

Supplement of

A food crop yield emulator for integration in the compact Earth system model OSCAR (OSCAR-crop v1.0)

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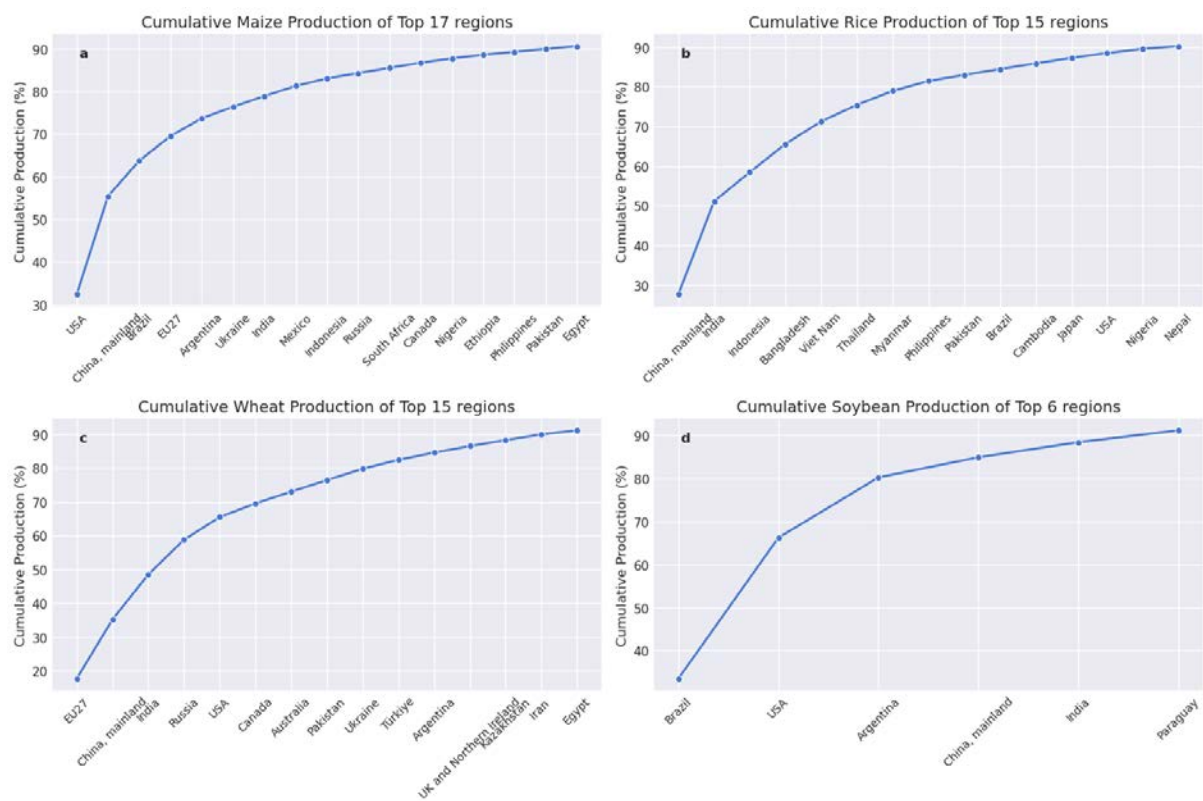


Figure S1. Top producing regions during the period of 2014 to 2023.

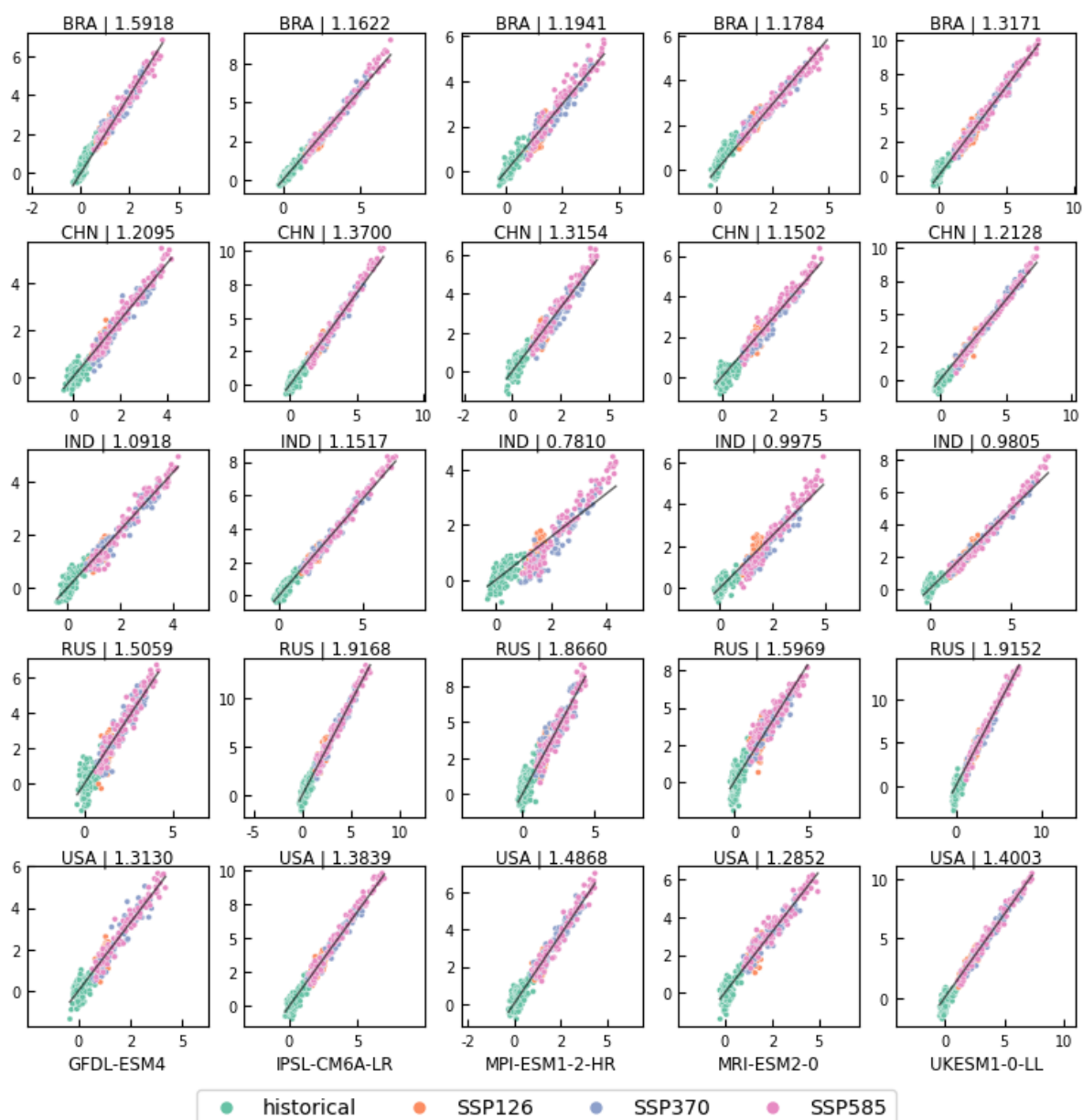


Figure S2. Relationship between global mean temperature differences and local temperature differences using the first concatenation scheme. Subplots in each row and column represent results from different countries (Brazil, mainland China, India, Russia, and the USA) and ESMs (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL). The values next to the regional code represent the linear coefficients.

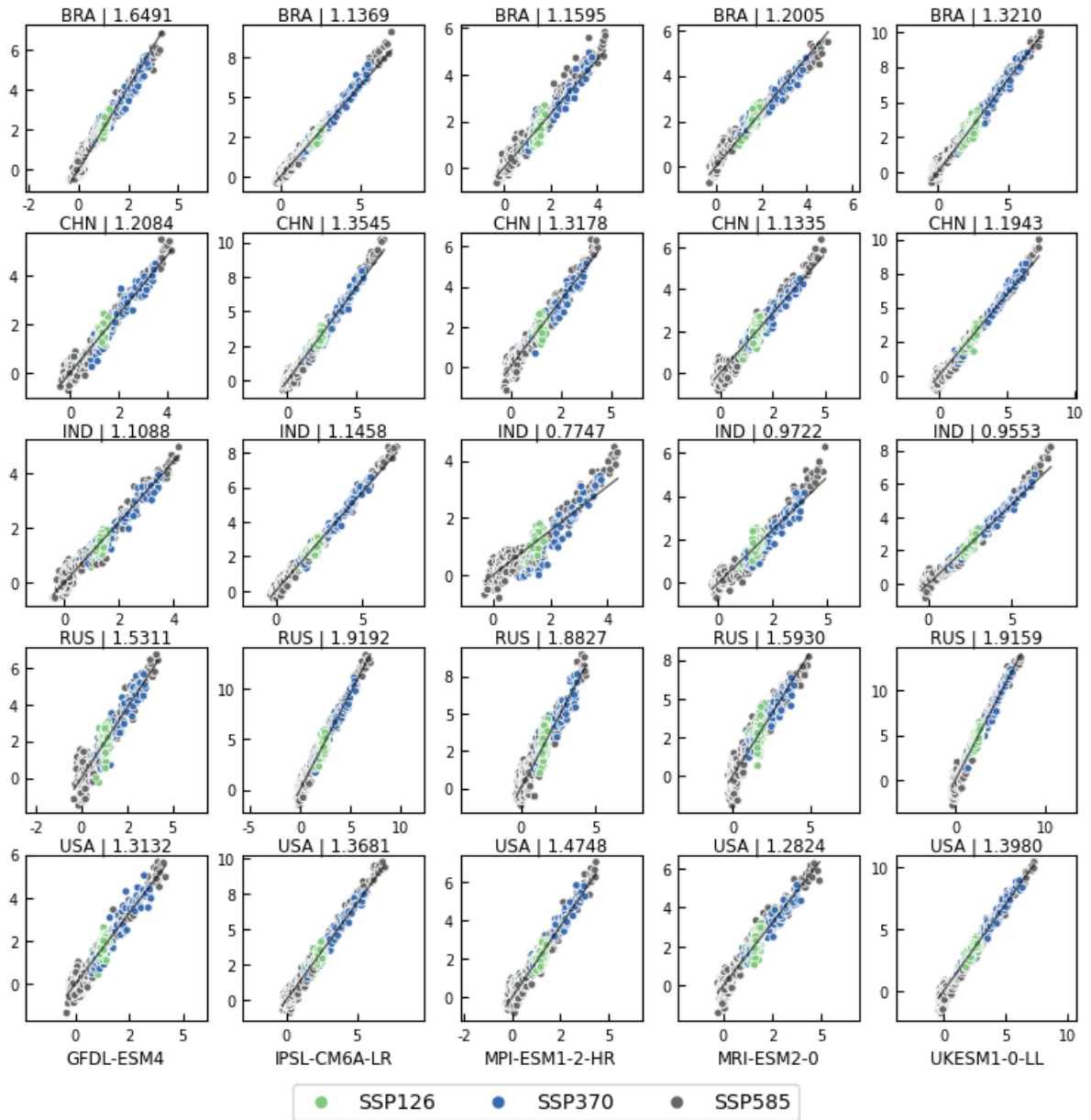


Figure S3. Relationship between global mean temperature differences and local temperature differences using the second concatenation scheme. Subplots in each row and column represent results from different countries (Brazil, mainland China, India, Russia, and the USA) and ESMs (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL), respectively. The values next to the regional code represent the linear coefficients.

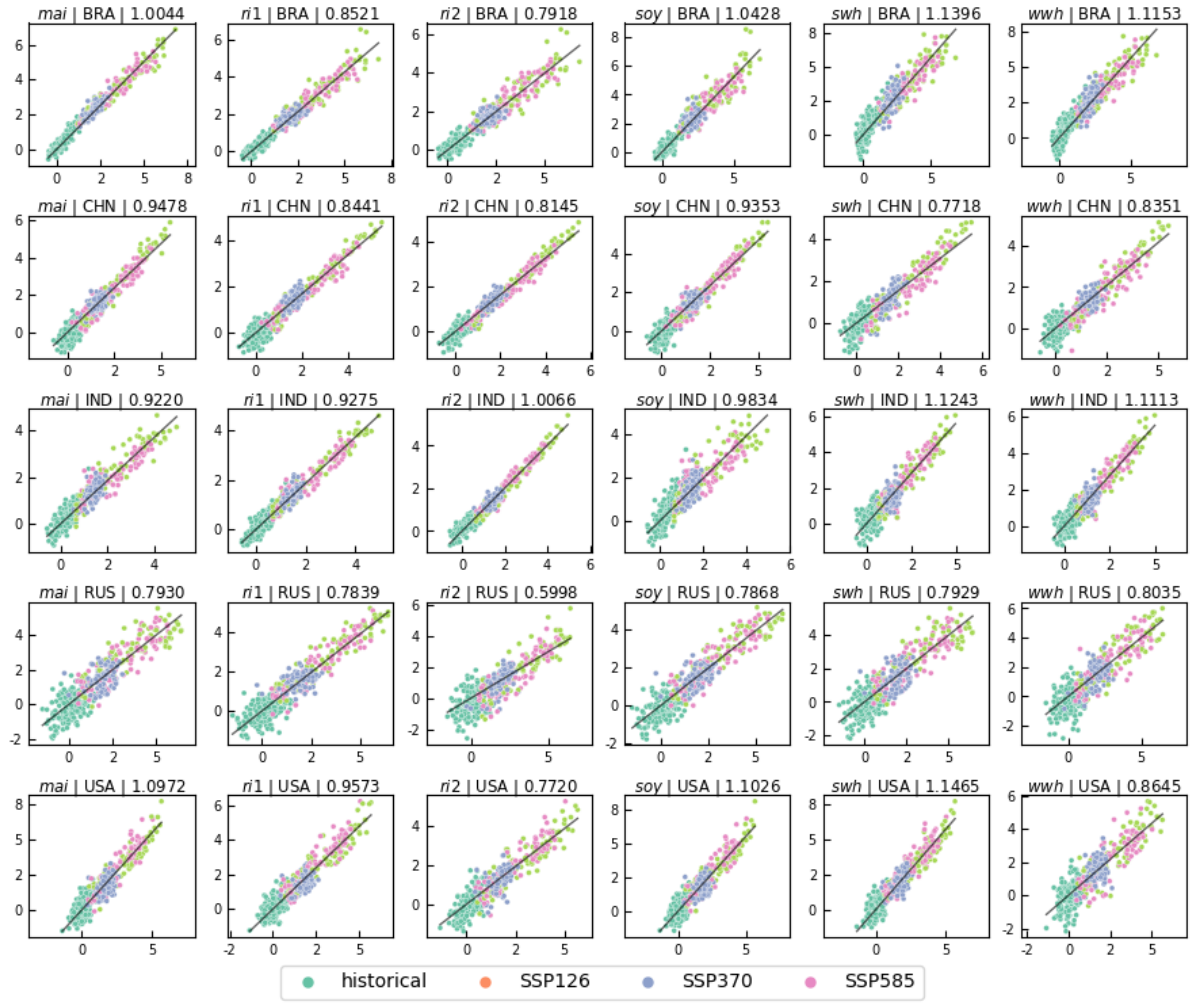


Figure S4. Relationship between local temperature differences and crop-specific growing season temperature differences under rainfed condition using the first concatenation scheme. Subplots in each row and column represent results from different countries (Brazil, mainland China, India, Russia, and the USA) and crop species. The results are from GFDL-ESM4. The values next to the regional code represent the linear coefficients.

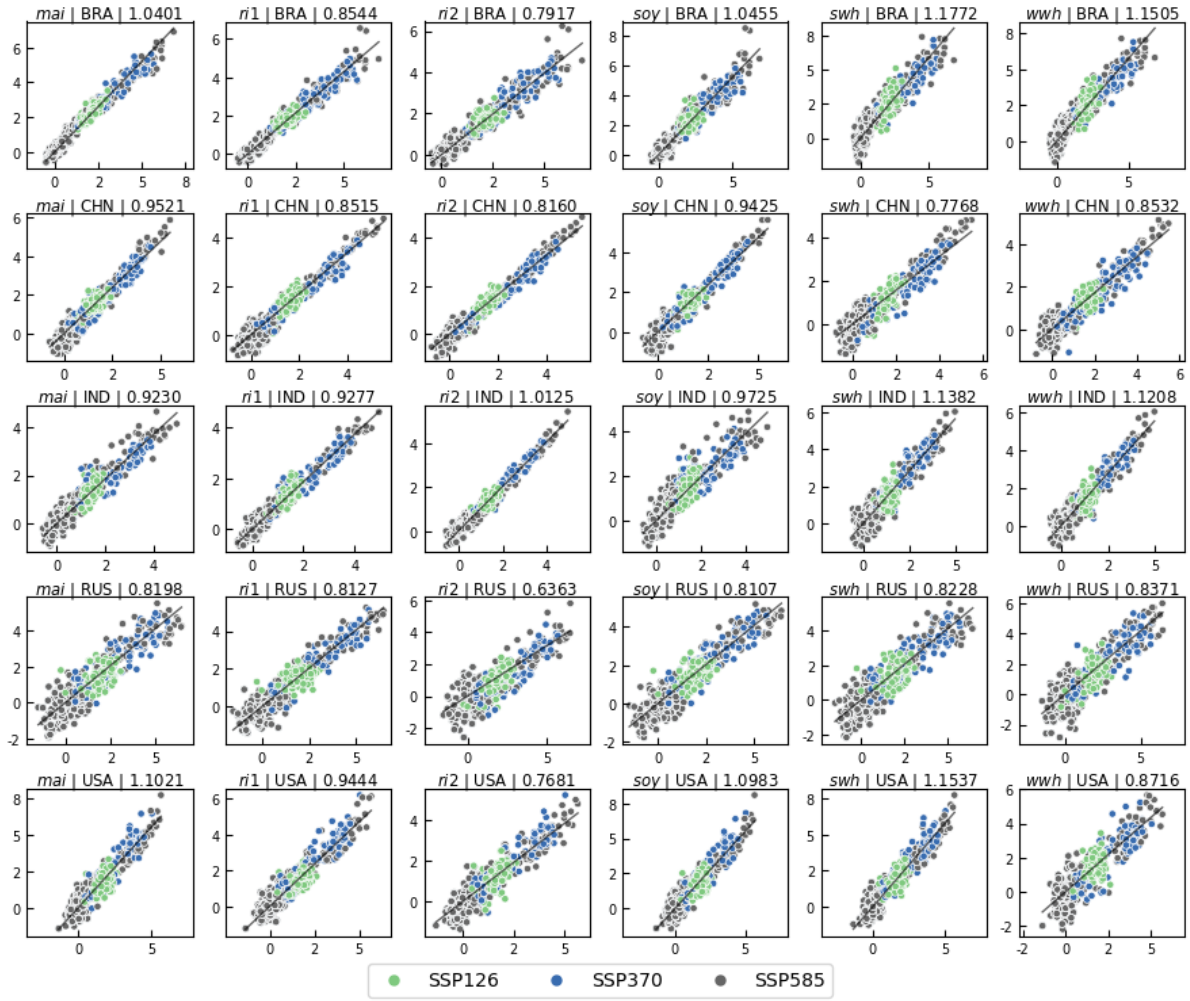


Figure S5. Relationship between local temperature differences and crop-specific growing season temperature differences under rainfed condition using the second concatenation scheme. Subplots in each row and column represent results from different countries (Brazil, mainland China, India, Russia, and the USA) and crop species. The results are from GFDL-ESM4. The values next to the regional code represent the linear coefficients.

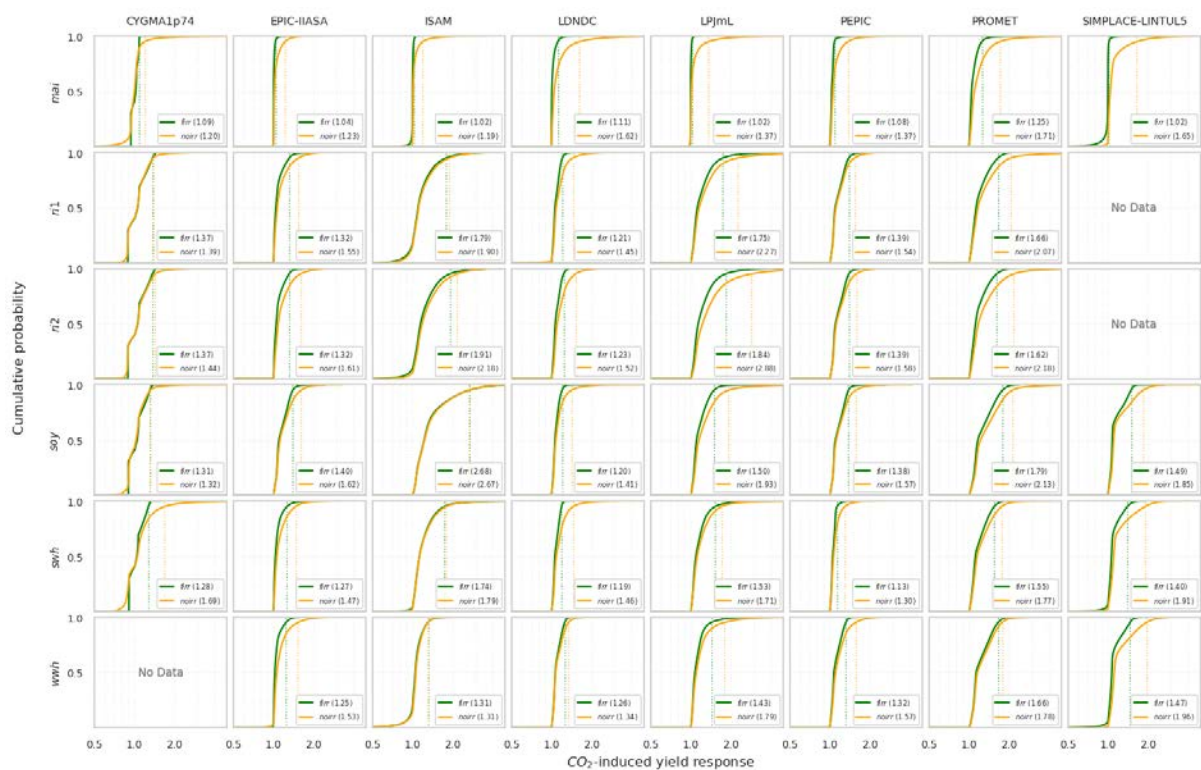


Figure S6. Cumulative probability of regional crop- and model-specific yield responses induced by CO₂. Values in the brackets represent the 95% percentiles of *frr* and *noirr* crops.

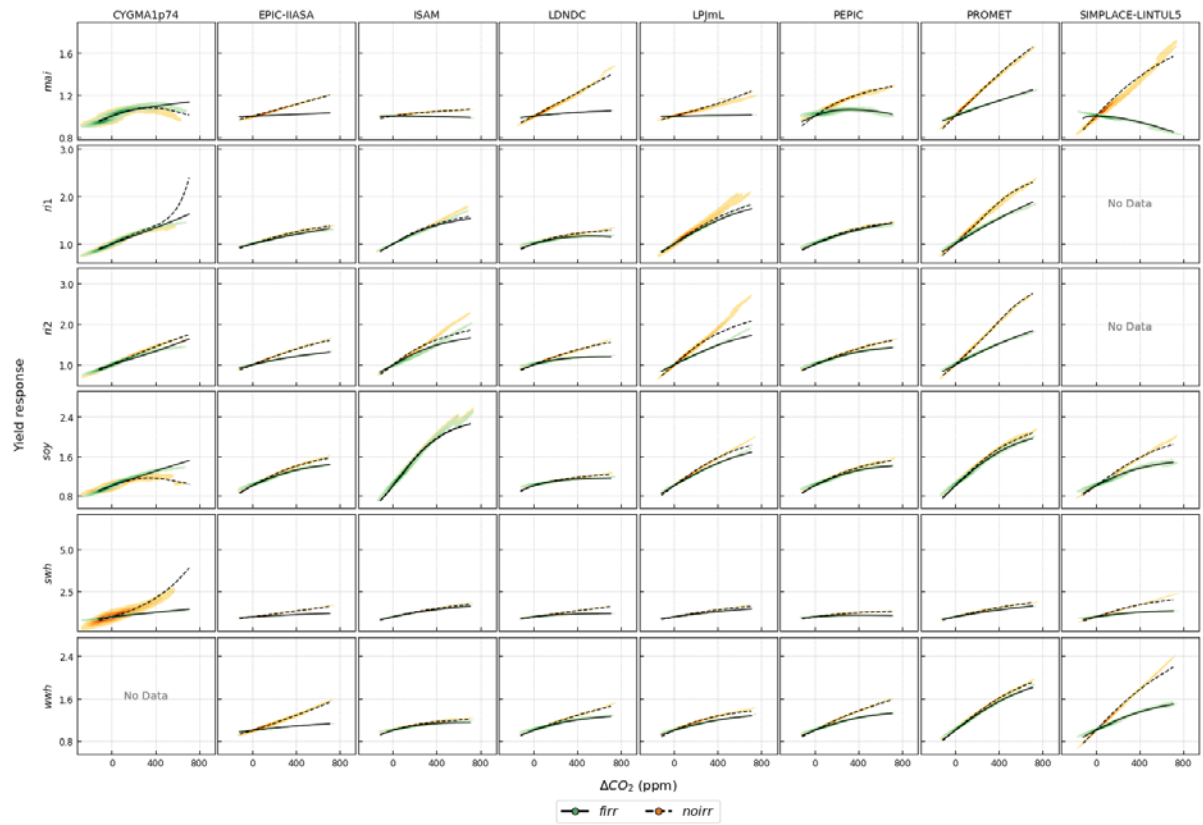


Figure S7. Kernel density estimation of global crop yield responses [CO_2] change (ppm) across eight GCMs under historical, SSP126, SSP370, and SSP585, including extreme-value regions. Black lines indicate aggregated results from the crop emulator. Black lines indicate aggregated results from the crop emulator. Green shades and orange shades represent *frr* and *noirr* conditions, separately. Darker shades suggest higher density.

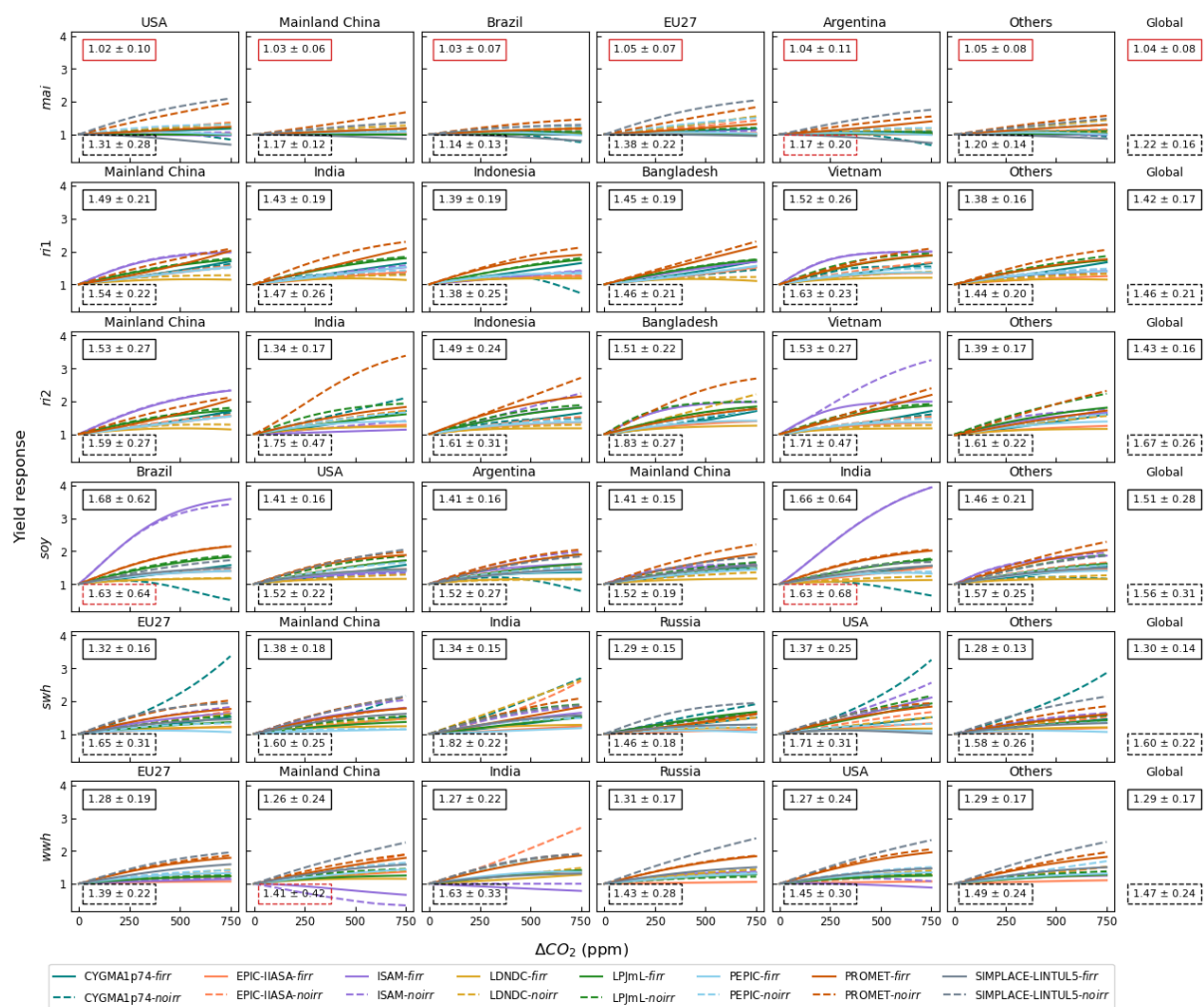


Figure S8. Region- and crop-specific yield responses to $[\text{CO}_2]$ change (ppm). Boxes show averages and standard deviations of end-of-century (2069–2099) yield responses for *frr* (solid lines) and *noirr* (dashed lines) crops under SSP585. Red box outlines indicate negative net yield responses.

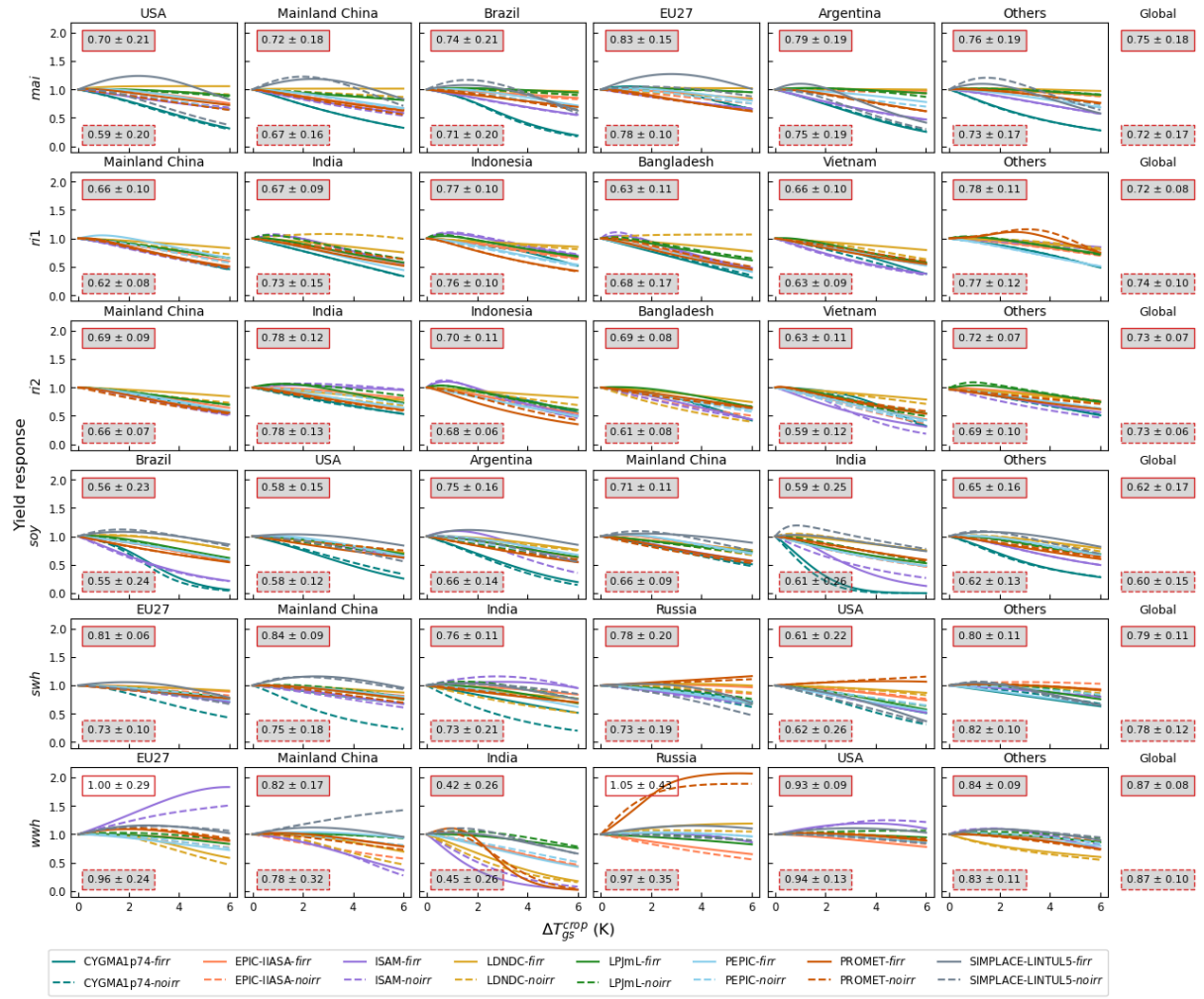


Figure S9. Region- and crop-specific yield responses to growing season temperature change (K). Boxes show averages and standard deviations of end-of-century (2069–2099) yield responses for *frr* (solid lines) and *noirr* (dashed lines) crops under SSP585. Boxes with gray shades indicate end-of-century negative net yield responses. Red box outlines indicate negative net yield responses.

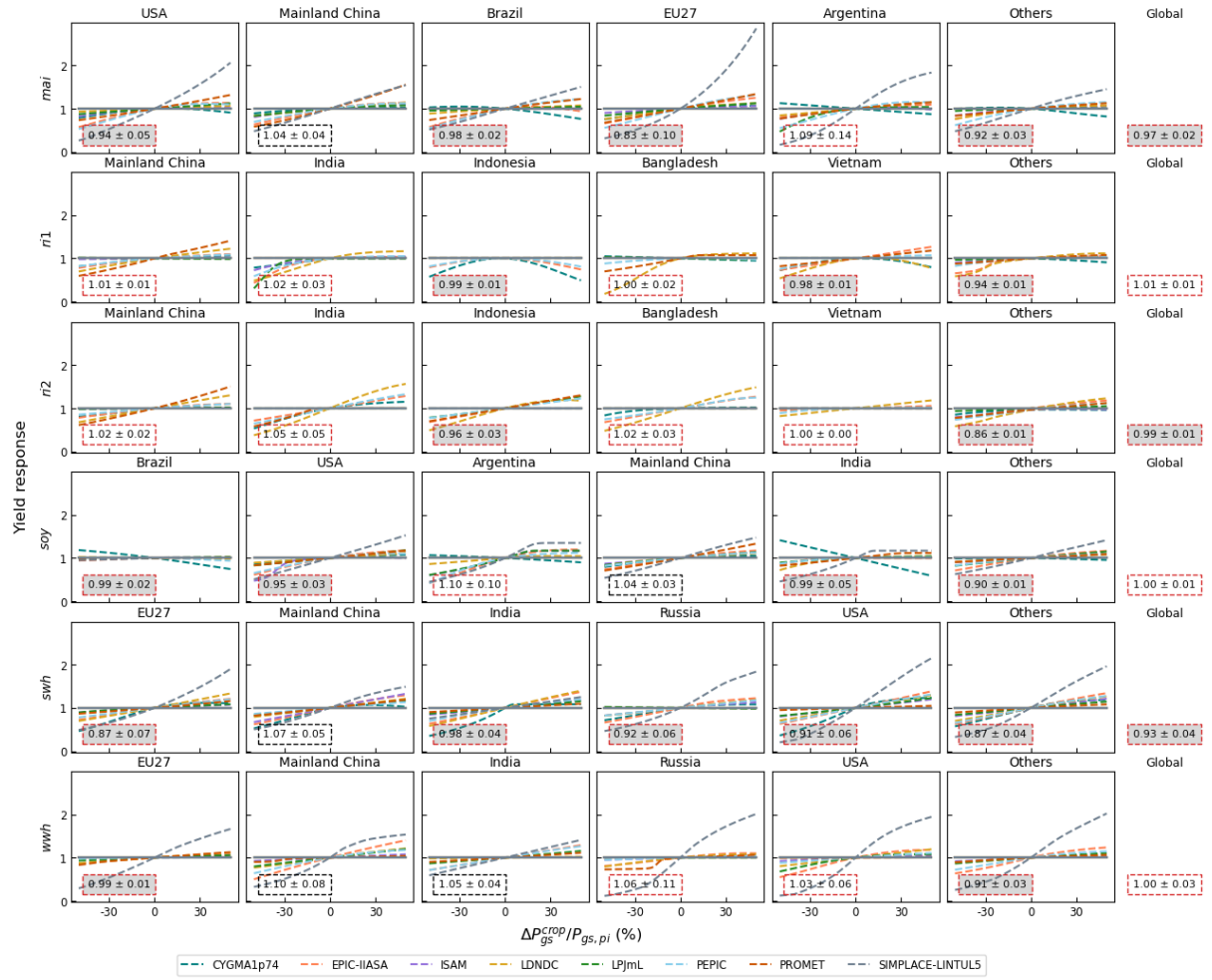


Figure S10. Region- and crop-specific yield responses to relative precipitation change (%). Boxes show averages and standard deviations of end-of-century (2069–2099) yield responses for *noirr* (dashed lines) crops under SSP585. Boxes with gray shades indicate end-of-century negative yield responses. Red box outlines indicate negative net yield responses.

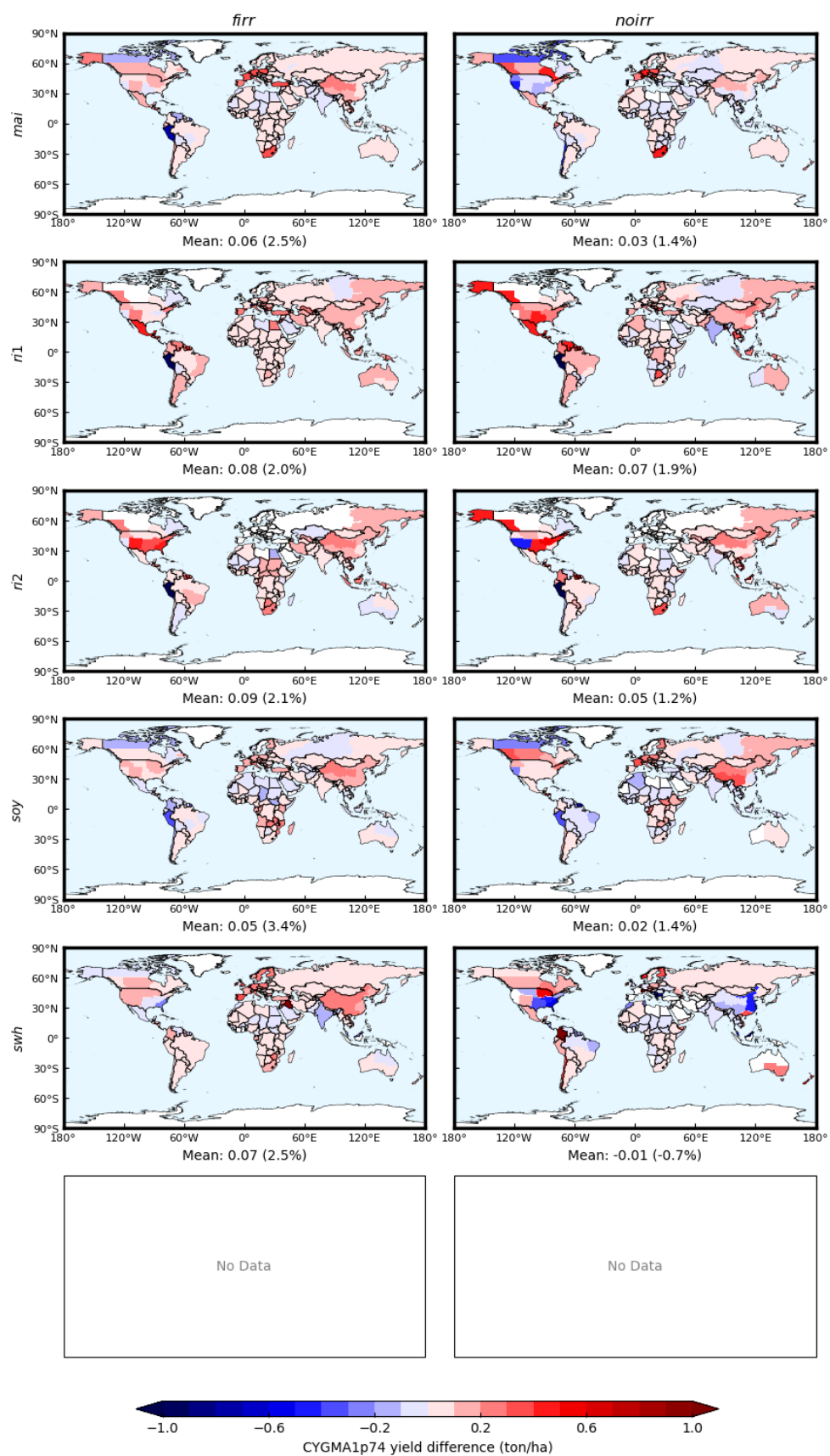


Figure S11. Yield differences between original and CYGMA1p74-based emulated crop yields under SSP585.

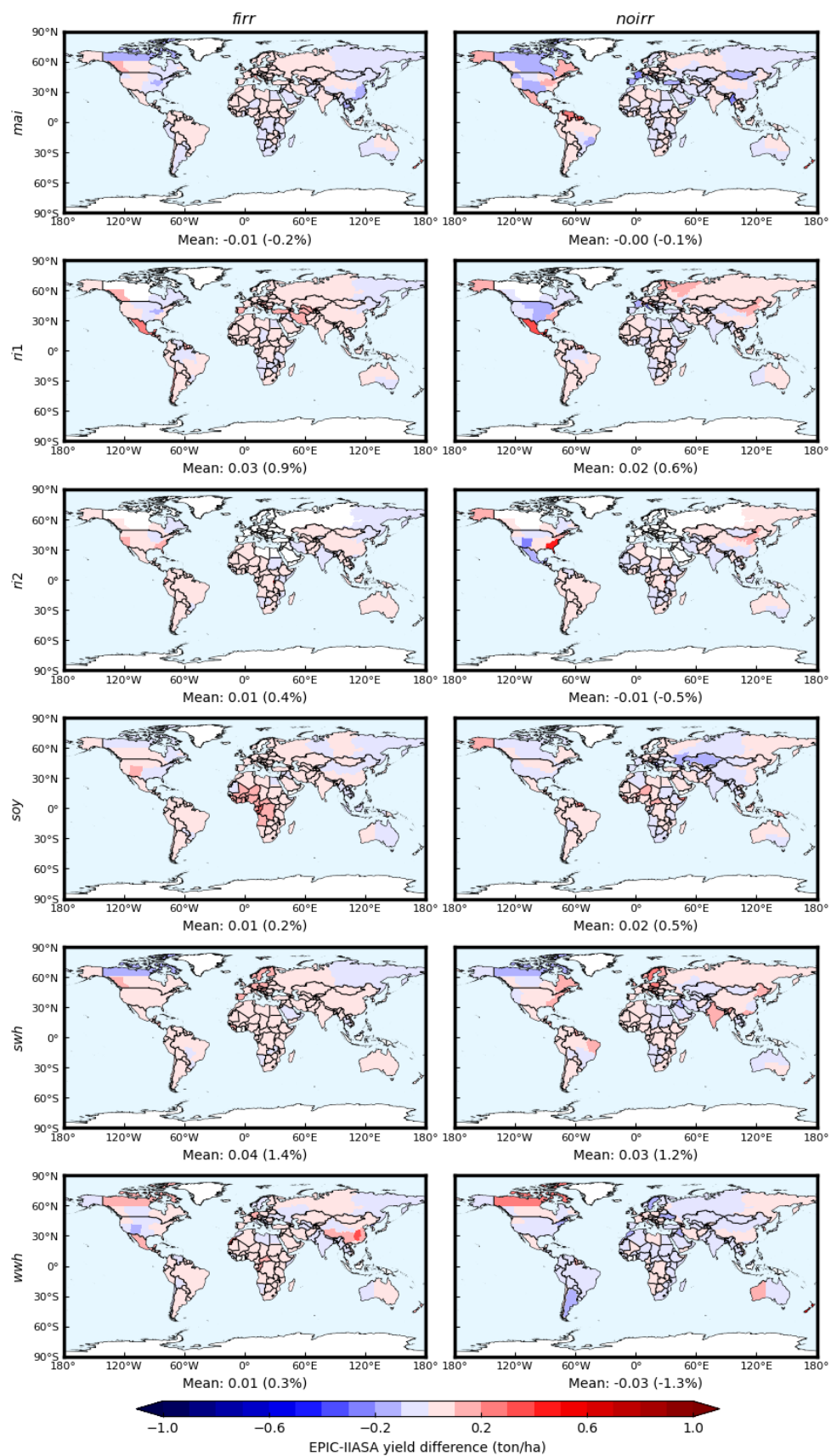


Figure S12. Yield differences between original and EPIC-IIASA-based emulated crop yields under SSP585.

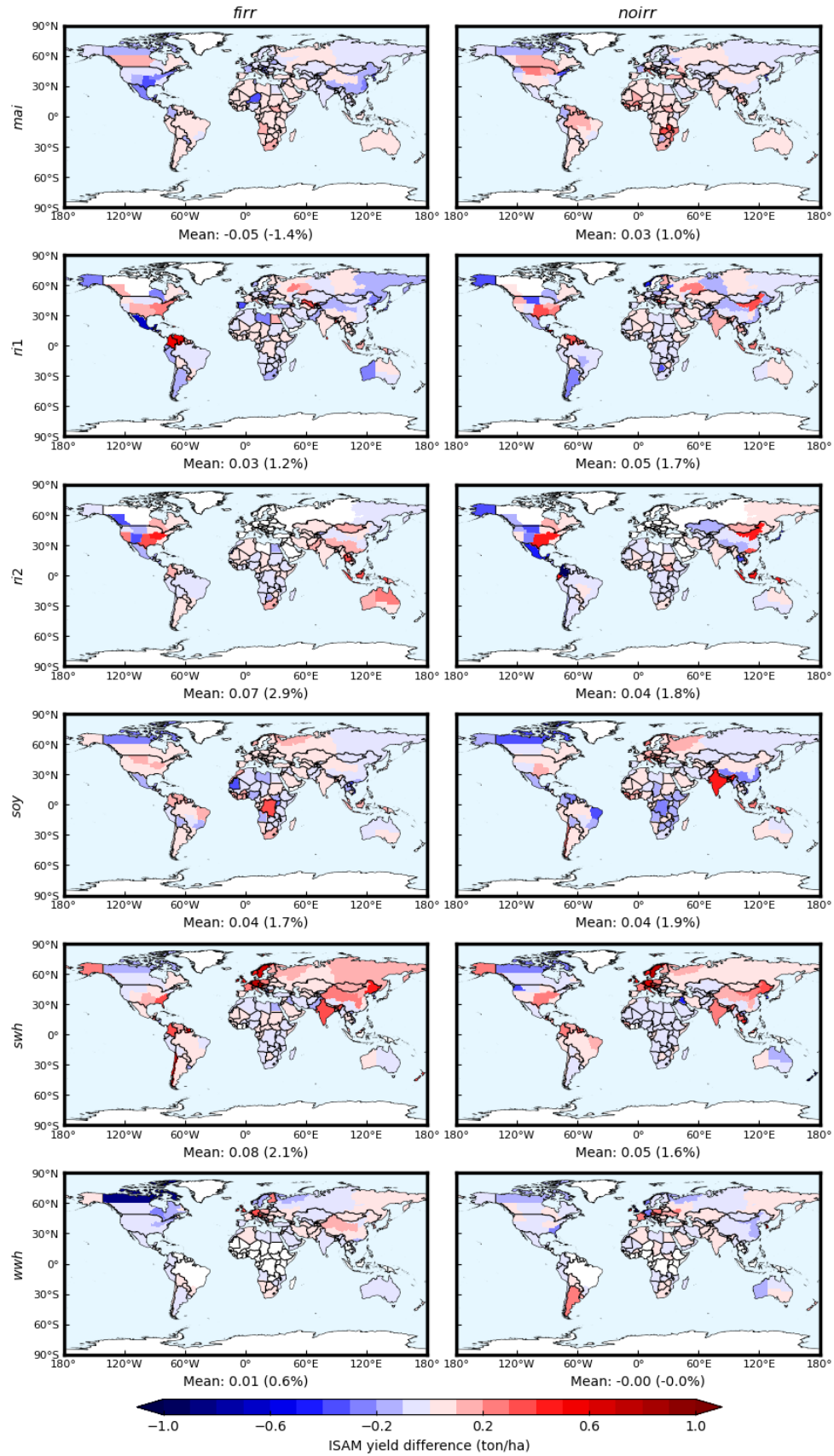


Figure S13. Yield differences between original and ISAM-based emulated crop yields under SSP585.

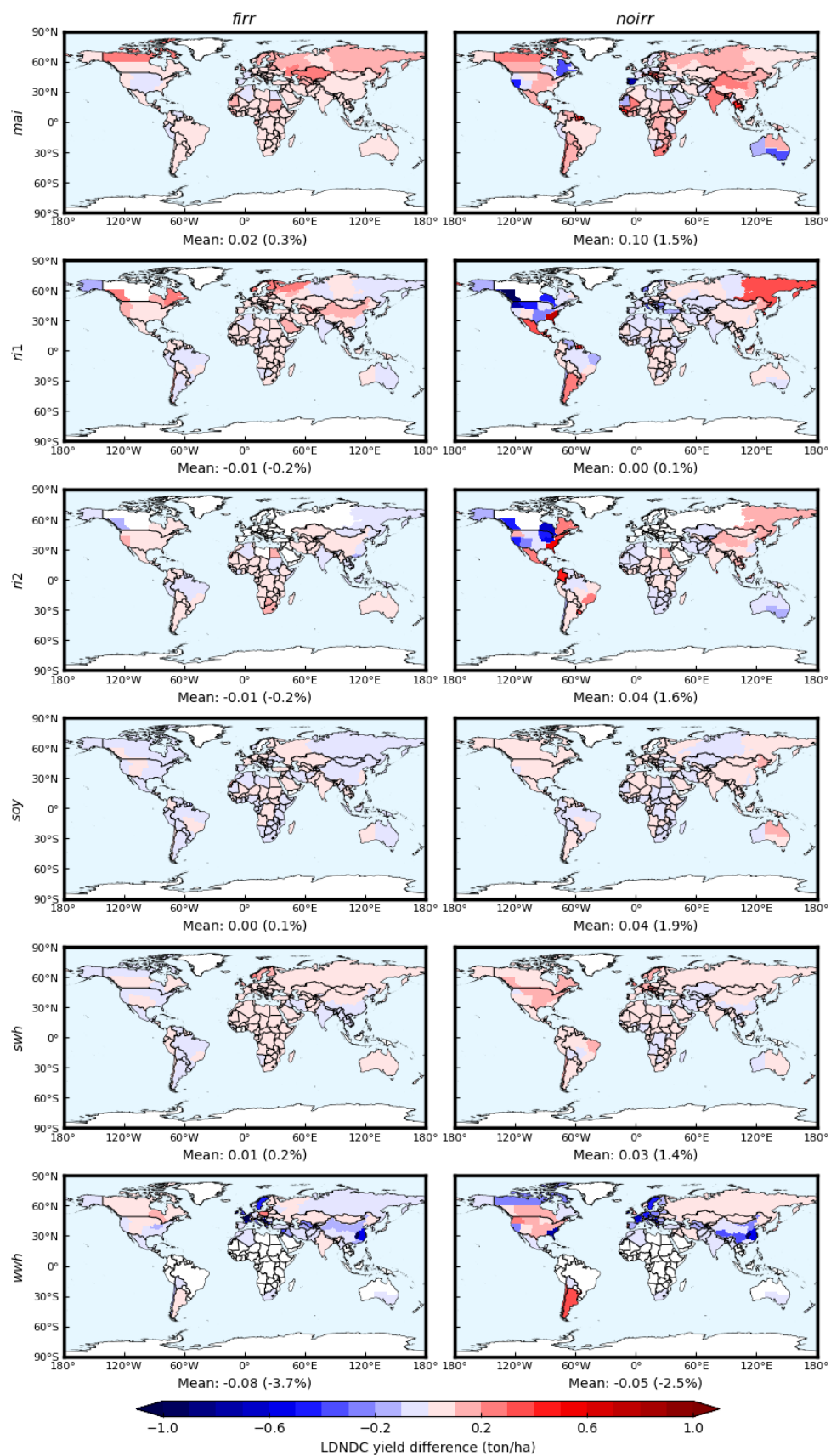


Figure S14. Yield differences between original and LDNDC-based emulated crop yields under SSP585.

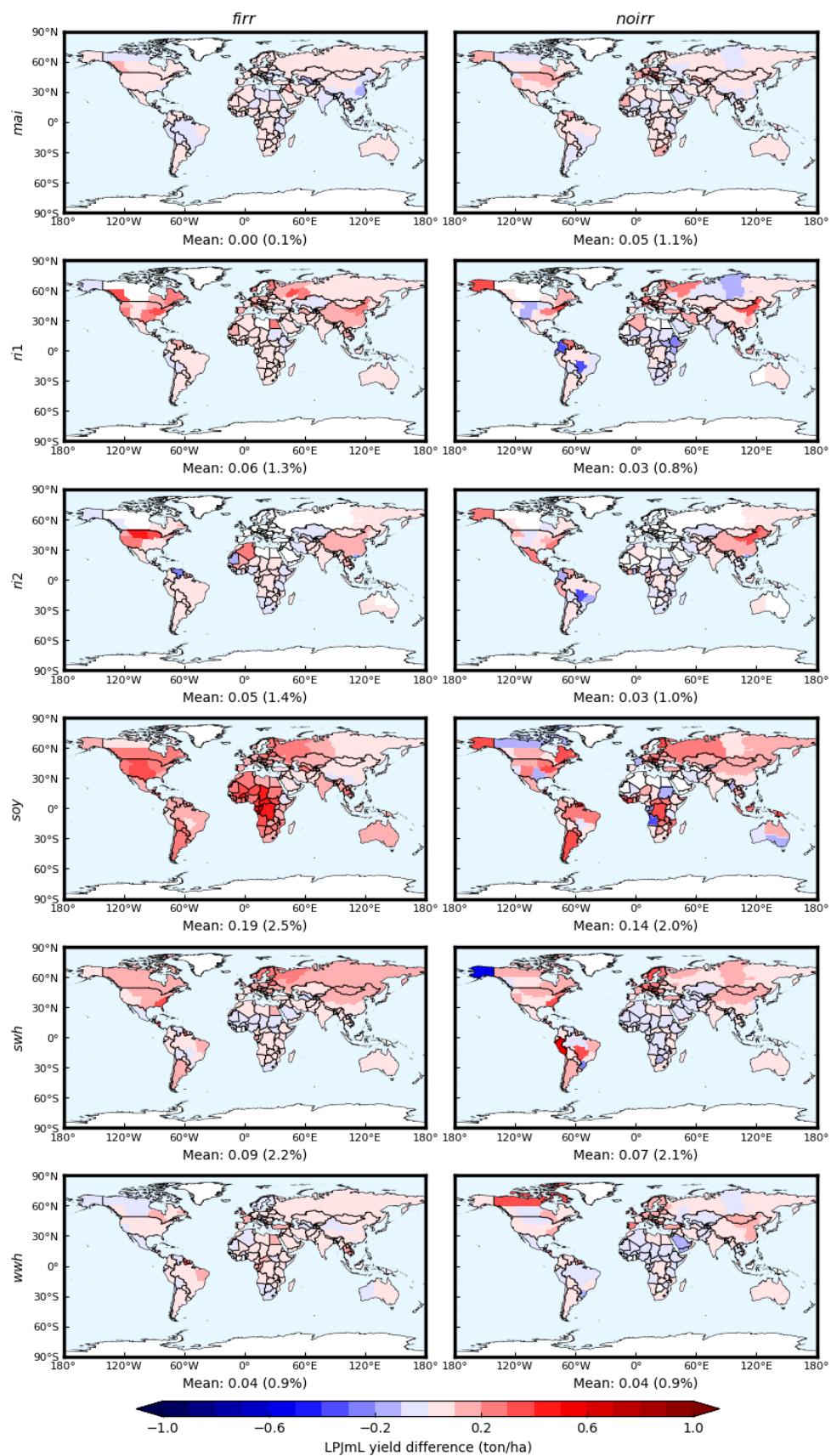


Figure S15. Yield differences between original and LPJmL-based emulated crop yields under SSP585.

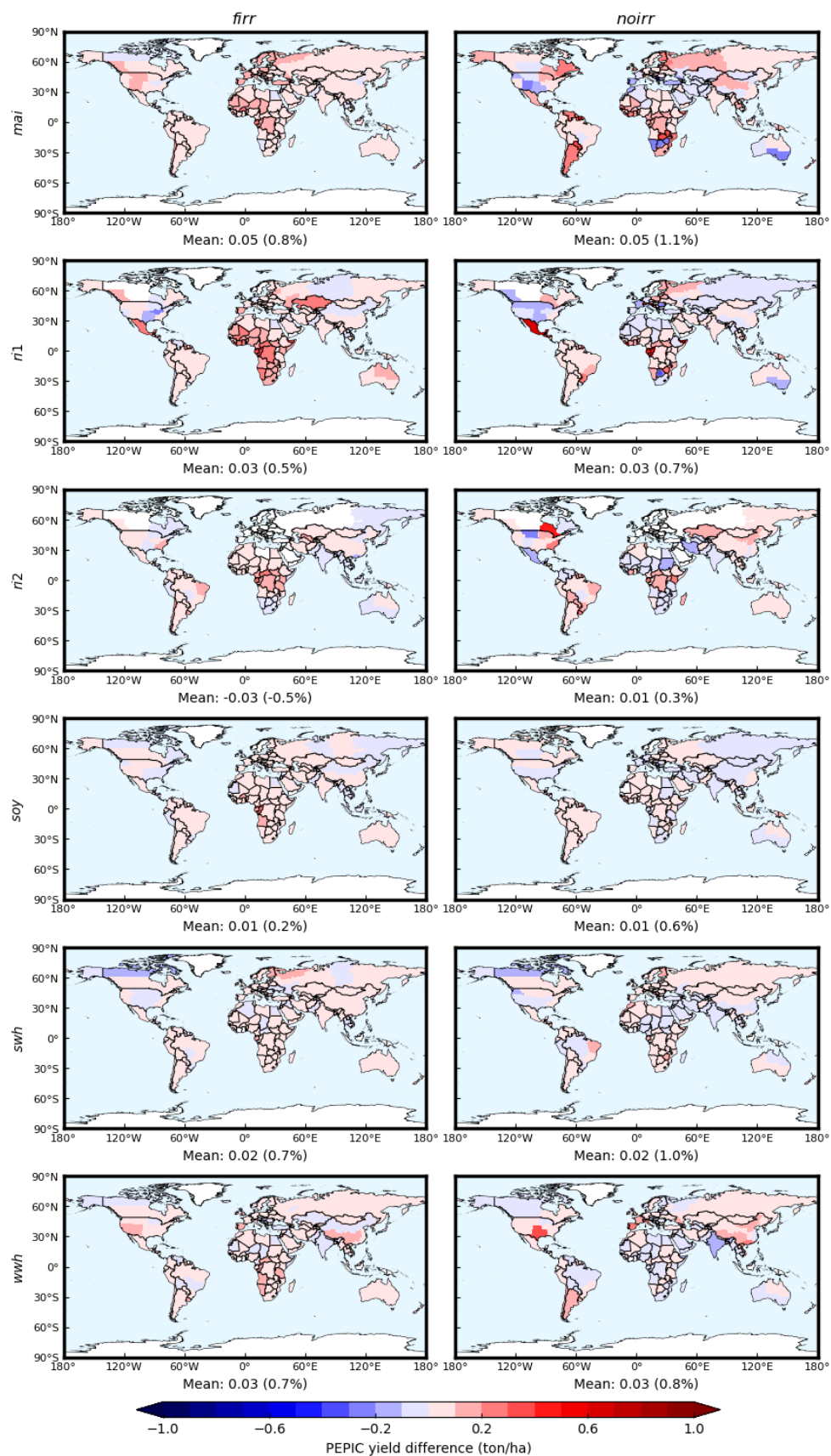


Figure S16. Yield differences between original and PEPIC-based emulated crop yields under SSP585.

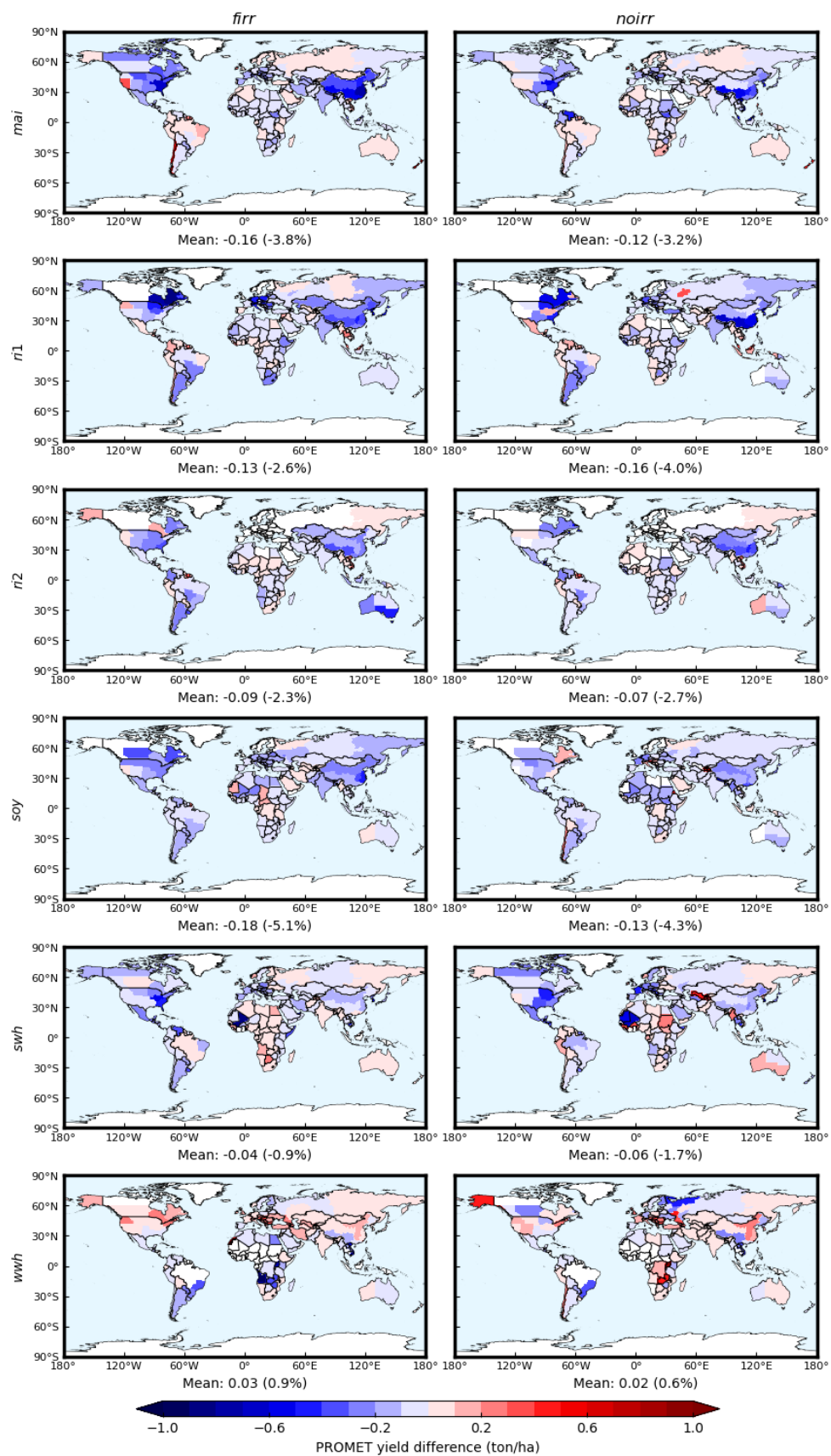


Figure S17. Yield differences between original and PROMET-based emulated crop yields under SSP585.

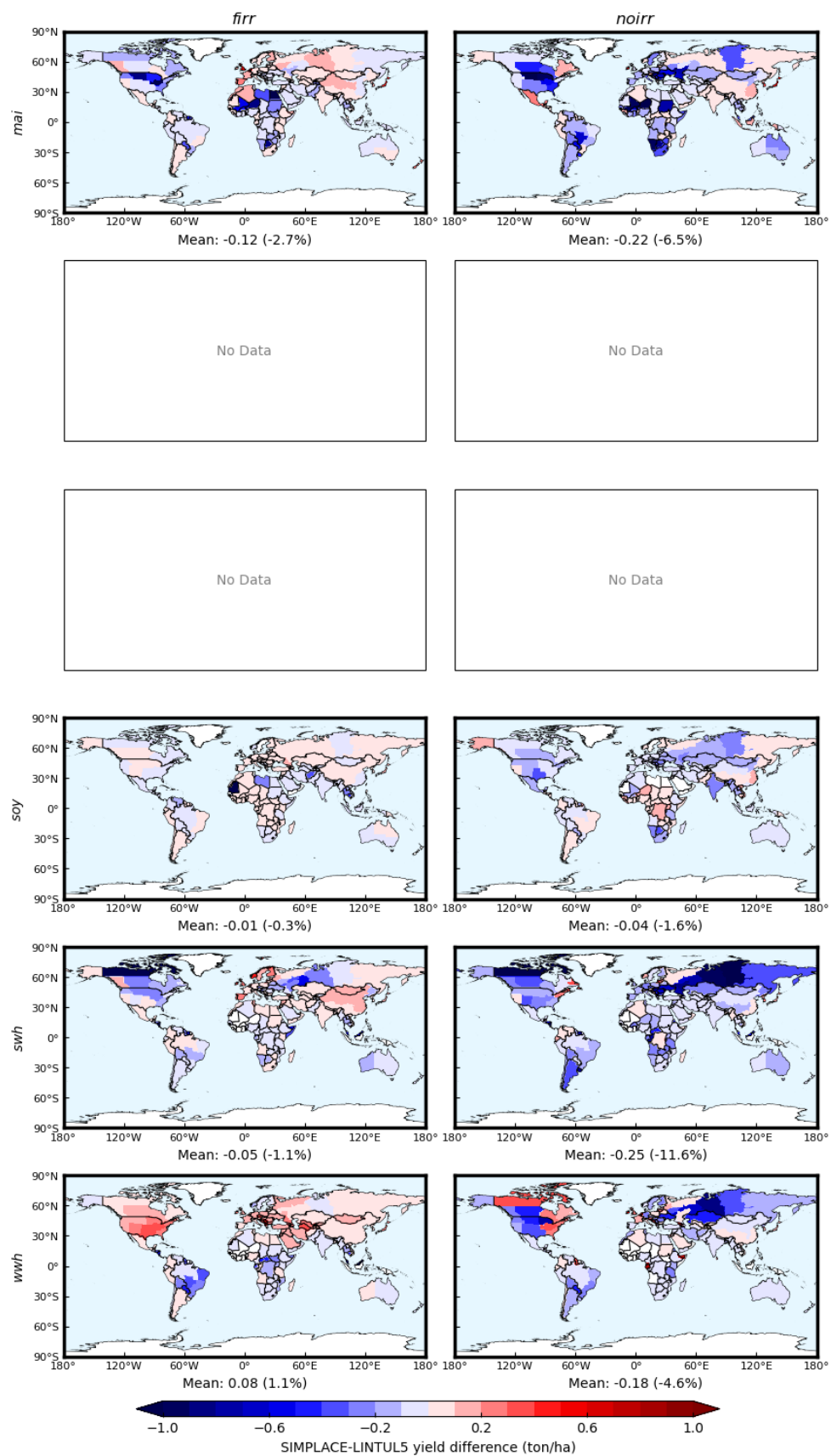


Figure S18. Yield differences between original and SIMPLACE-LINTUL5-based emulated crop yields under SSP585.

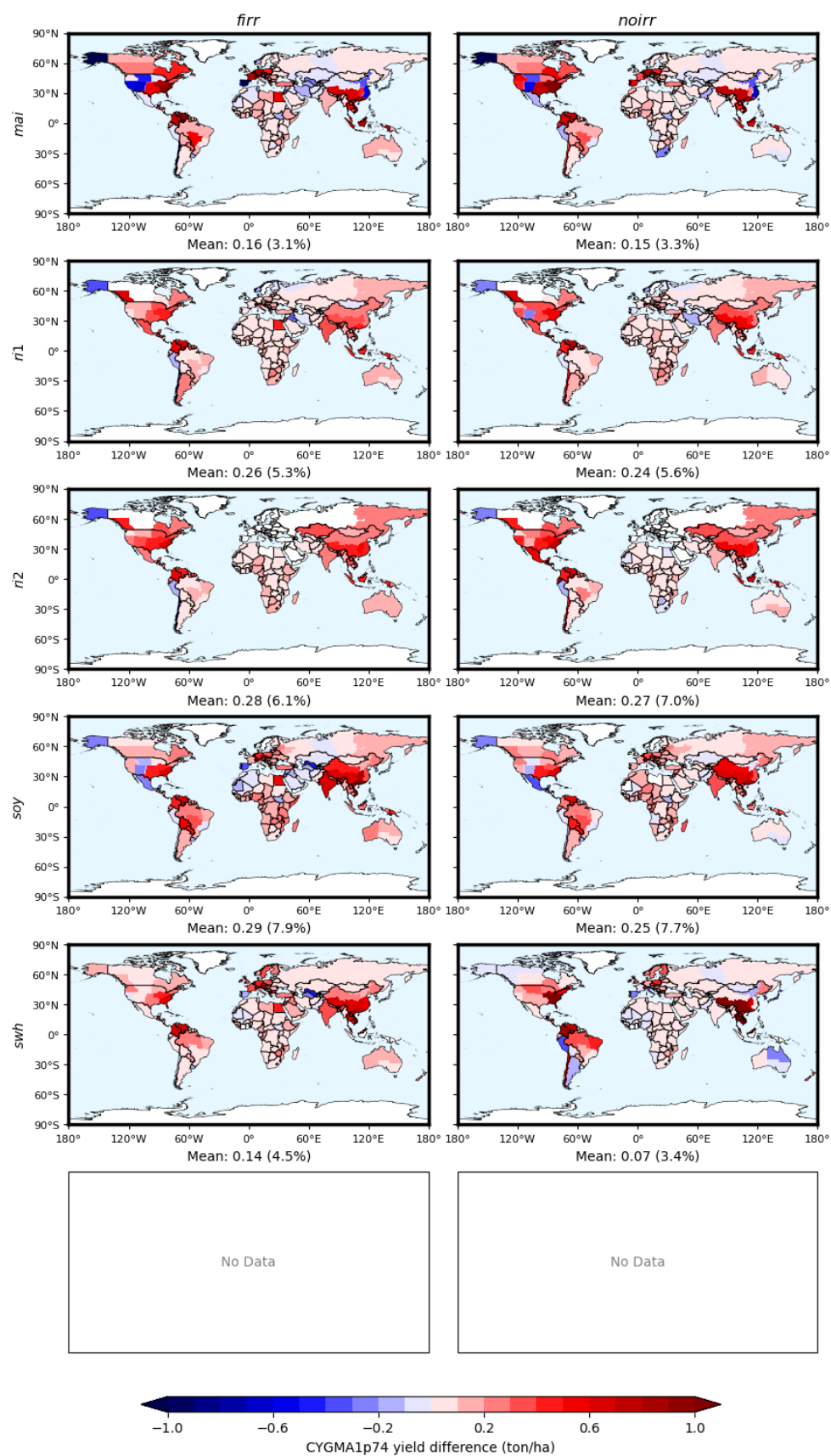


Figure S19. Yield differences between original and CYGMA1p74-based emulated crop yields under GSWP3-W5E5 climate.

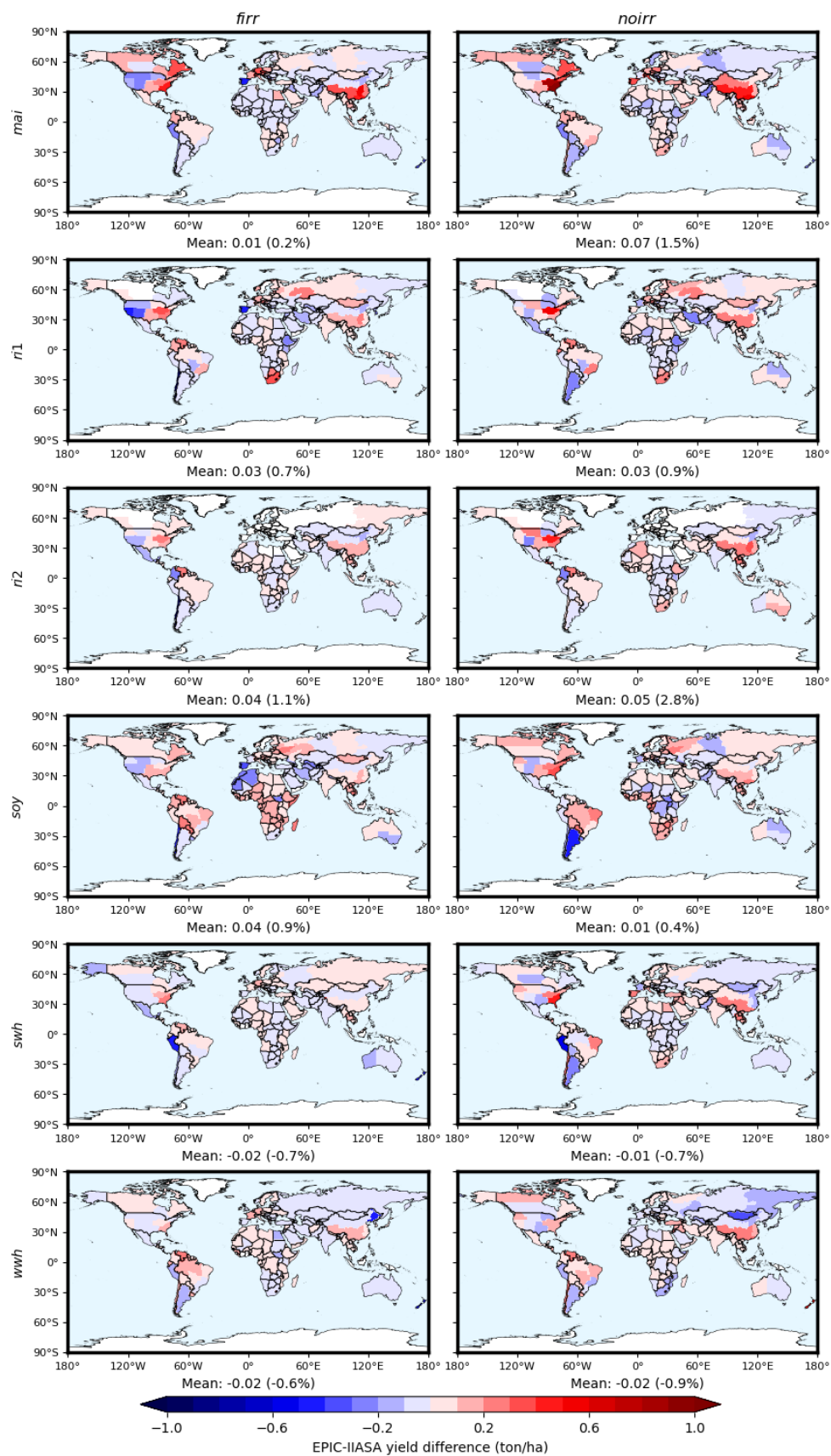


Figure S20. Yield differences between original and EPIC-IIASA-based emulated crop yields under GSWP3-W5E5 climate.

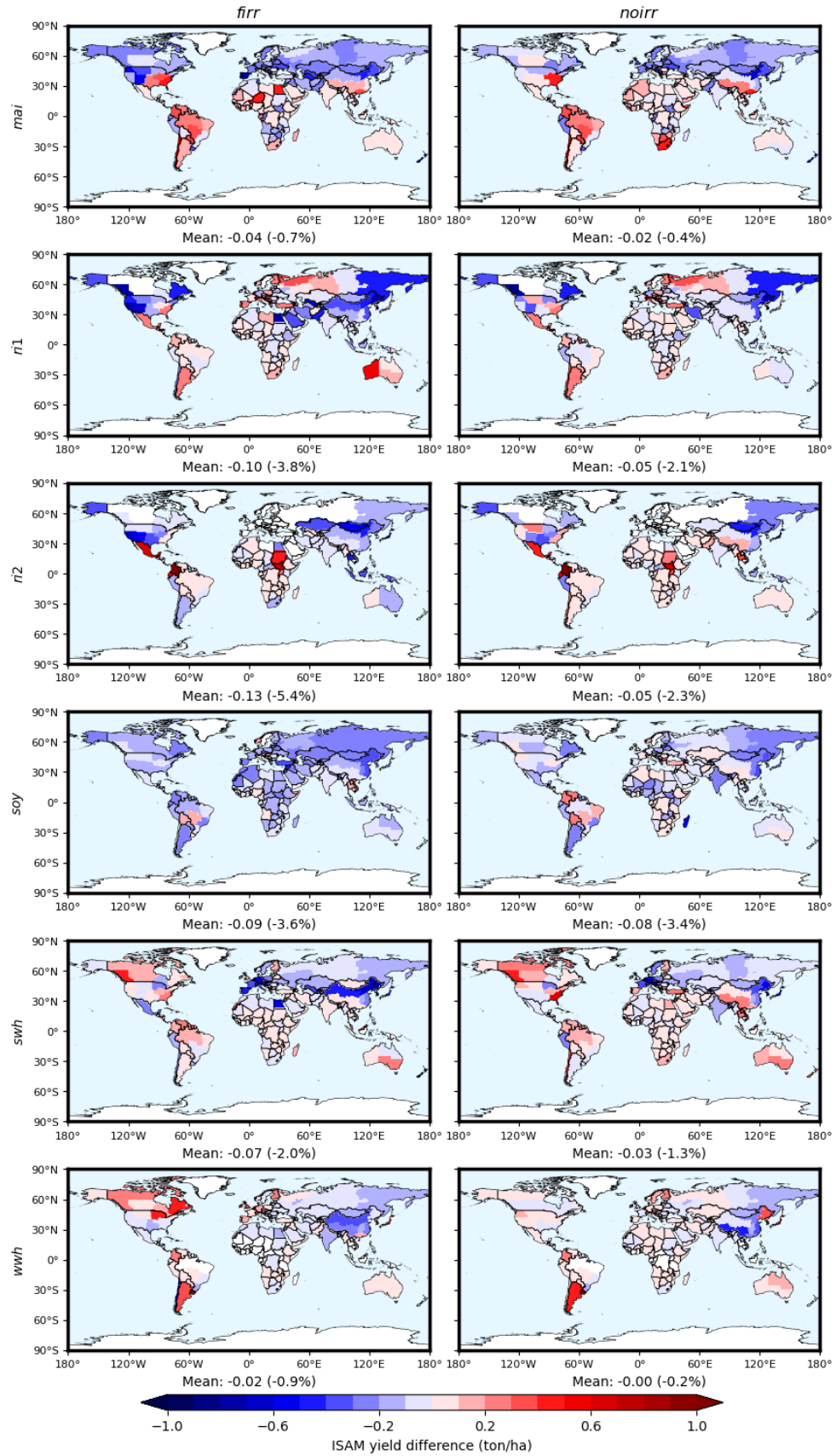


Figure S21. Yield differences between original and ISAM-based emulated crop yields under GSWP3-W5E5 climate.

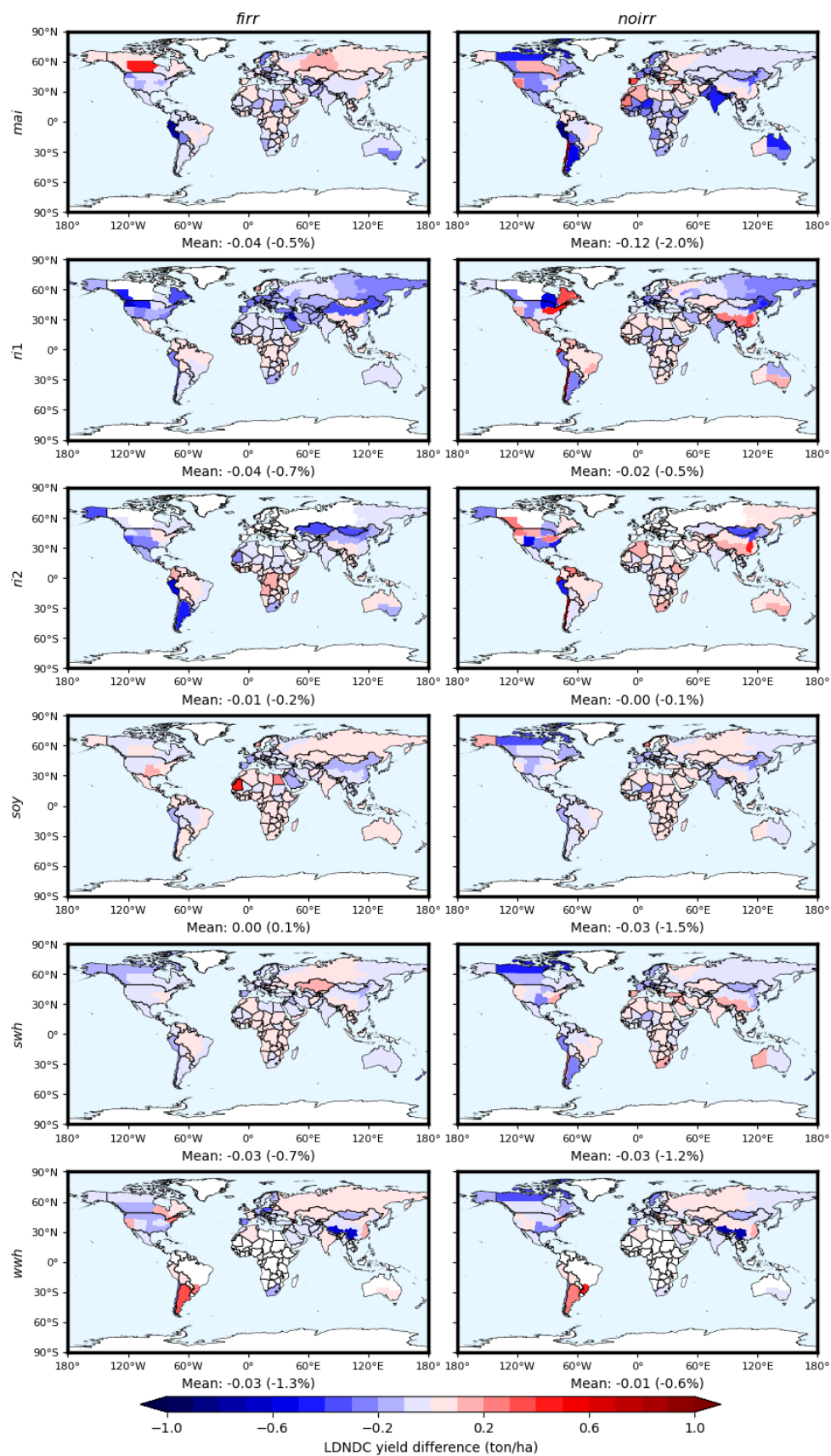


Figure S22. Yield differences between original and LDNDC-based emulated crop yields under GSWP3-W5E5 climate.

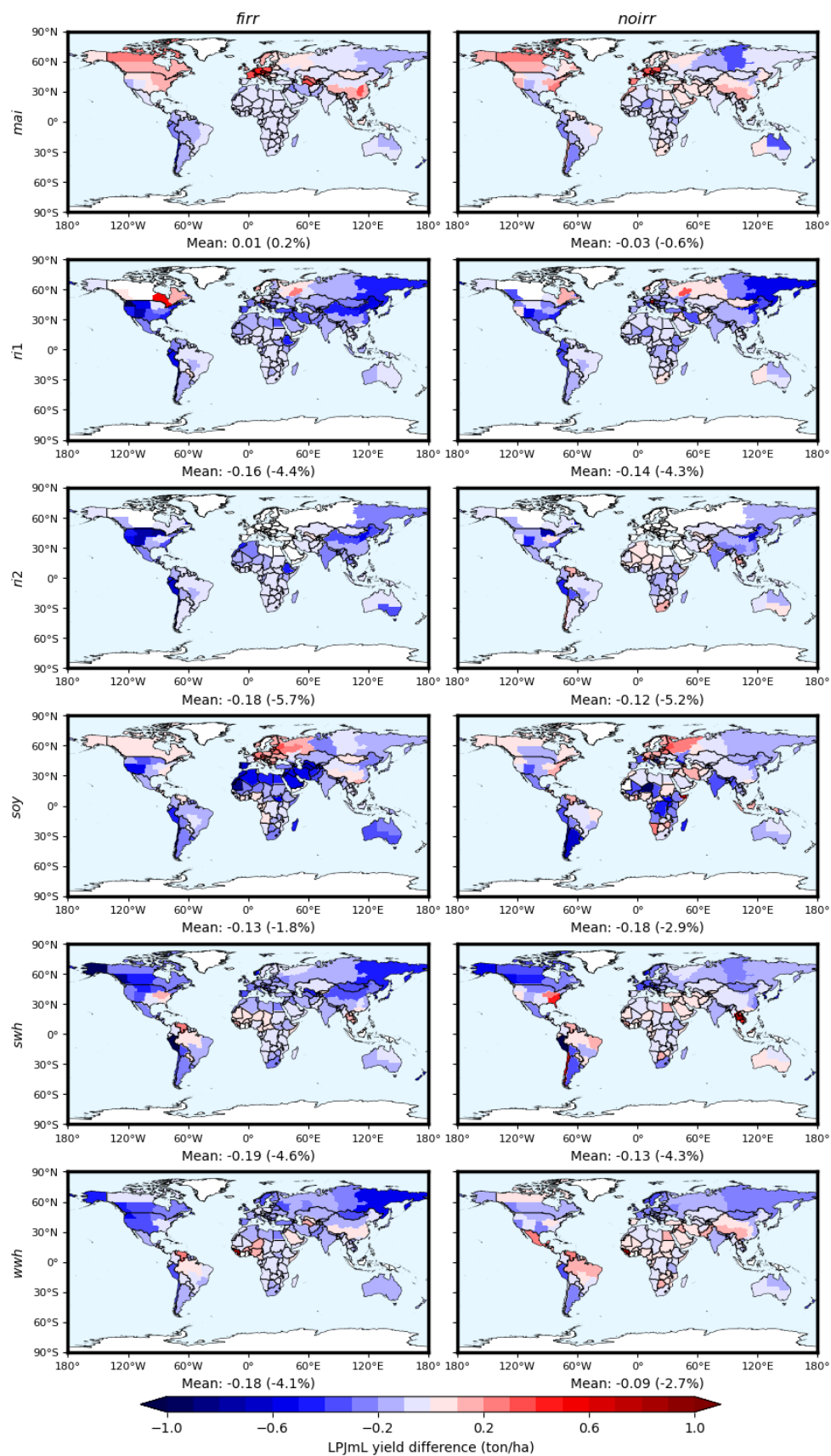


Figure S23. Yield differences between original and LPJmL-based emulated crop yields under GSWP3-W5E5 climate.

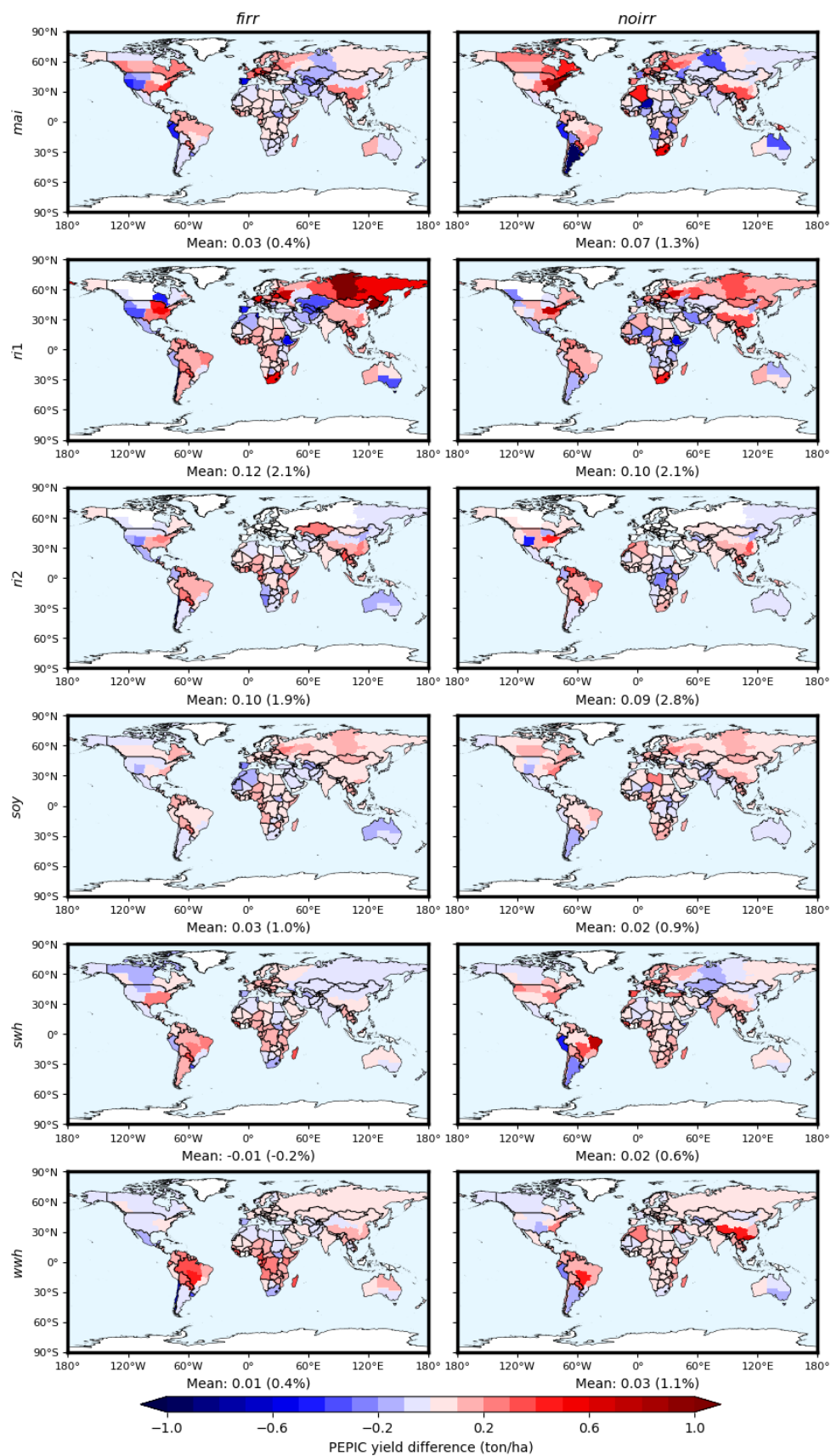


Figure S24. Yield differences between original and PEPIC-based emulated crop yields under GSWP3-W5E5 climate.

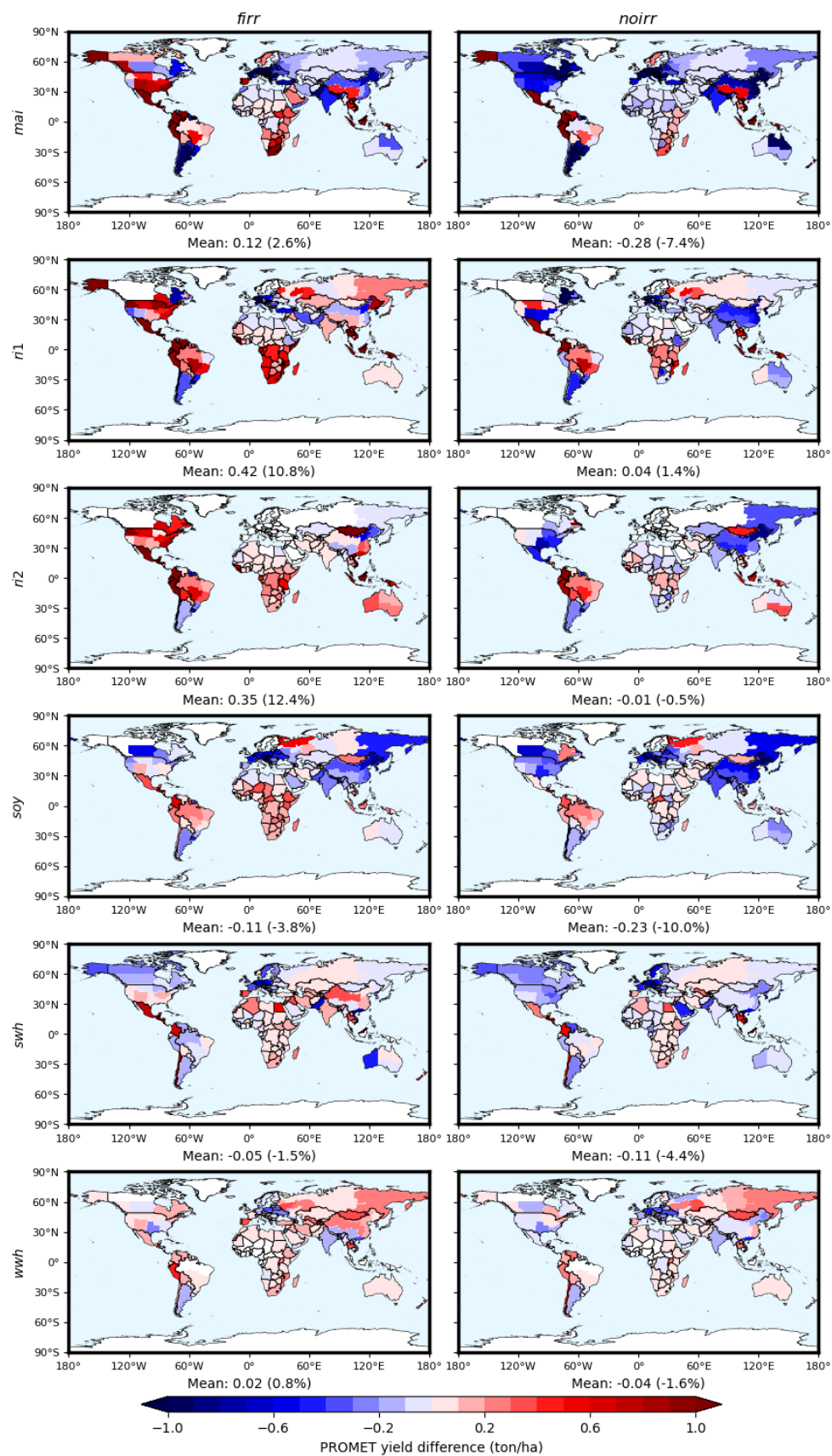


Figure S25. Yield differences between original and PROMET-based emulated crop yields under GSWP3-W5E5 climate.

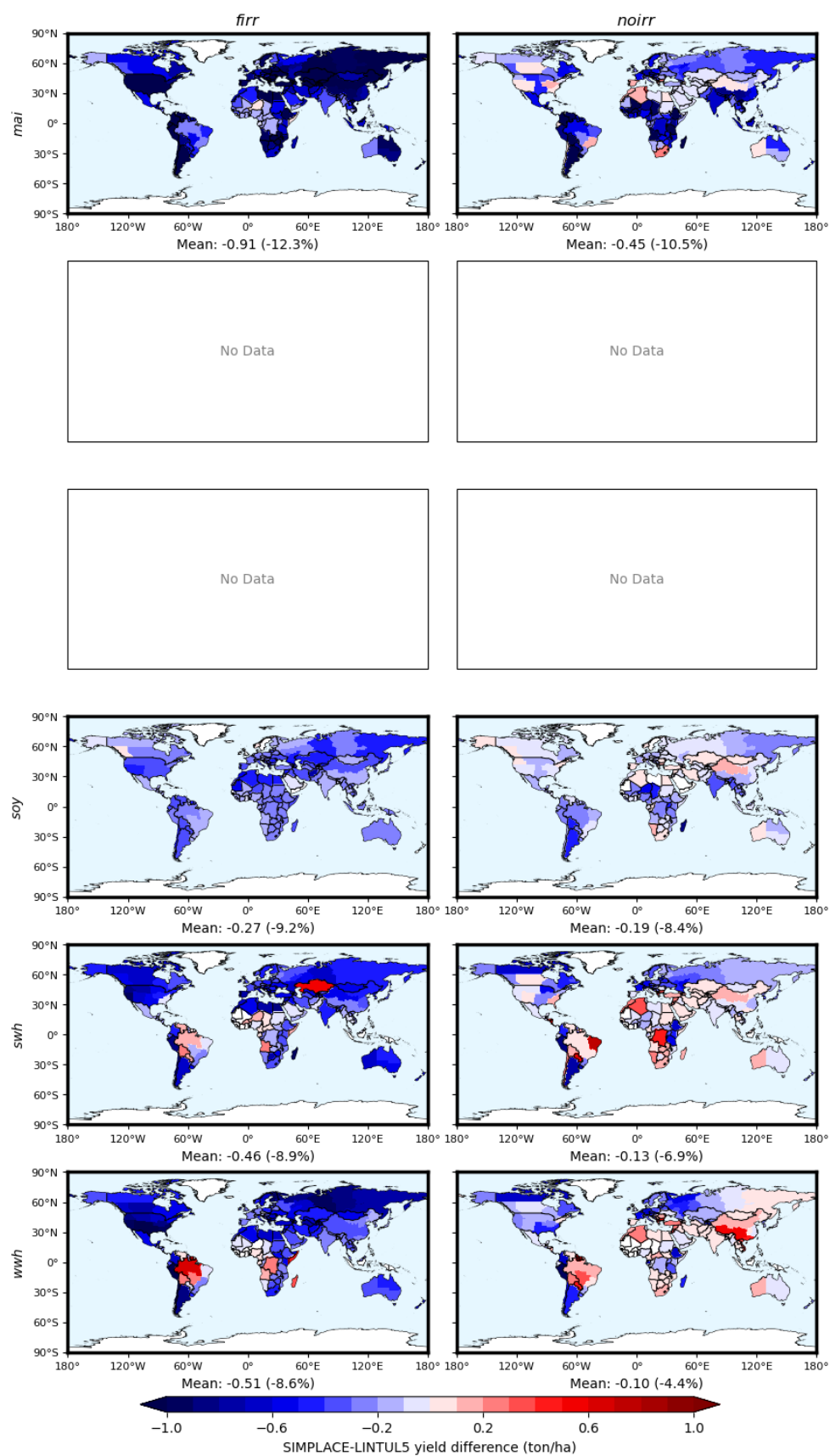


Figure S26. Yield differences between original and SIMPLACE-LINTUL5-based emulated crop yields under GSHP3-W5E5 climate.

Table S1. Six major production regions by crop.

Crop	Regions					
	R1	R2	R3	R4	R5	R6
Maize	USA	Mainland China	Brazil	EU27	Argentina	Others
Rice	Mainland China	India	Indonesia	Bangladesh	Vietnam	Others
Soybean	Brazil	USA	Argentina	Mainland China	India	Others
Wheat	EU27	Mainland China	India	Russia	USA	Others

Table S2. Crops and corresponding land-use categories.

Crop	Specifier	Land-use variables
Maize	<i>mai</i>	maize_rainfed, maize_irrigated
Rice (first growing season)	<i>ri1</i>	rice_rainfed, rice_irrigated
Rice (second growing season)	<i>ri2</i>	rice_rainfed, rice_irrigated
Soybean	<i>soy</i>	oil_crops_soybean_rainfed, oil_crops_soybean_irrigated
Spring wheat	<i>swh</i>	temperate_cereals_rainfed, temperate_cereals_irrigated
Winter wheat	<i>wwh</i>	temperate_cereals_rainfed, temperate_cereals_irrigated

Table S3. Functional forms and parameters for GGCM-based calibration.

Number	Functional form	Parameters	Descriptions	Maximum point	Asymptotic maximum value
①	$\alpha x + 1$	α	Linear	/	/
②	$e^{\alpha x}$	α	Exponential	/	/
③	$e^{(-\alpha \times (x-\beta)^2 + \alpha \beta^2)}$	α, β	Bell-shaped	$x = \beta$ $y = e^{\alpha \beta^2}$	/
④	$\frac{2}{e^{\alpha x} + e^{-\beta x}}$	α, β	Peak-and-decline	$x = \frac{\ln \beta - \ln \alpha}{\alpha + \beta}$ $y = \frac{2\alpha}{\alpha + \beta} \left(\frac{\beta}{\alpha}\right)^{\frac{\beta}{\alpha + \beta}}$	/
⑤	$\frac{e^{\beta} + 1}{e^{-\alpha x + \beta} + 1}$	α, β	S-shaped		$y = e^{\beta} + 1$
⑥	$\frac{e^{-\alpha \gamma} + e^{\beta \gamma}}{e^{\alpha(x-\gamma)} + e^{-\beta(x-\gamma)}}$	α, β, γ	Skewed bell-shaped	$x = \gamma + \frac{\ln \beta - \ln \alpha}{\alpha + \beta}$ $y = \frac{\alpha(e^{-\alpha \gamma} + e^{\beta \gamma})}{\alpha + \beta} \left(\frac{\beta}{\alpha}\right)^{\frac{\beta}{\alpha + \beta}}$	/
⑦	$\left(\frac{e^{\beta} + 1}{e^{-\alpha x + \beta} + 1}\right)^{\gamma}$	α, β, γ	Skewed S-shaped	/	$y = (e^{\beta} + 1)^{\gamma}$

Table S4. Parameter limits for each driver and functional form.

Functional form	Parameter	$(CO_2 - CO_{2,2015})/CO_{2,2015}$		$T_{gs}^c - T_{gs,pl}^c$		$(P_{gs}^c - P_{gs,pl}^c)/P_{gs,pl}^c$	
		Lower limit	Upper limit	Lower limit	Upper limit	Lower limit	Upper limit
①	α	-1	1	-10	10	-1000	1000
②	α	-10	10	-10	10	-10	10
③	α	0	10	0	10	0	10
	β	-1	4	-30	30	-1	100
④	α	0	10	0	10	1	10
	β	0	10	0	10	0	10
⑤	α	0	100	0	100	0	100
	β	-10	10	-10	10	-10	10
⑥	α	0	100	0	100	0	100
	β	0	100	0	100	0	100
	γ	-10	10	-10	10	-10	10
⑦	α	0	100	0	100	0	100
	β	-10	10	-10	10	-10	10
	γ	0	10	0	10	0	10

Table S5. GGCM-irrigation-crop combinations of extreme-value yield responses with corresponding regional occurrences.

GGCM	Irrigation	Crop (Occurrence)
CYGMA1p74	<i>noirr</i>	<i>mai</i> (9), <i>ri1</i> (8), <i>ri2</i> (5), <i>soy</i> (7), <i>swh</i> (34)
LDNDC	<i>noirr</i>	<i>mai</i> (9)
LPJmL	<i>firr</i>	<i>ri1</i> (4), <i>ri2</i> (1)
	<i>noirr</i>	<i>mai</i> (4), <i>ri1</i> (18), <i>ri2</i> (17), <i>soy</i> (14), <i>swh</i> (6), <i>wwh</i> (7)
PEPIC	<i>noirr</i>	<i>mai</i> (1)
PROMET	<i>noirr</i>	<i>mai</i> (6), <i>ri1</i> (9), <i>ri2</i> (7), <i>soy</i> (8), <i>swh</i> (3), <i>wwh</i> (2)
SIMPLACE-LINTUL5	<i>noirr</i>	<i>soy</i> (2), <i>wwh</i> (1)

Extreme-value yield occurrences are in parentheses.

Table S6. Functional forms and parameters for nitrogen responses.

Model	Functional form	Parameters
Michaelis-Menten	$\frac{\alpha x}{x + \beta}$	α, β
Mitscherlich	$\alpha(e^{\beta x} - 1)$	α, β
George	$\alpha(0.99^x - 1) + \beta x$	α, β