nature plants

SUPPLEMENTARY INFORMATION

VOLUME: 3 | ARTICLE NUMBER: 16202

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Plausible rice yield losses under future climate warming

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Supplementary methods

Data collection. To remove bias, our screening of the literature applied the following six principles. (1), to avoid short-term noise (short-term warming is possibly more biologically relevant and thus usually generates relatively higher sensitivity[1]), we only selected the studies including warming treatments of more than two months duration and which included the reproduction stage of the growing season. Thus those focusing on only a single period of time, such as particular days with anthesis or grain filling, or contrasting daytime and nighttime[2,3], were excluded. (2), warming experiments were restricted to field conditions; no laboratory incubators or controlled environments with constant day-night temperature treatment[4-7] were considered. (3), we excluded some studies which just reported the absolute yield changes under warming because these could not be transform into relative changes (e.g., ref. 3). (4), those producing temperature sensitivity of more than 50% K^{-1} were deemed as outliers and removed[8]. (5), studies presenting the results as a map or figure that could not be digitized using the software "GetData Graph digitizer" (GetData Graph Digitizer, 2008), were abandoned (e.g., refs 9, 10). (6), as we focus on the single temperature effect, only those warming treatments with ambient CO_2 concentration, solar radiation and precipitation were selected. As a result of this filtering, a total of 506 data points from 77 studies were included in the following analysis.

The field warming experiments in our database include two different warming designs: passive and active warming (Supplementary Table 1). Passive warming designs include closed-top chambers, temperature-gradient chambers or tunnels, and traditional open-top chambers. This type of heating equipment is partly or fully isolated from the surrounding natural environment; active designs include those with field open-air and artificial heaters, such as large-area open-top chambers[11] and free-air above-canopy heaters.

Constraint method. To constrain the GGCM-derived long-term temperature sensitivity, a linear least-squares regression model was first built between the present-day temperature sensitivity ($S_{\mathrm{Y,T}}^{\mathrm{int}}$) and the long-term temperature sensitivity ($S_{\mathrm{Y,T}}^{\mathrm{lt}}$) across the models: $\hat{y}_i = a\hat{x}_i + b + \varepsilon_i$. The least squares error of the regression model is calculated as: $s^2 = \frac{1}{n-2}\sum_1^n (y_i - \hat{y}_i)^2$. Where n is the number of data points in the regression.

For a given x, the predicted error for y, $\sigma(\hat{y}|x)$, is: $\sigma(\hat{y}|x) = s\sqrt{1 + \frac{1}{n} + \frac{(x-\bar{x})^2}{n\sigma_x^2}}$, where $\bar{x}$ is the average of series x, and σ_x^2 is the variance of x: $\sigma_x^2 = \sum_1^n (x_i - \bar{x})^2\,/\mathrm{n}$. The predicted variable ($\hat{y}$) then defines a Gaussian probability density function for y, with a standard deviation of $\sigma(\hat{y}|x)$: $p(\hat{y}|x) \sim N(f(x), \sigma(\hat{y}|x)^2)$. We can therefore obtain the probability density function (PDF) for the corresponding long-term temperature sensitivity for a given present-day temperature sensitivity: $p(\widehat{S_{\mathrm{Y,T}}^{\mathrm{lt}}}|S_{\mathrm{Y,T}}^{\mathrm{int}})$.

The present-day temperature sensitivity can be estimated from the field observations, so the model-derived relationship between the present and future is combined with the observations to produce a maximum-likelihood long-term temperature sensitivity. Field observations have their own uncertainties and provide another PDF with the assumption that all observations can be represented by a Gaussian distribution: $p\left(S_{\mathrm{Y,T}}^{\mathrm{obs}}\right) \sim N(\overline{S_{\mathrm{Y,T}}^{\mathrm{obs}}}, {\sigma_{S_{\mathrm{Y,T}}^{\mathrm{obs}}}}^2)$, where $\overline{S_{\mathrm{Y,T}}^{\mathrm{obs}}}$ and $\sigma_{S_{\mathrm{Y,T}}^{\mathrm{obs}}}$ are the average and standard deviation of $S_{\mathrm{Y,T}}^{\mathrm{obs}}$, respectively. Integrating the two PDFs produces continuous probabilities of a modelled sensitivity given an observation-derived sensitivity. The integral of contours across the horizontal-axis variable is thus the observation-constrained PDF for the long-term temperature sensitivity ($S_{\mathrm{Y,T}}^{\mathrm{lt}}$):

$$p_c\left(S_{\mathrm{Y,T}}^{\mathrm{lt}}\right) = \int_{-\infty}^{+\infty} p(S_{\mathrm{Y,T}}^{\mathrm{obs}})\, p(\widehat{S_{\mathrm{Y,T}}^{\mathrm{lt}}}|S_{\mathrm{Y,T}}^{\mathrm{int}})\mathrm{d}S_{\mathrm{Y,T}}^{\mathrm{obs}} \qquad (2)$$

Meanwhile, we can obtain another PDF for the unconstrained $S_{\mathrm{Y,T}}^{\mathrm{lt}}$ by assuming that the spread of the model ensemble can be represented by a Gaussian distribution: $p_u\left(S_{\mathrm{Y,T}}^{\mathrm{lt}}\right) \sim N(\overline{S_{\mathrm{Y,T}}^{\mathrm{lt}}}, \sigma_{S_{\mathrm{Y,T}}^{\mathrm{lt}}}{}^2)$, where $\overline{S_{\mathrm{Y,T}}^{\mathrm{lt}}}$ and $\sigma_{S_{\mathrm{Y,T}}^{\mathrm{lt}}}$ are the average and standard deviation of $S_{\mathrm{Y,T}}^{\mathrm{lt}}$, respectively.

The historical temperature sensitivity of rice yield for each grid cell was derived from the following regression models:

$$Y_t = \beta_0 + S_{\mathrm{Y,T}}^{\mathrm{int}}\, T_t + S_{\mathrm{Y,P}}^{\mathrm{int}}\, P_t + S_{\mathrm{Y,R}}^{\mathrm{int}}\, R_t + \varepsilon_t \qquad (3)$$

where Y_t, T_t, P_t, *and* R_t represent rice yield, temperature, precipitation and solar radiation of the growing season in year *t*, respectively. $S_{\mathrm{Y,T}}^{\mathrm{int}}$, $S_{\mathrm{Y,P}}^{\mathrm{int}}$ and $S_{\mathrm{Y,R}}^{\mathrm{int}}$ represents temperature sensitivity, precipitation sensitivity and radiation sensitivity of rice yield, respectively. The 0.5×0.5 degree gridded crop calendars including the start and end month of the main growing season for rice is compiled by ref. 12, with Chinese crop data updated from more exact *Chinese Agricultural Phenology Atlas*[13]. The grid cells with crop failure (i.e., yield equals zero) or yield data of less than ten years duration were not included in the regression model. To obtain the global average $S_{\mathrm{Y,T}}^{\mathrm{int}}$, each grid cell was weighted by its production, based on modelled yield and the current rice area[14]. For future climate scenarios, we calculated the long-term temperature sensitivity ($S_{\mathrm{Y,T}}^{\mathrm{lt}}$) from climate impacts using the simple formula:

$$S_{\mathrm{Y,T}}^{\mathrm{lt}} = (Y_{2070\text{-}2099} - Y_{1971\text{-}2000}) / \Delta T \qquad (4)$$

where $Y_{2070\text{-}2099}$ and $Y_{1971\text{-}2000}$ represent the averaged rice yield during 2070-2099 and 1971-2000, respectively. ΔT is growing-season temperature change between the two time periods.

Supplementary References

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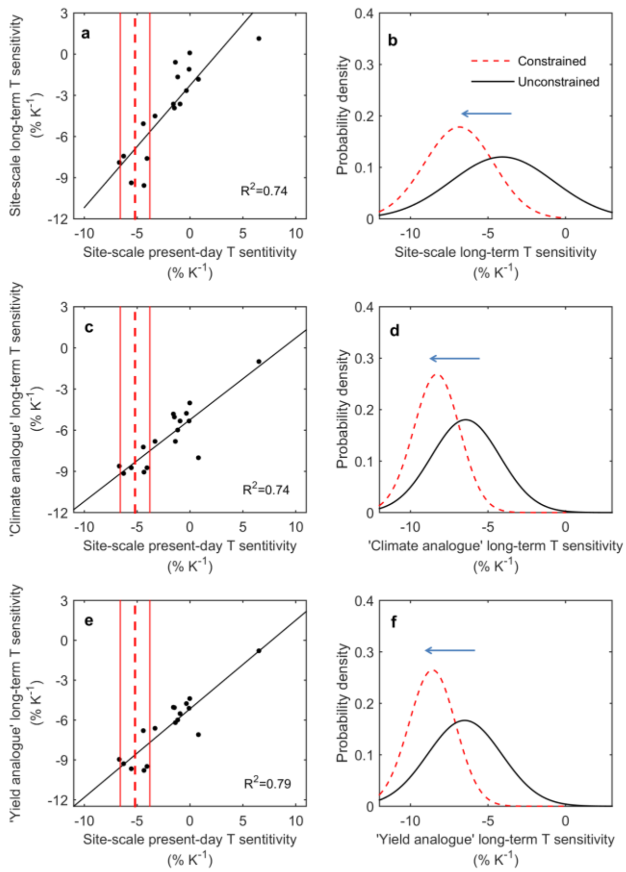
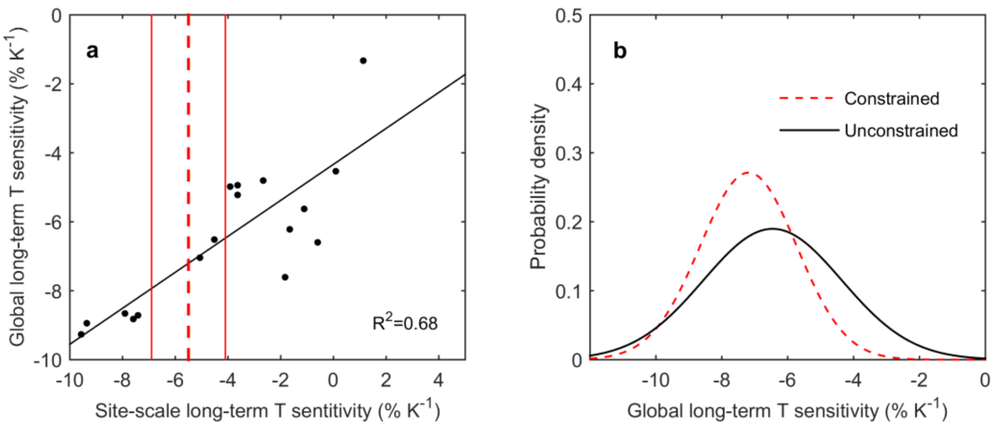
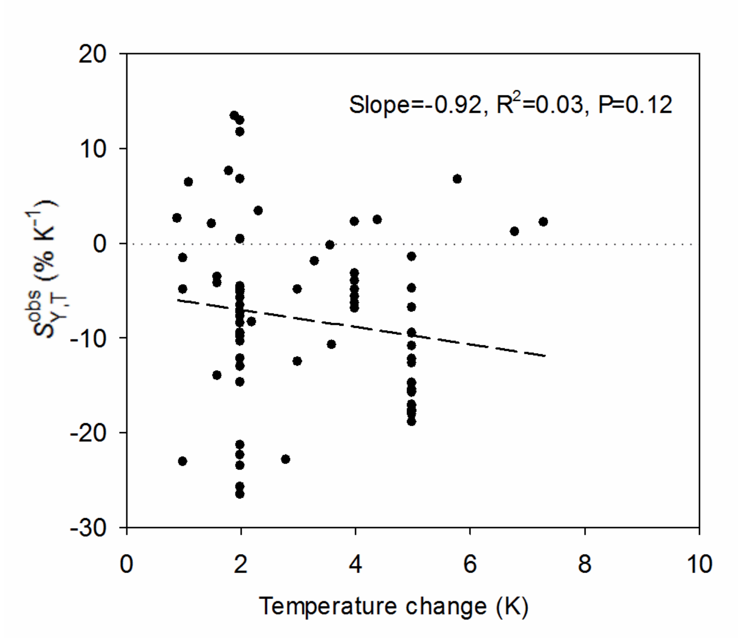


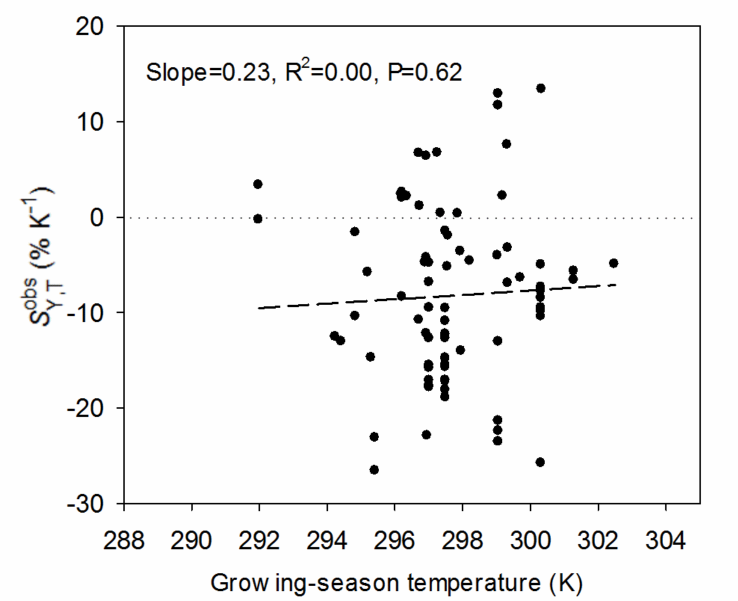
Supplementary Figure 1. Same as Fig. 2 in the main text but the long-term temperature sensitivity is the average of the grid cells where experimental sites are located (**a,b**) and the grid cells with similar climate (**c,d**) or rice yield (**e,f**). The ‘climate analogue’ grid cells were extracted when the growing-season mean temperature differs by less than 0.5 ℃ and growing-season precipitation by less than 50 mm from the grid cells of experimental sites. The ‘yield analogue’ grid cells were extracted when the annual mean yield differs by less than 0.2 t ha^{-1} from the grids cells of experimental sites.



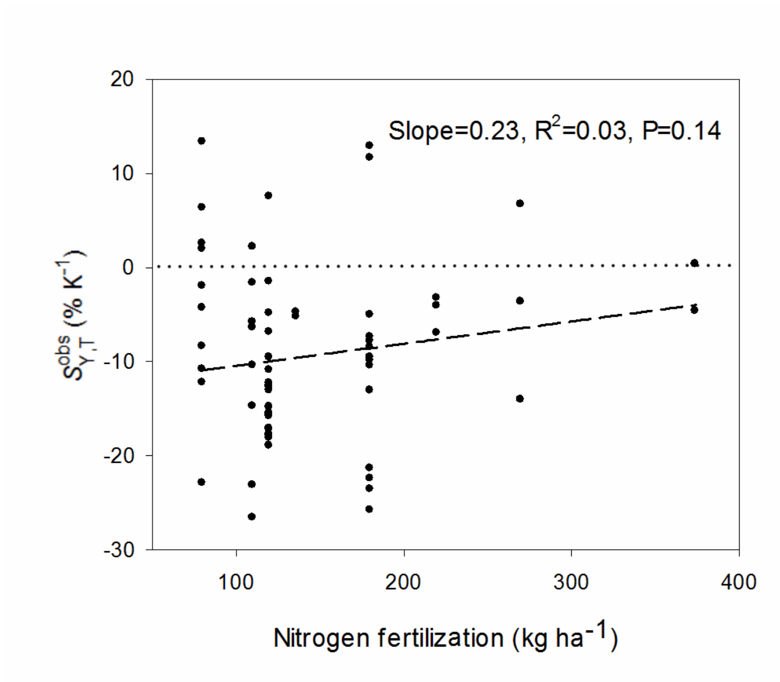
Supplementary Figure 2. Same as Fig. 2 in the main text but the temperature sensitivity from field warming experiments were considered as the long-term.



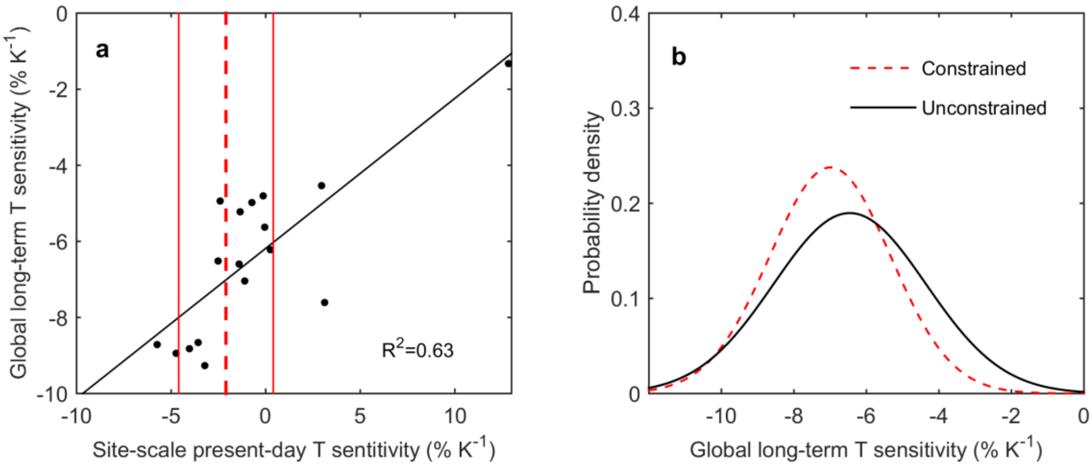
Supplementary Figure 3. Temperature sensitivity of rice yield ($S_{Y,T}^{obs}$) under different magnitudes of warming derived from field warming experiments.



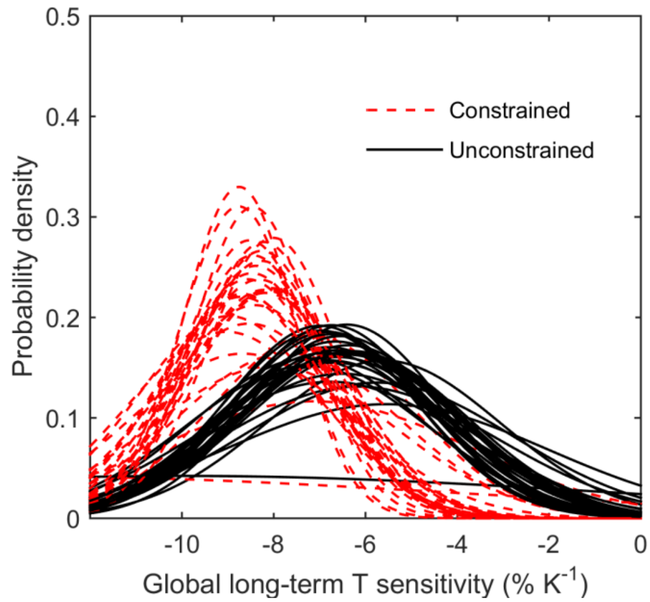
Supplementary Figure 4. Temperature sensitivity of rice yield ($S_{\mathrm{Y,T}}^{\mathrm{obs}}$) under different local growing-season temperatures derived from field warming experiments.



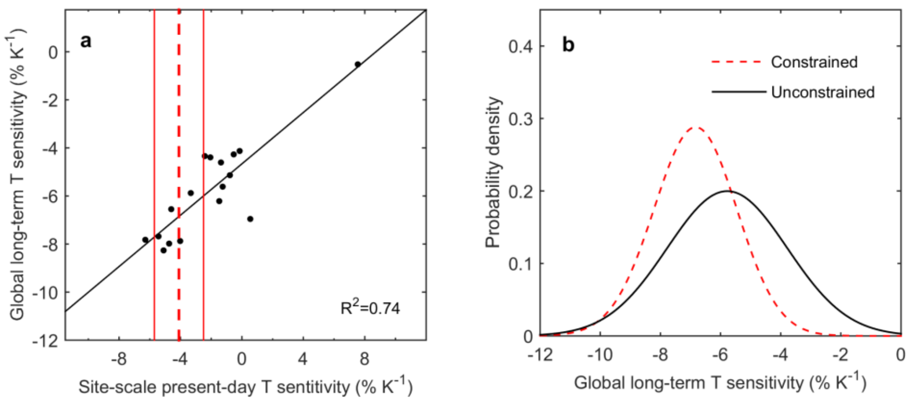
Supplementary Figure 5. Temperature sensitivity of rice yield ($S_{\mathrm{Y,T}}^{\mathrm{obs}}$) under different amounts of nitrogen fertilization derived from field warming experiments.



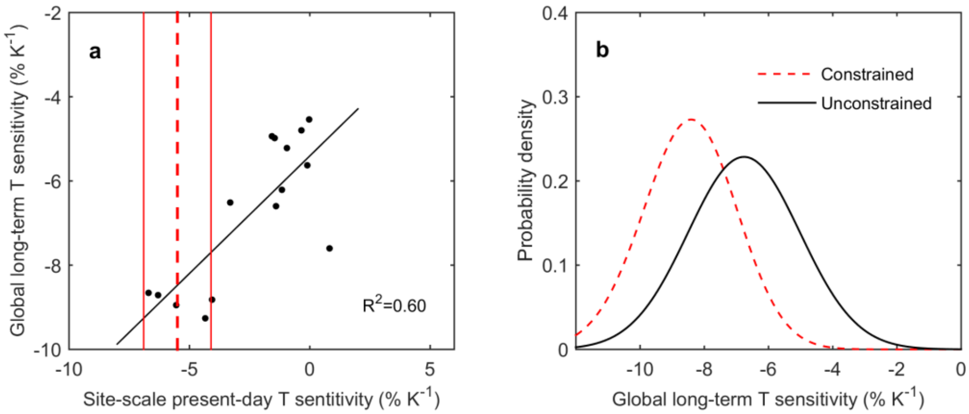
Supplementary Figure 6. Same as Fig. 2 in main text but $S_{\mathrm{Y,T}}^{\mathrm{lt}}$ was constrained by field warming experiments with active warming design.



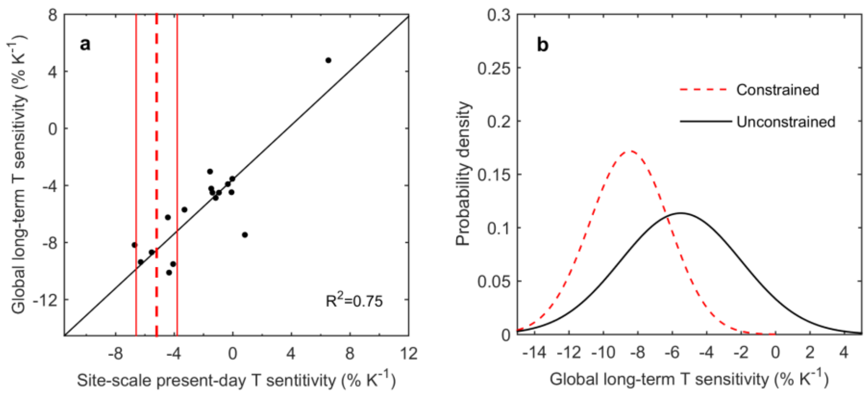
Supplementary Figure 7. Same as Fig. 2b in main text but $S_{\mathrm{Y,T}}^{\mathrm{lt}}$ was calculated based on each year of yield and temperature, not on the average of many years.



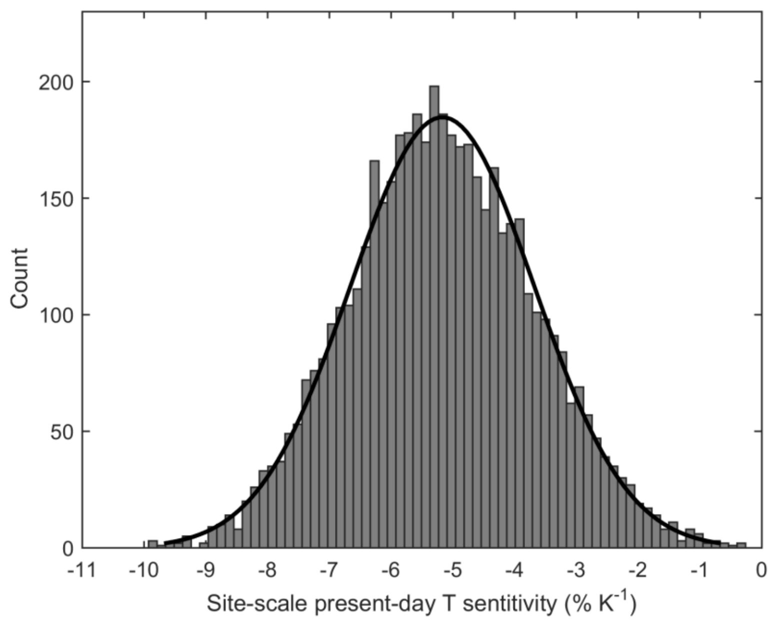
Supplementary Figure 8. Same as Fig. 2 in main text but the constraint was restricted to the regions of Asia.



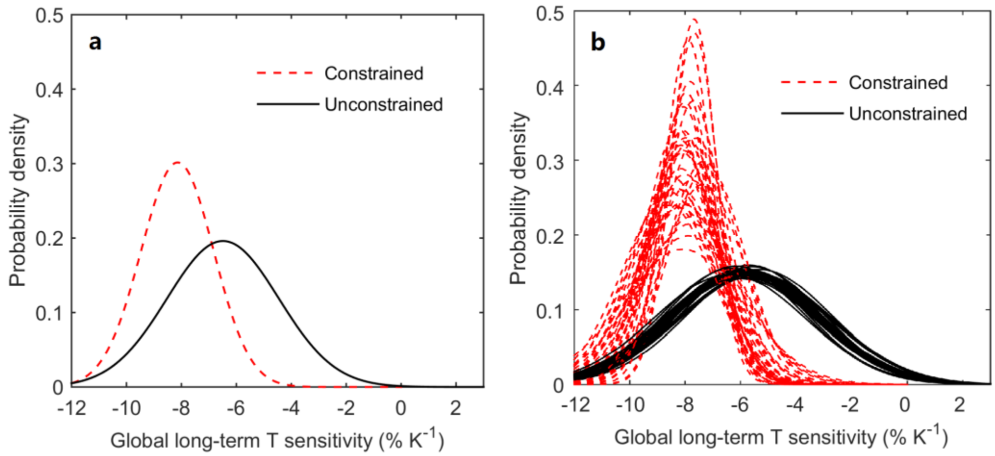
Supplementary Figure 9. Same as Fig. 2 in main text but LPJ-GUESS and GEPIC modelling results were removed in the constraint.



Supplementary Figure 10. Same as Fig. 2 in main text but the long-term temperature sensitivity for GGCMs was calculated based on the yield and temperature differences between the 2050s (2036-2065) and the baseline (1971-2000).



Supplementary Figure 11. The bootstrap distribution of average temperature sensitivity for all the experimental sites from 5000 times of bootstrap resampling. The black line shows the fitting curve using the normal equation.



Supplementary Figure 12. Same as Fig. 2b but different GGCM-CM combinations were used**. a,** All GGCM-CM combinations**. b,** five crop models but randomly selecting one CM 50 times.

Supplementary Table 1. The temperature sensitivity of rice yield ($S_{\mathrm{Y,T}}^{\mathrm{obs}}$) and relative information for field warming experiments all over the globe. N.A. represent the information is not available.

Cultivar	Country	Site name	Latitude	Longtitude	Research time (year)	Nitrogen (kg ha^{-1})	Warming design	Warming type	Temperature change (ΔK)	Growing season temperature (K)	$S_{\mathrm{Y,T}}^{\mathrm{obs}}$ (% K^{-1})
IR72	Philippines	Los Banos	14.22	121.25	1994	110	Open top camber	Passive	4.0	299.7	-6.4
IR72	Philippines	Los Banos	14.22	121.25	1995	220	Open top camber	Passive	4.0	299.1	-4.1
N.A.	Nepal	Khumaltar	27.65	85.33	2001	N.A.	Open top camber	Passive	6.8	296.8	1.1
N.A.	Nepal	Khumaltar	27.65	85.33	2002	N.A.	Open top camber	Passive	4.4	296.2	2.3
N.A.	Nepal	Khumaltar	27.65	85.33	2003	N.A.	Open top camber	Passive	5.8	296.7	6.6
N.A.	Nepal	Khumaltar	27.65	85.33	2004	N.A.	Open top camber	Passive	7.3	296.4	2.1
Nipponbare	Japan	Okayama	34.67	135.92	2002	80	Temperature gradient chamber	Passive	2.0	297.0	-12.3
Nipponbare	Japan	Okayama	34.67	135.92	2002	80	Temperature gradient chamber	Passive	1.6	297.0	-4.3
Nipponbare	Japan	Okayama	34.67	135.92	2002	80	Temperature gradient chamber	Passive	1.1	297.0	6.3
Nipponbare	Japan	Okayama	34.67	135.92	2003	80	Temperature gradient chamber	Passive	2.2	296.2	-8.4
Nipponbare	Japan	Okayama	34.67	135.92	2003	80	Temperature gradient chamber	Passive	1.5	296.2	1.9
Nipponbare	Japan	Okayama	34.67	135.92	2003	80	Temperature gradient chamber	Passive	0.9	296.2	2.5
Nipponbare	Japan	Okayama	34.67	135.92	2004	80	Temperature gradient chamber	Passive	3.3	297.6	-2.0

Nipponbare	Japan	Okayama	34.67	135.92	2005	80	Temperature gradient chamber	Passive	2.8	297.0	-23.0
Nipponbare	Japan	Okayama	34.67	135.92	2006	80	Temperature gradient chamber	Passive	3.6	296.7	-10.9
Nampyeon, Saegyewha, Unkwang	Korea	Gwangju	35.17	126.88	2009	110	Temperature gradient chamber	Passive	1.0	294.9	-1.7
Nampyeon, Saegyewha, Unkwang	Korea	Gwangju	35.17	126.88	2009	110	Temperature gradient chamber	Passive	2.0	294.9	-10.5
Nampyeon, Saegyewha, Unkwang	Korea	Gwangju	35.17	126.88	2010	110	Temperature gradient chamber	Passive	1.0	295.4	-23.2
Nampyeon, Saegyewha, Unkwang	Korea	Gwangju	35.17	126.88	2010	110	Temperature gradient chamber	Passive	2.0	295.4	-26.6
IR72	Philippines	Los Banos	14.22	121.25	1996	220	Open top camber	Passive	4.0	299.4	-3.3
NPT2	Philippines	Los Banos	14.22	121.25	1996	220	Open top camber	Passive	4.0	299.4	-7.0
N-22	Philippines	Los Banos	14.22	121.25	1995	110	Open top camber	Passive	4.0	299.2	2.2
CORH3	India	Tamil Nadu	11	77	2012	N.A.	Control chamber	Passive	2.0	301.3	-6.7
CORH3	India	Tamil Nadu	11	77	2012	N.A.	Control chamber	Passive	4.0	301.3	-5.8
Ariete	Portugal	Tagus Valley	39.04	-8.74	2011	120	Open top camber	Passive	2.0	294.4	-13.1
Ariete	Portugal	Tagus Valley	39.04	-8.74	2012	120	Open top camber	Passive	3.0	294.3	-12.6
Pusa44	India	New Delhi	28.58	77.2	2009 2010 2011	N.A.	Temperature tunnels	Passive	1.0	302.5	-5.0

Pusa44	India	New Delhi	28.58	77.2	2009 2010 2011	N.A.	Temperature tunnels	Passive	2.0	302.5	-5.0
Pusa44	India	New Delhi	28.58	77.2	2009 2010 2011	N.A.	Temperature tunnels	Passive	3.0	302.5	-5.0
Pusa44	India	New Delhi	28.58	77.2	2009 2010 2011	N.A.	Temperature tunnels	Passive	4.0	302.5	-5.0
Liangyou287	China	Jingzhou	30.35	112.15	2012	N.A.	Open top camber	Passive	2.0	297.3	6.7
Dongjinbyeo	Korea	Gwangju	35.17	126.88	2007	110	Temperature gradient chamber	Passive	2.0	295.3	-14.8
Dongjinbyeo	Korea	Gwangju	35.17	126.88	2008	110	Temperature gradient chamber	Passive	2.0	295.2	-5.9
Angelica	Philippines	Laguna	14.22	121.25	2010	80	Above-canopy heater	Active	1.9	300.4	13.3
Angelica	Philippines	Laguna	14.22	121.25	2011	120	Above-canopy heater	Active	1.8	299.3	7.5
huaidao5	China	Nanjing	32.12	118.83	2011	136	Above-canopy heater	Active	2.0	296.9	-4.8
huaidao5	China	Nanjing	32.12	118.83	2012	136	Above-canopy heater	Active	2.0	297.6	-5.3
L-204	USA	Gainesville	29.68	-82.27	2001	120	Temperature gradient chamber	Passive	5.0	297.0	-17.8
M-202	USA	Gainesville	29.68	-82.27	2001	120	Temperature gradient chamber	Passive	5.0	297.0	-17.2
Labelle	USA	Gainesville	29.68	-82.27	2001	120	Temperature gradient chamber	Passive	5.0	297.0	-15.9

Italica Livorna	USA	Gainesville	29.68	-82.27	2001	120	Temperature gradient chamber	Passive	5.0	297.0	-17.8
S-102	USA	Gainesville	29.68	-82.27	2001	120	Temperature gradient chamber	Passive	5.0	297.0	-17.9
Koshihikari	USA	Gainesville	29.68	-82.27	2001	120	Temperature gradient chamber	Passive	5.0	297.0	-15.6
M-103	USA	Gainesville	29.68	-82.27	2001	120	Temperature gradient chamber	Passive	5.0	297.0	-12.8
N-22	USA	Gainesville	29.68	-82.27	2001	120	Temperature gradient chamber	Passive	5.0	297.0	-9.6
IR-8	USA	Gainesville	29.68	-82.27	2001	120	Temperature gradient chamber	Passive	5.0	297.0	-4.9
IR-72	USA	Gainesville	29.68	-82.27	2001	120	Temperature gradient chamber	Passive	5.0	297.0	-6.9
L-204	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-17.2
M-202	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-15.8
Labelle	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-19.0
Italica Livorna	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-14.9
S-102	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-12.3
Koshihikari	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-14.8
M-103	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-15.6

N-22	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-1.5
WAB-12	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-12.4
WAB-16	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-12.8
CG-14	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-17.3
CG-17	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-18.2
IR-8	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-9.6
IR-72	USA	Gainesville	29.68	-82.27	2002	120	Temperature gradient chamber	Passive	5.0	297.5	-11.0
WYJ7	China	Nanjing	32.03	118.86	2006	374	Above-canopy heater	Active	2.0	298.2	-4.7
WYJ7	China	Nanjing	32.03	118.86	2007	374	Above-canopy heater	Active	2.0	297.9	0.3
NJ44	China	Nanjing	32.03	118.86	2008	374	Above-canopy heater	Active	2.0	297.4	0.4
DN425	China	Harbin	45.75	126.73	2011	N.A.	Above-canopy heater	Active	2.3	292.0	3.3
DN425	China	Harbin	45.75	126.73	2011	N.A.	Above-canopy heater	Active	3.6	292.0	-0.3
XWX1	China	Wuhan	30.47	114.35	2009	180	Open-top & heater	Active	2.0	300.3	-5.1
SKC	China	Wuhan	30.47	114.35	2009	180	Open-top & heater	Active	2.0	300.3	-9.6
DTWX	China	Wuhan	30.47	114.35	2009	180	Open-top & heater	Active	2.0	300.3	-8.5
ZX232	China	Wuhan	30.47	114.35	2009	180	Open-top & heater	Active	2.0	300.3	-7.8

CNSJ	China	Wuhan	30.47	114.35	2009	180	Open-top & heater	Active	2.0	300.3	-10.0
DY5	China	Wuhan	30.47	114.35	2009	180	Open-top & heater	Active	2.0	300.3	-9.6
JWR221	China	Wuhan	30.47	114.35	2009	180	Open-top & heater	Active	2.0	300.3	-10.5
ZH8	China	Wuhan	30.47	114.35	2009	180	Open-top & heater	Active	2.0	300.3	-7.4
J87-304	China	Wuhan	30.47	114.35	2009	180	Open-top & heater	Active	2.0	300.3	-25.8
DTWX	China	Wuhan	30.47	114.35	2010	180	Open-top & heater	Active	2.0	299.1	11.6
ZX232	China	Wuhan	30.47	114.35	2010	180	Open-top & heater	Active	2.0	299.1	-21.4
CNSJ	China	Wuhan	30.47	114.35	2010	180	Open-top & heater	Active	2.0	299.1	12.8
DY5	China	Wuhan	30.47	114.35	2010	180	Open-top & heater	Active	2.0	299.1	-13.1
JWR221	China	Wuhan	30.47	114.35	2010	180	Open-top & heater	Active	2.0	299.1	-22.5
ZH8	China	Wuhan	30.47	114.35	2010	180	Open-top & heater	Active	2.0	299.1	-23.6
XY933	China	Shanghai	31.21	121.13	2008	270	Above-canopy heater	Active	1.6	298.0	-3.7
XS128	China	Shanghai	31.21	121.13	2009	270	Above-canopy heater	Active	1.6	298.0	-14.1

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