	2.62	7.47
		<i>indica</i>	60	24.55	40.44	46	18	2.62	7.47
Gwangju OTC	47	<i>japonica</i>	266	25.70	19.42	69	11	2	4.7
		<i>japonica</i>	266	27.60	13.38	69	11	2	4.7
		<i>japonica</i>	280	25.70	11.29	69	11	2	4.7
		<i>japonica</i>	280	27.60	8.12	69	11	2	4.7
Kyoto	48	<i>japonica</i>	340	28.30	3.30	20	24	6.55	11.95
OTC		<i>japonica</i>	340	29.40	-1.29	20	24	6.55	11.95

		<i>japonica</i>	340	31.10	-9.94	20	24	6.55	11.95
Sanming	49	<i>japonica</i>	400	25.00	10.13	24	20	3.06	5.81
OTC									
Nanjing	50	<i>japonica</i>	120	27.00	3.74	23.88	25	6.55	12.45
OTC		<i>japonica</i>	200	27	2.85	23.88	25	6.55	12.45
		<i>japonica</i>	200	23	11.56	23.88	25	6.55	12.45
		<i>japonica</i>	160	23	5.22	23.88	25	6.55	12.45

Supplementary Table 3

Overview of the models of Coupled Model Intercomparison Project 6 (CMIP6) included in the main analysis.

Model	Sponsor
CESM2 (Community Earth System Model)	National Center for Atmospheric Research (NCAR)
CMCC-CM2-SR5 (Centro Euro-Mediterraneo sui Cambiamenti Climatici-Coupled Model 2-ScenarioMIP SR5)	Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC)
CMCC-ESM2 (Centro Euro-Mediterraneo sui Cambiamenti Climatici-Earth System Model 2)	Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC)
NorESM2-MM (Norwegian Earth System Model 2-Medium Resolution)	Norwegian Climate Center

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