Table supporting Section 2.1: Physically simulated crop yield data

Table S1. Correlation between simulated and reported crop yield anomalies at global level with the fullharm model set-up (harm-suffN for LPJmL and LPJ-GUESS). Table adopted from the results of Müller et al. (2017). Triple, double and single asterisks denote the confidence level at 99.9 %, 95 % and 90 %, respectively.

	maize	rice	soybean	wheat
CGMS-WOFOST	-	-	-	-
EPIC-Boku	0.663***	0.351*	0.603**	0.385*
EPIC-IIASA	0.700***	0.187	0.278	0.597**
EPIC-TAMU	0.667***	-	-	0.545**
GEPIC	0.749***	0.119	0.565**	0.371*
LPJ-GUESS	0.641***	0.224	0.472**	0.401**
LPJmL	0.741***	0.312	0.519**	0.516**
ORCHIDEE-crop	0.548**	0.256	0.266	0.395*
pAPSIM	0.774***	-	0.615**	0.346*
pDSSAT	0.843***	0.288	0.544**	0.531**
PEGASUS	0.244	-	0.254	0.299
PEPIC	0.687***	0.373*	0.389*	0.397**

Table supporting Section 3.1: Global extent of climate oscillation impacts

Table S2. Extent of significant anomalies. Crop-specific harvested area (10^6 ha) extent (and percent of total crop-specific harvested area), where actual crop yield shows statistically significant anomalies during the strong phases of ENSO, IOD and NAO.

	Positive ENSO (El Niño)	Negative ENSO (La Niña)	Positive IOD	Negative IOD	Positive NAO	Negative NAO
Maize	72 (48%)	66 (43%)	53 (35%)	58 (38%)	28 (18%)	45 (29%)
Rice	63 (38%)	42 (25%)	49 (30%)	39 (23%)	21 (13%)	27 (16%)
Soybeans	15 (20%)	39 (52%)	18 (24%)	35 (46%)	4 (6%)	16 (21%)
Wheat	68 (32%)	78 (36%)	84 (39%)	95 (44%)	36 (17%)	49 (23%)

Figures supporting Section 3.2: Impacts in different areas

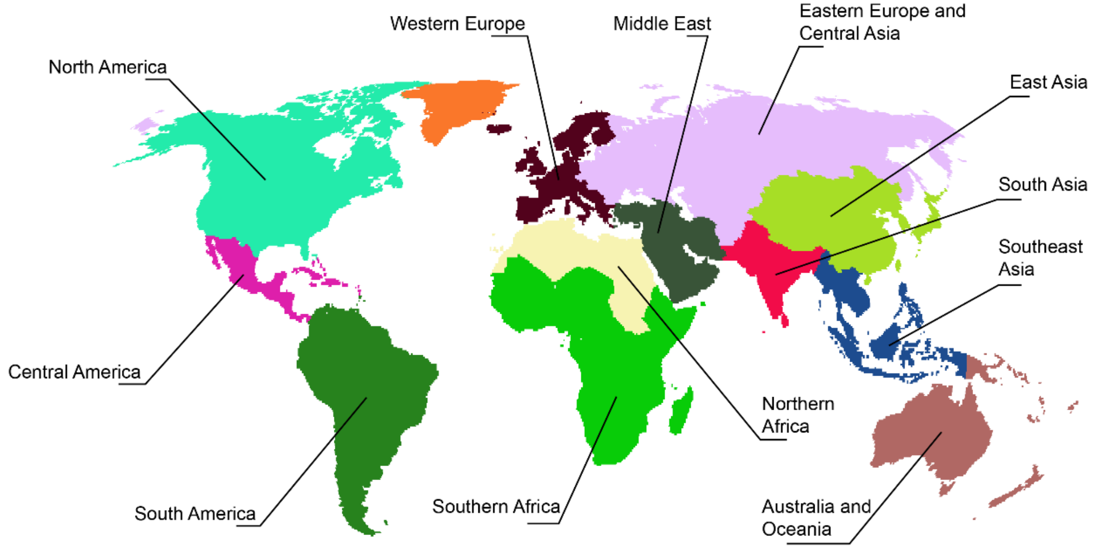

Figure S1. Global regions used for describing the results in the main text (modified from Heino et al. (2018)).

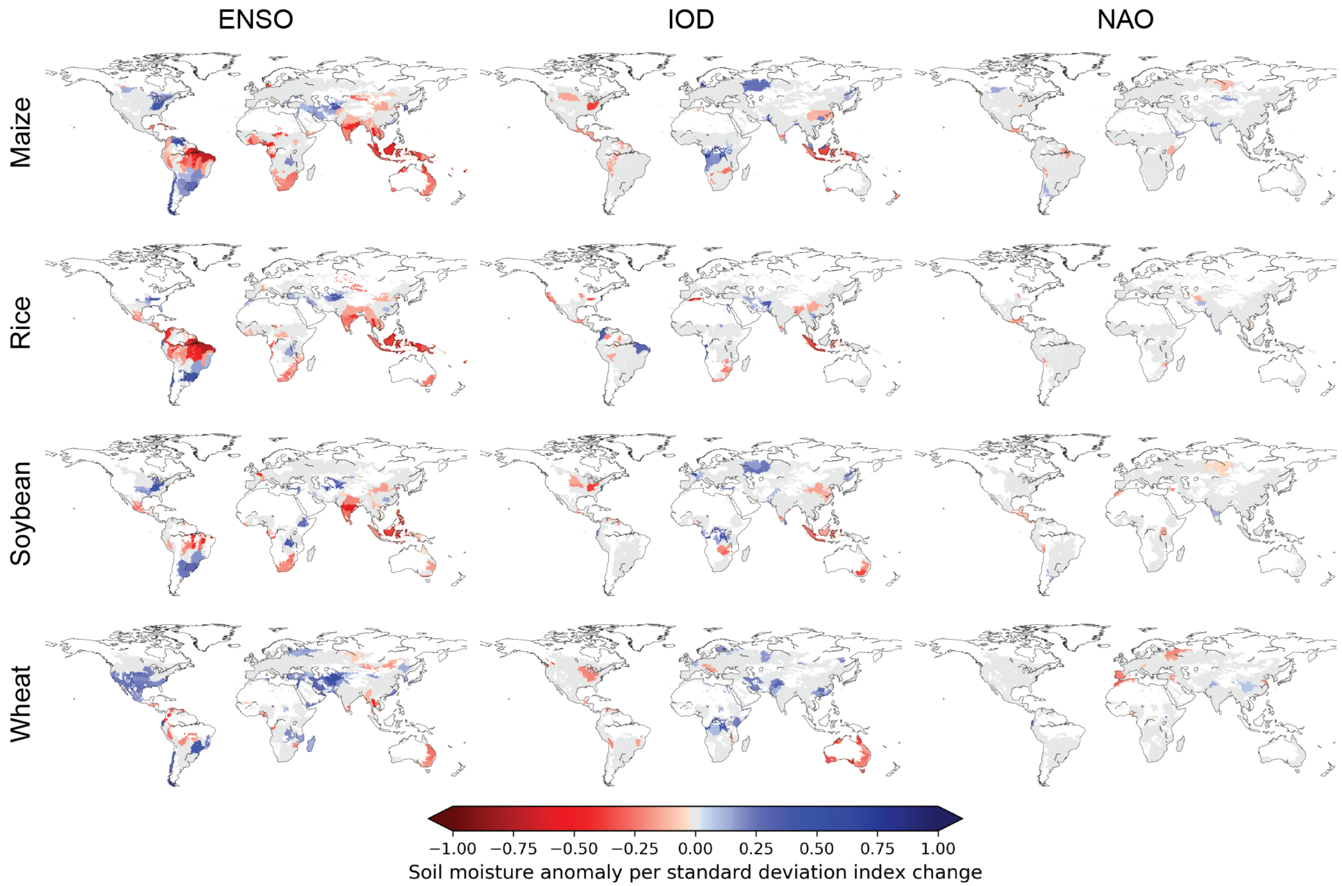

Figure S2. Soil moisture (Martens et al. 2017) anomaly sensitivity to ENSO, IOD and NAO at FPU scale. The growing season average soil moisture anomalies were aggregated from raster scale by calculating a harvested area weighted average anomaly for each FPU and crop. The sensitivity values are derived as for crop yields (see Section 2.4 Crop yield sensitivity to the oscillations). Statistically insignificant ($p > 0.1$) sensitivity values are marked as zero. White color denotes that the crop in question is not produced in that area.

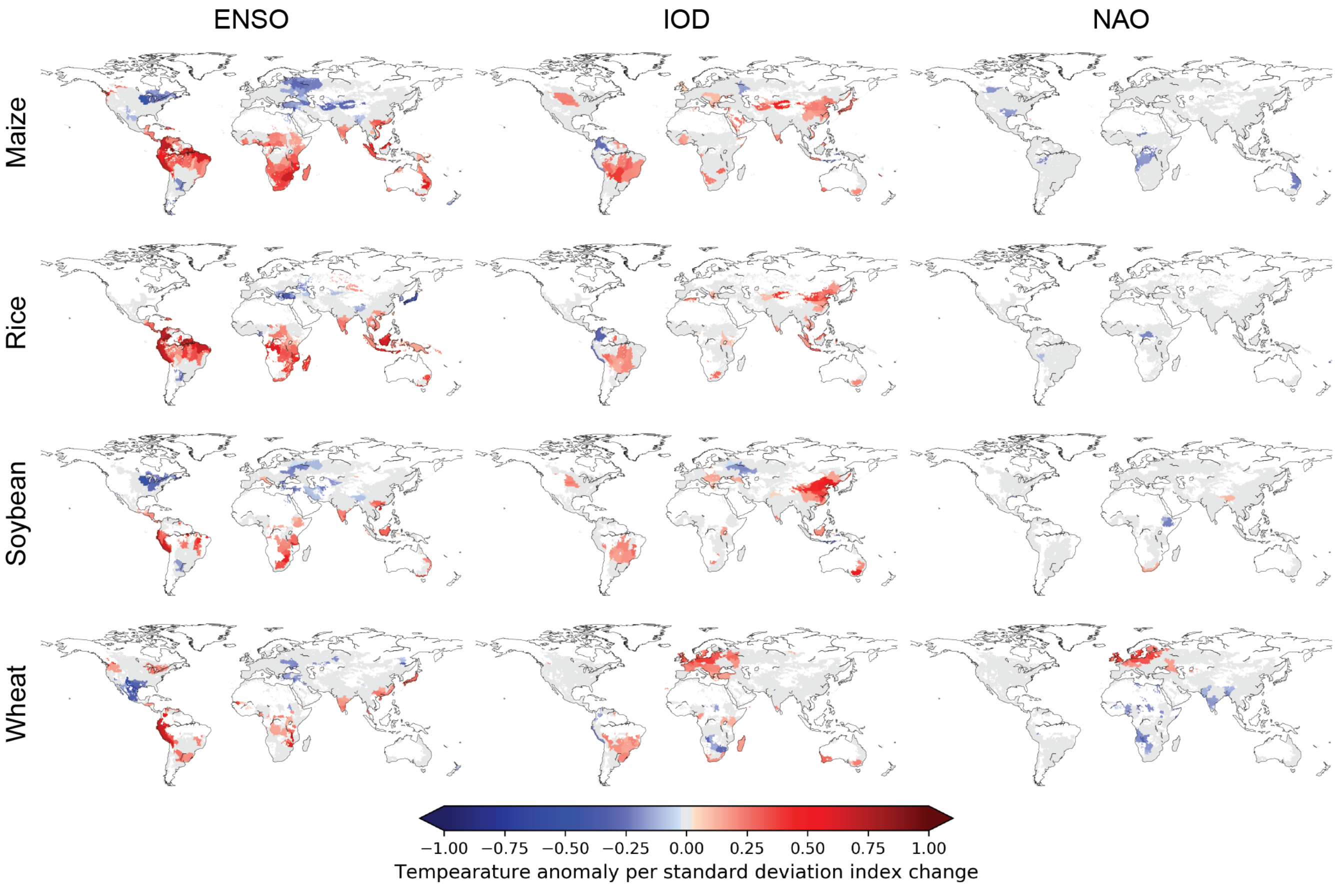

Figure S3. Temperature (Ruane et al. 2015) anomaly sensitivity to ENSO, IOD and NAO at FPU scale. The growing season average temperature anomalies were aggregated from raster scale by calculating a harvested area weighted average anomaly for each FPU and crop. The sensitivity values are derived as for crop yields (see Section 2.4 Crop yield sensitivity to the oscillations). Statistically insignificant ($p > 0.1$) sensitivity values are marked as zero. White color denotes that the crop in question is not produced in that area.

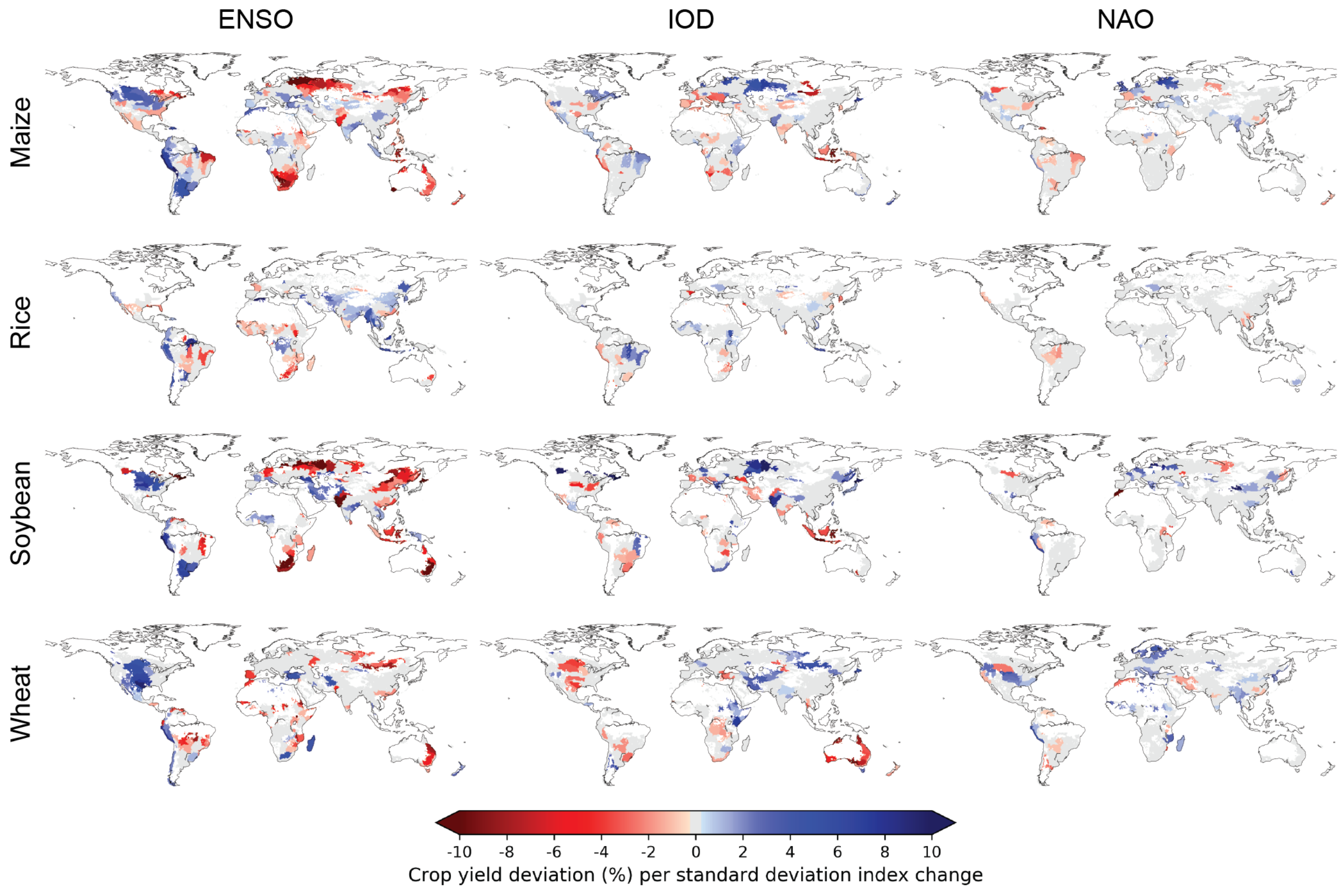

Figure S4. Actual crop yield sensitivity to ENSO, IOD and NAO at FPU scale using the Princeton dataset. The sensitivity values are derived from all GGCMs that simulate the crop in question with the Princeton Global Forcing data set (Princeton) climate input using the fullharm (harm-suffN for LPJmL and LPJ-GUESS) model setup. Statistically insignificant ($p > 0.1$) sensitivity values are marked as zero. White color denotes that the crop in question is not produced in that area. Results with AgMERRA climate input are shown in Figure 1 in the main text.

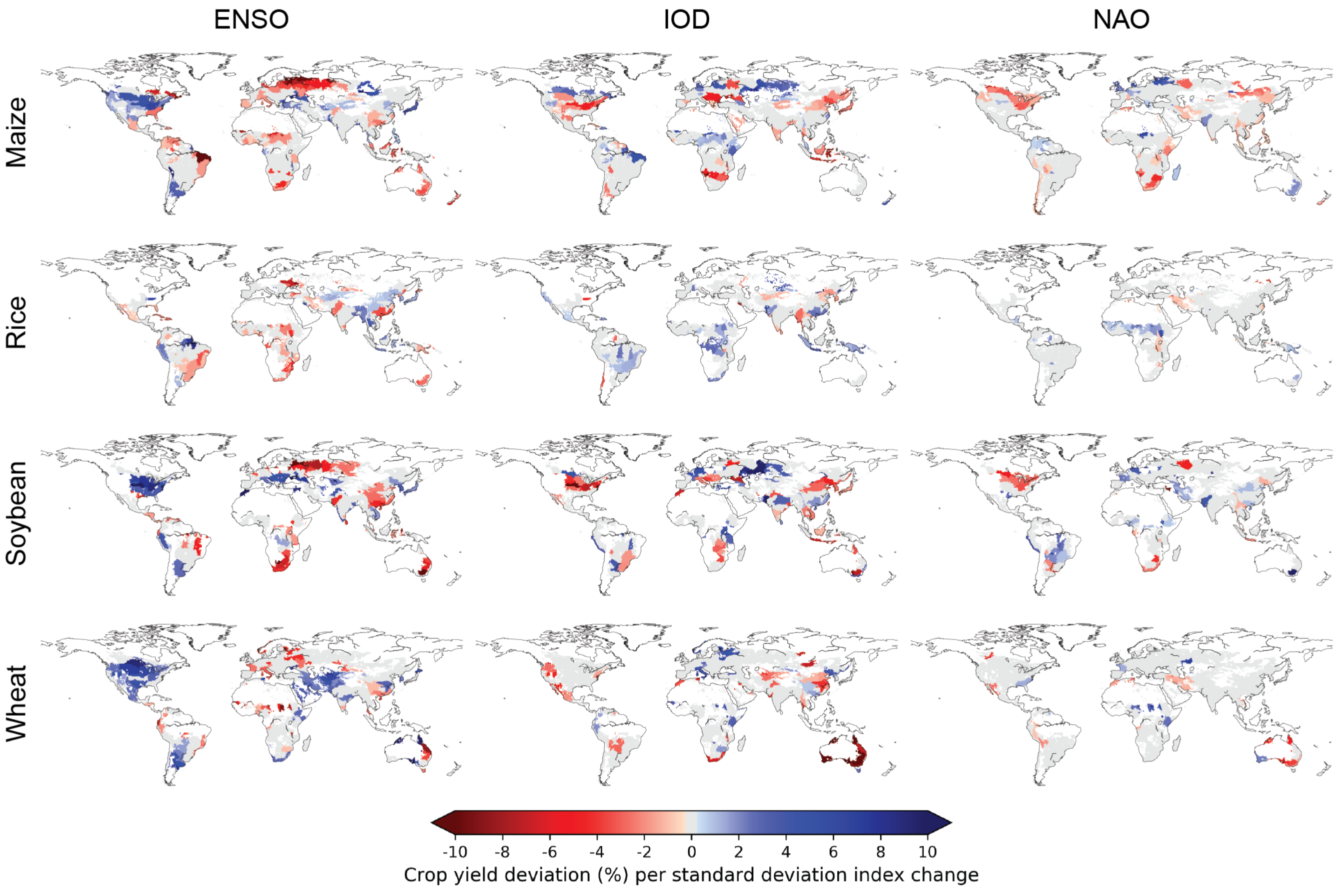

Figure S5. Actual crop yield sensitivity to ENSO, IOD and NAO at FPU scale using the default setup. The sensitivity values are derived from all GGCMs that simulate the crop in question with the AgMERRA climate input. Statistically insignificant ($p > 0.1$) sensitivity values are marked as zero. White color denotes that the crop in question is not produced in that area. Results with fullharm (harm-suffN for LPJmL and LPJ-GUESS) model setup are shown in Figure 1 in the main text.

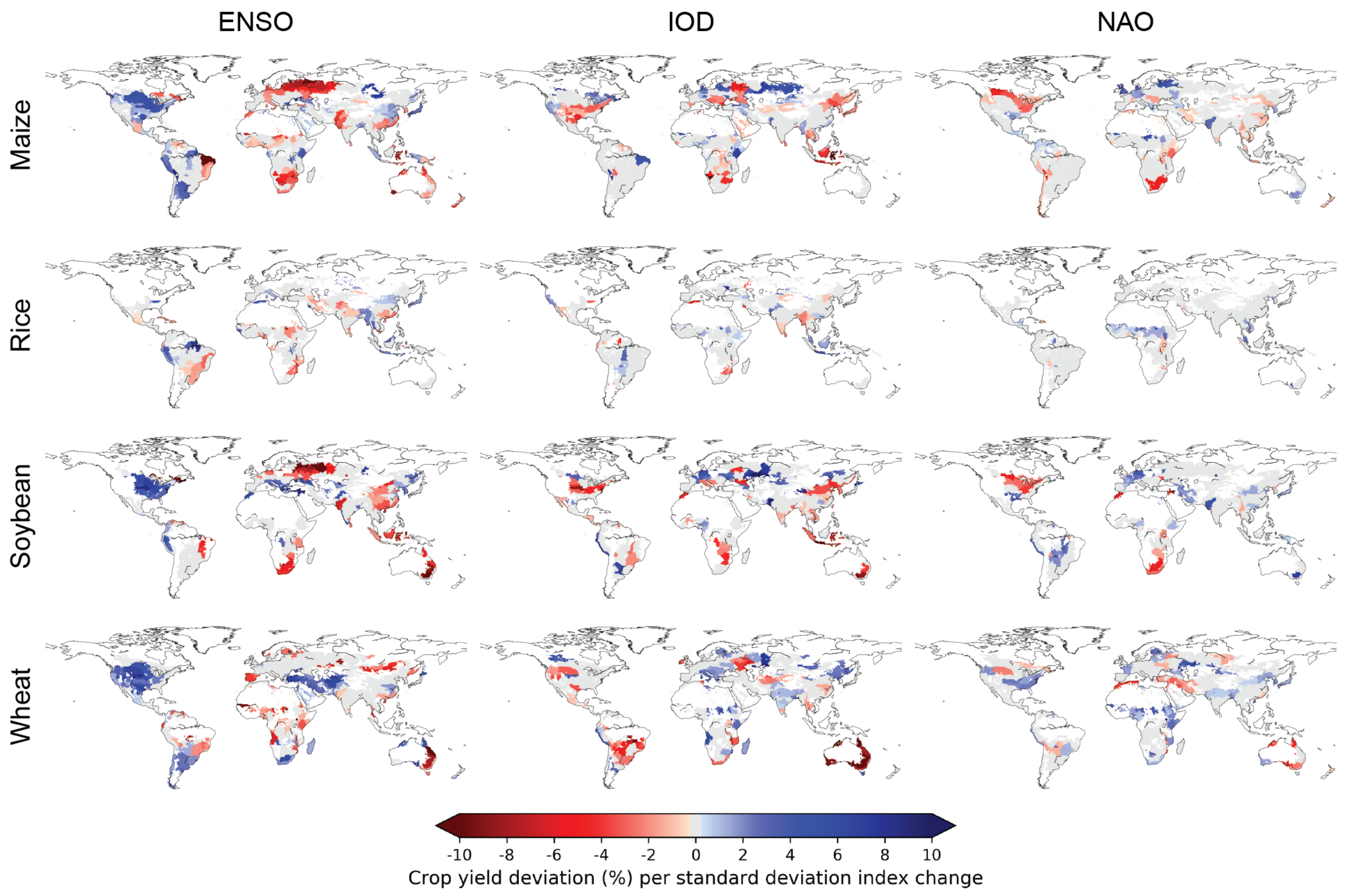

Figure S6. Actual crop yield sensitivity to ENSO, IOD and NAO at FPU scale using the Niño 3.4 index (NOAA Earth System Research Laboratory 2019) for ENSO. The sensitivity values are derived using crop yield data from all GGCMs that simulate the crop in question with the AgMERRA climate input using the fullharm (harm-suffN for LPJmL and LPJ-GUESS) model setup. Statistically insignificant ($p > 0.1$) sensitivity values are marked as zero. White color denotes that the crop in question is not produced in that area. Results with AgMERRA climate input are shown in Figure 1 in the main text.

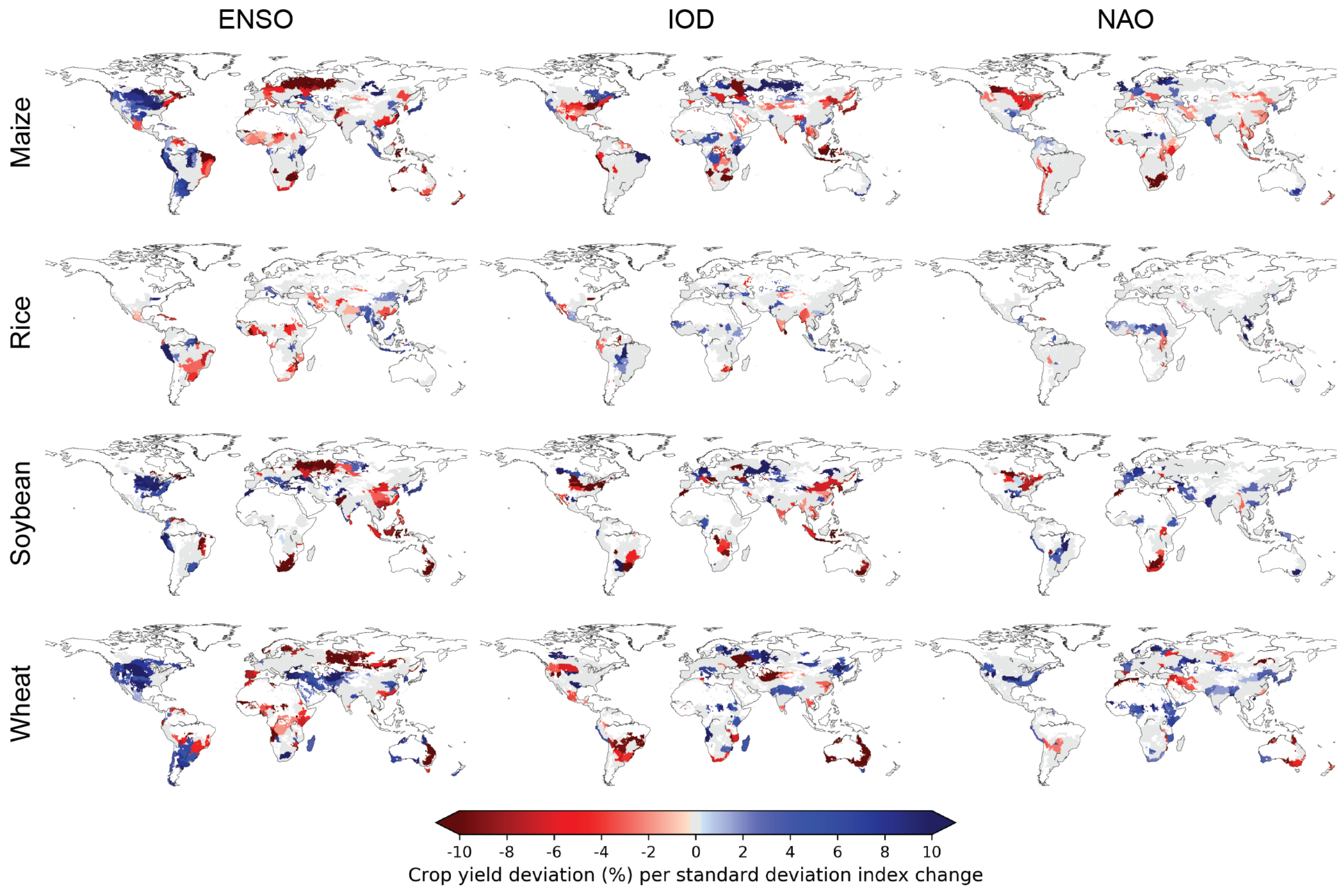

Figure S7. Median actual crop yield sensitivity to ENSO, IOD and NAO of the individual model results. The sensitivity values are derived from the models that simulate the crop in question with the AgMERRA climate input. Statistically insignificant ($p > 0.1$) sensitivity values (in the ensemble or all individual model results) are marked as zero. White color denotes that the crop in question is not produced in that area. Results across the full ensemble are shown in Figure 1 in the main text.

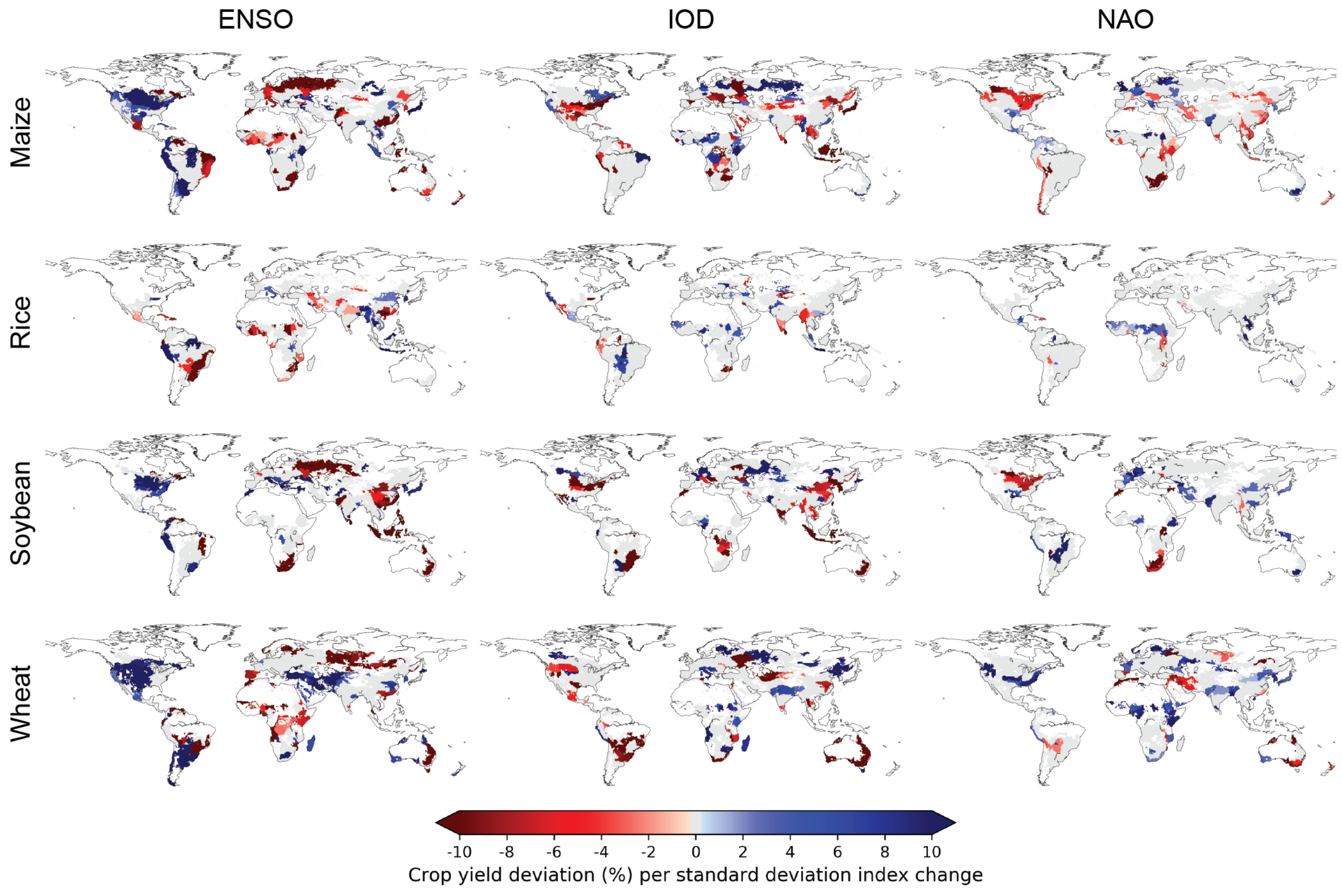

Figure S8. Maximum (in terms of magnitude) actual crop yield sensitivity to ENSO, IOD and NAO of the individual model results that show significant sensitivity of same sign compared to the ensemble results. The sensitivity values are derived from all the models that simulate the crop in question with the AgMERRA climate input. Statistically insignificant ($p > 0.1$) sensitivity values (in the ensemble or all individual model results) are marked as zero. White color denotes that the crop in question is not produced in that area.

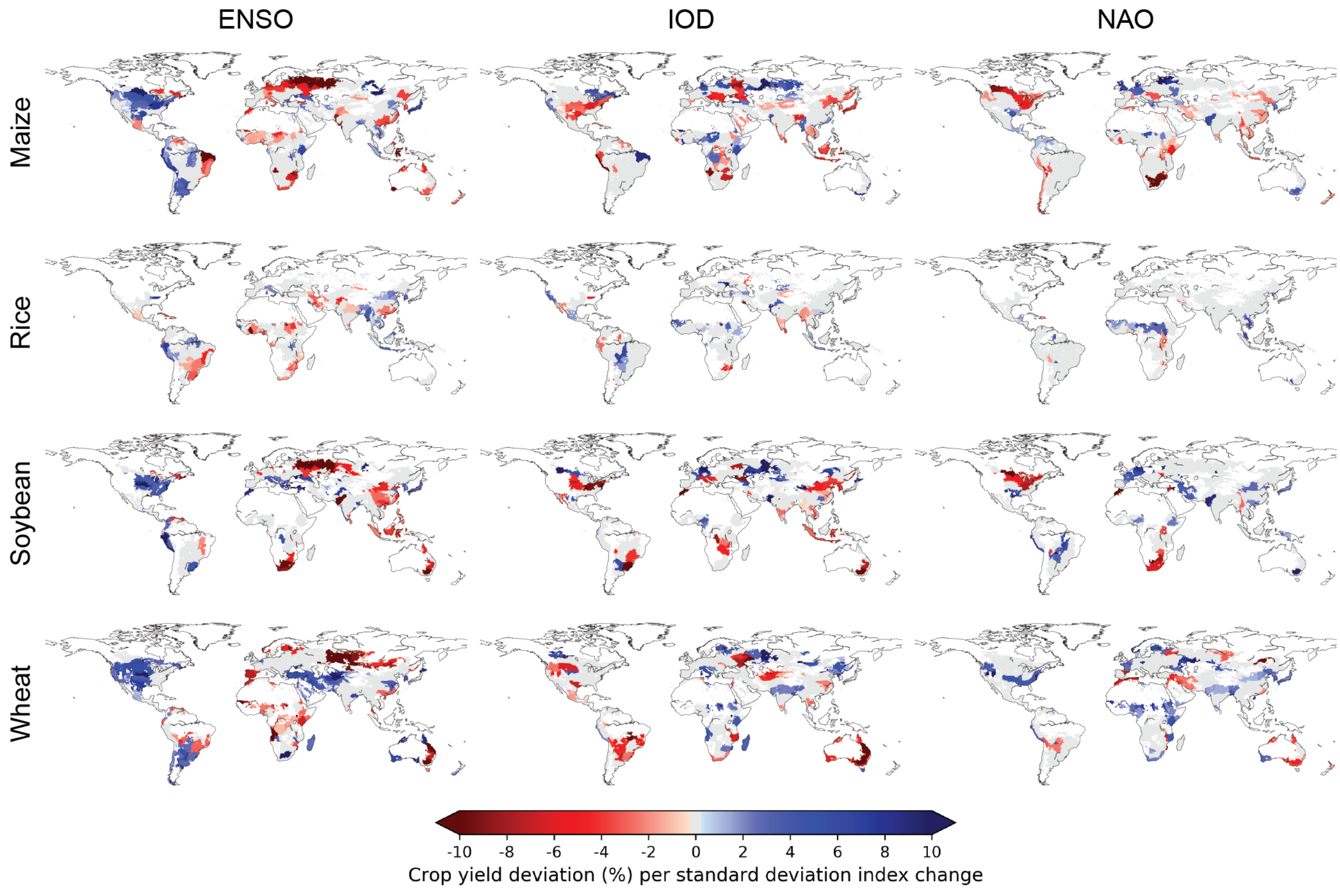

Figure S9. Minimum (in terms of magnitude) actual crop yield sensitivity to ENSO, IOD and NAO of the individual model results that show significant sensitivity of same sign compared to the ensemble results. The sensitivity values are derived from the models that simulate the crop in question with the AgMERRA climate input. Statistically insignificant ($p > 0.1$) sensitivity values (in the ensemble or all individual model results) are marked as zero. White color denotes that the crop in question is not produced in that area.

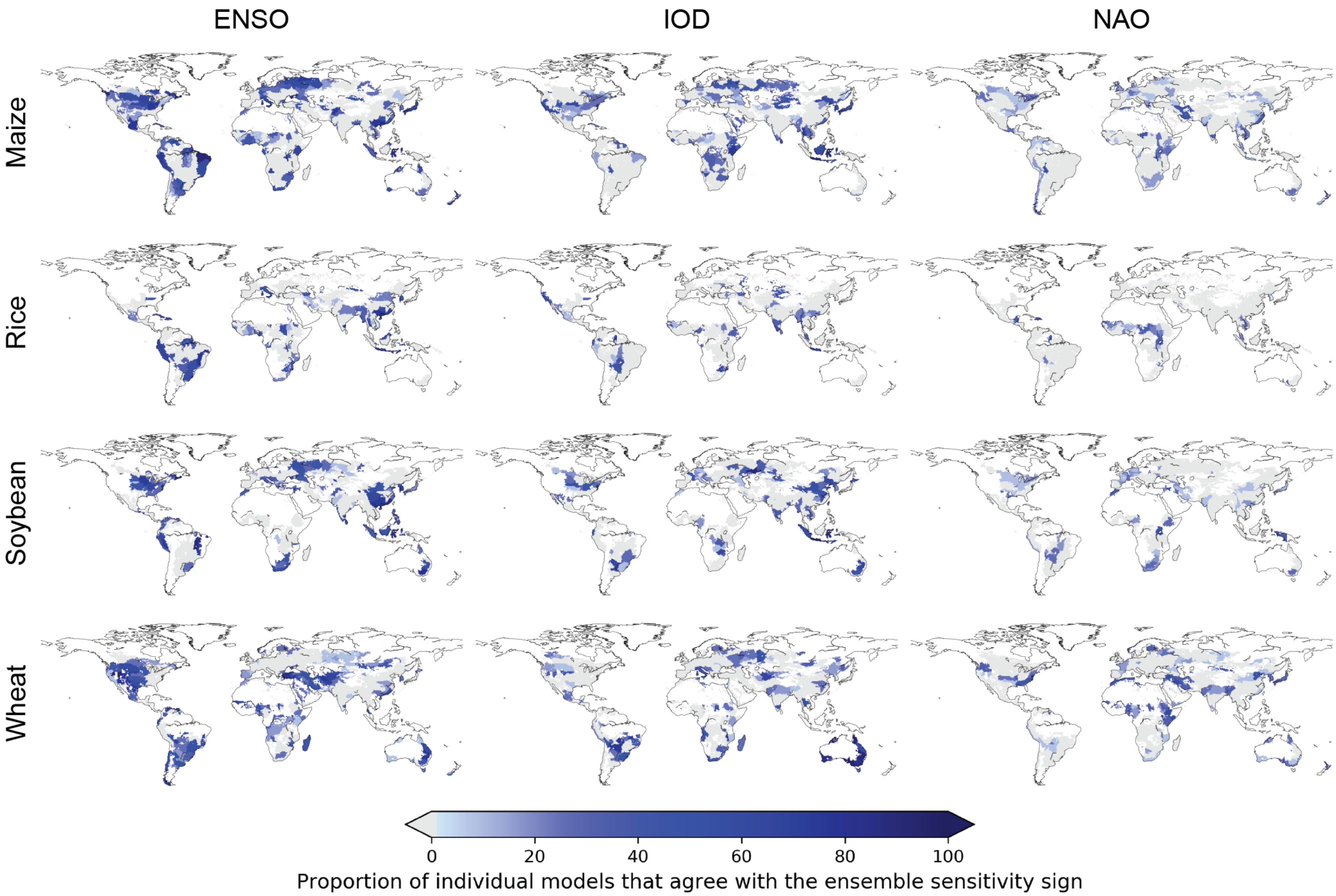

Figure S10. Consistency across models. Proportion of individual models that show significant sensitivity of same sign compared to the result from the ensemble sensitivity analysis (Figure 1). Areas where the ensemble results or individual model results do not show a statistically significant relationship are marked as zero. White color denotes that the crop in question is not grown in that area.

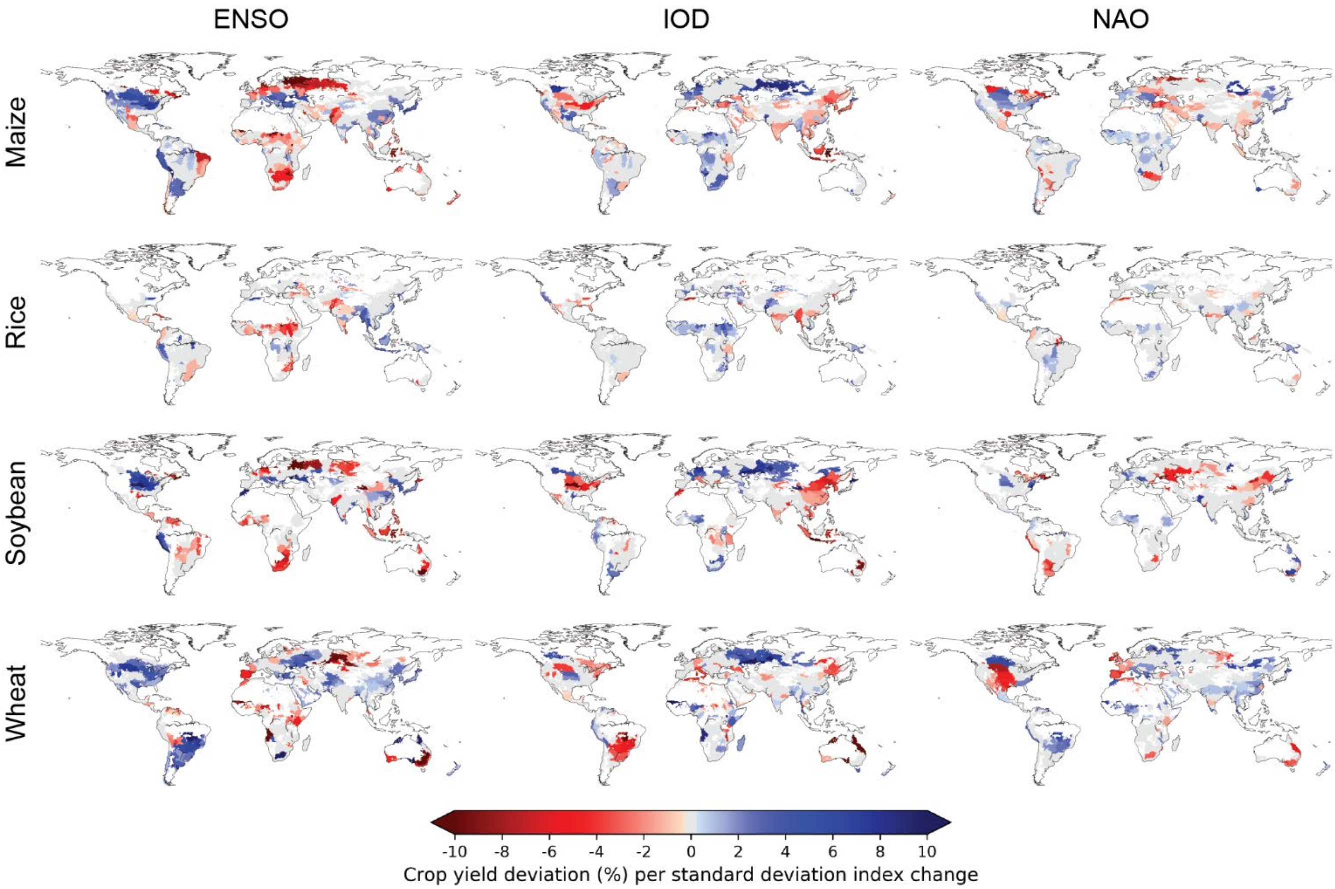

Figure S11. Actual crop yield sensitivity to harvest season ENSO, IOD and NAO at FPU scale. The sensitivity values are derived from a sample including crop yield data from all GGCMs that simulate the crop in question with the AgMERRA climate input. Statistically insignificant ($p > 0.1$) sensitivity values are marked as zero. White color denotes that the crop in question is not produced in that area. Sensitivity with oscillation indices calculated for the months when the oscillations tend to have the strongest signal is shown in Figure 1 in the main text.

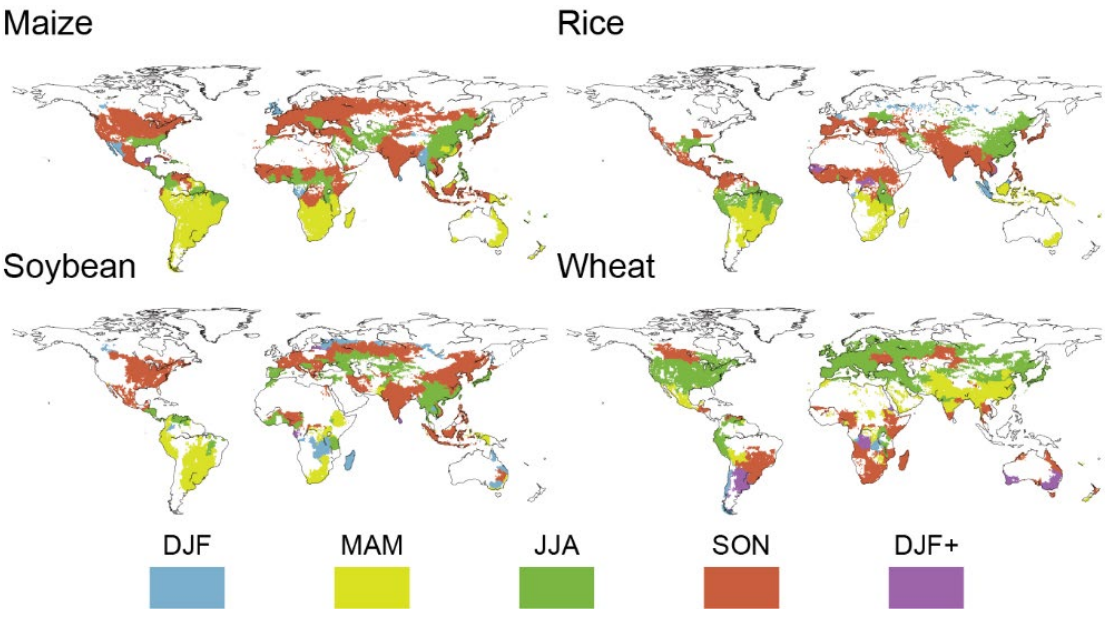

Figure S12. Seasons used for assessing the sensitivity of crop yield to the status of ENSO, IOD and NAO during harvesting season (Figure S11). DJF (DJF+) denotes that the start-of-the-year (end-of-the-year) DJF average index was used. The DJF (DJF+) was used if crops were harvested between January 1st and February 28th (December 1st and December 31st). As multiple harvesting dates exist inside each FPU, the season with the largest harvested area was selected for each FPU. White color denotes that the crop in question is not produced in that area.

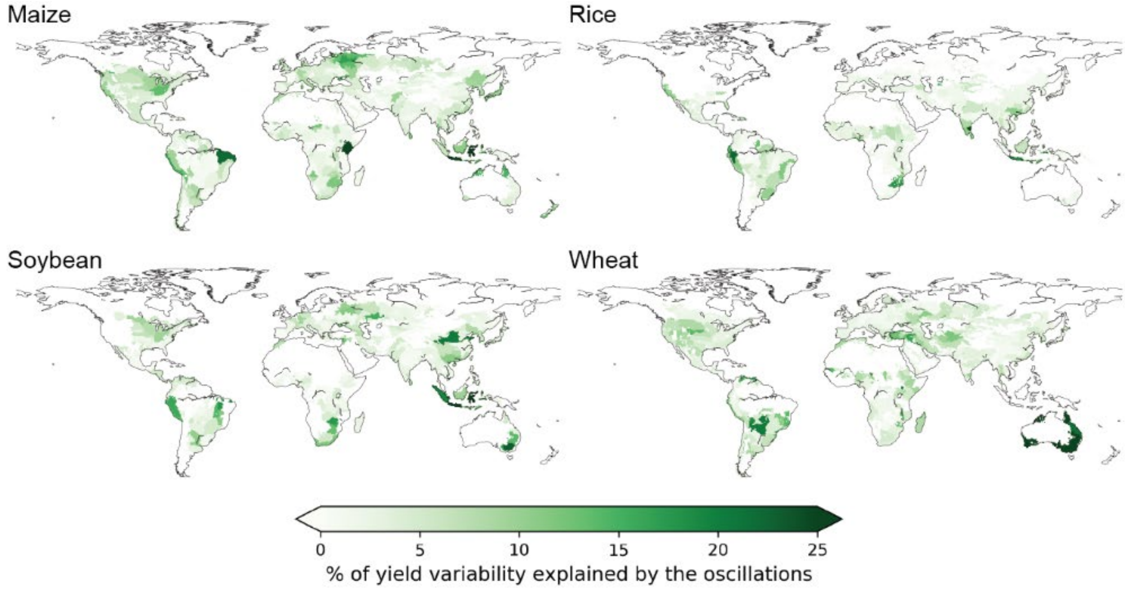

Figure S13. Percent of actual maize, rice, soybean, and wheat yield variability explained by ENSO, IOD and NAO at FPU scale according to the ridge regression model. The values are derived using crop yield data from all GGCMs that simulate the crop in question with the AgMERRA climate input.

Figures supporting Section 3.3 Magnitude of impacts in different cropping systems

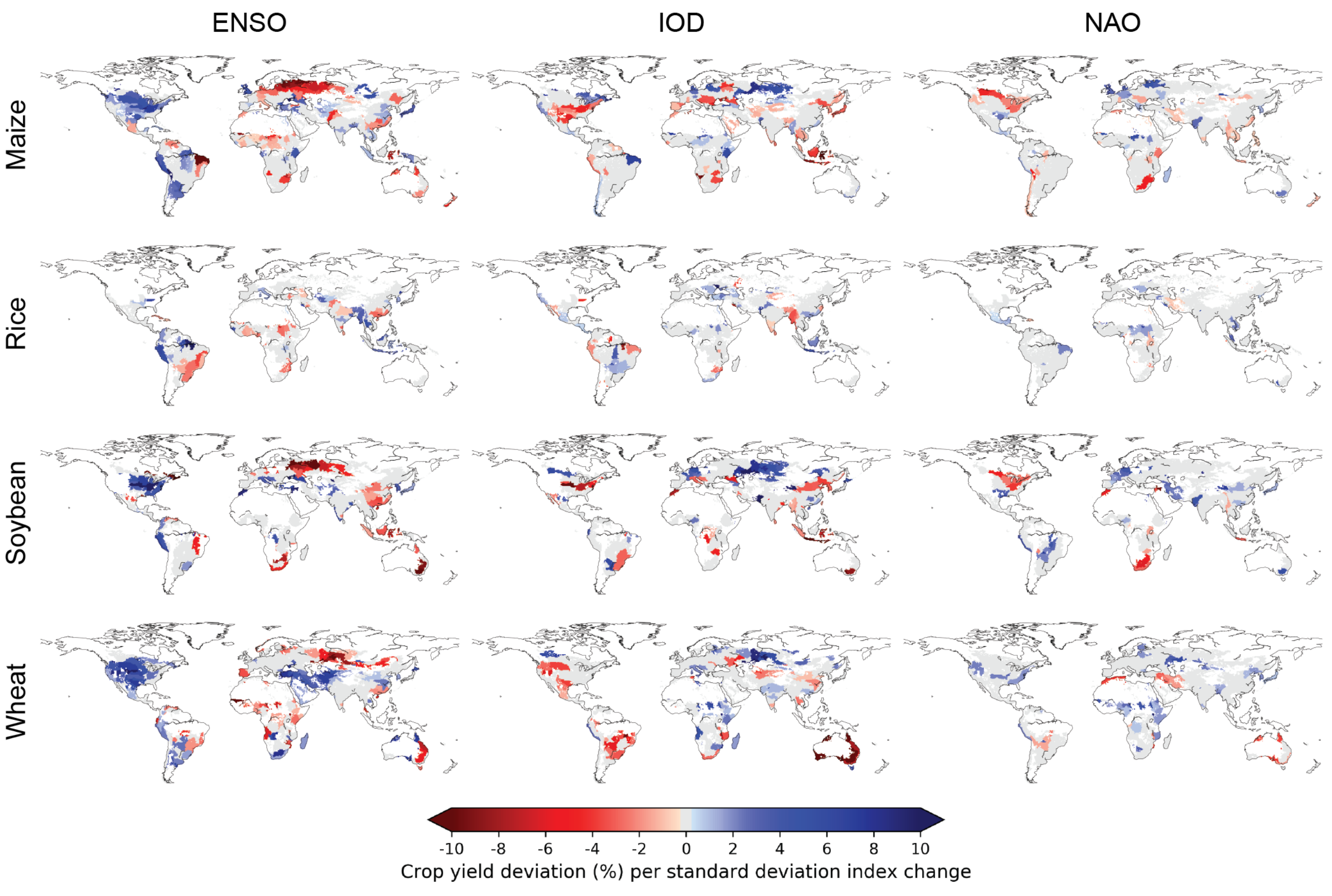

Figure S14. Actual crop yield sensitivity to ENSO, IOD and NAO at FPU scale. The sensitivity values are derived using crop yield data from all GGCMs that simulate the crop in question with the AgMERRA climate input, and have data for both 'fullharm' and 'harm-suffN settings: pDSSAT, EPIC-Boku, EPIC-IIASA, GEPIC, pAPSIM, PEGASUS, EPIC-TAMU, ORCHIDEE-crop, PEPIC. Statistically insignificant ($p > 0.1$) sensitivity values are marked as zero. White color denotes that the crop in question is not produced in that area. These results were used for comparison between cropping systems. Results for all models that simulate the crop in question are shown in Figure 1 in the main text.

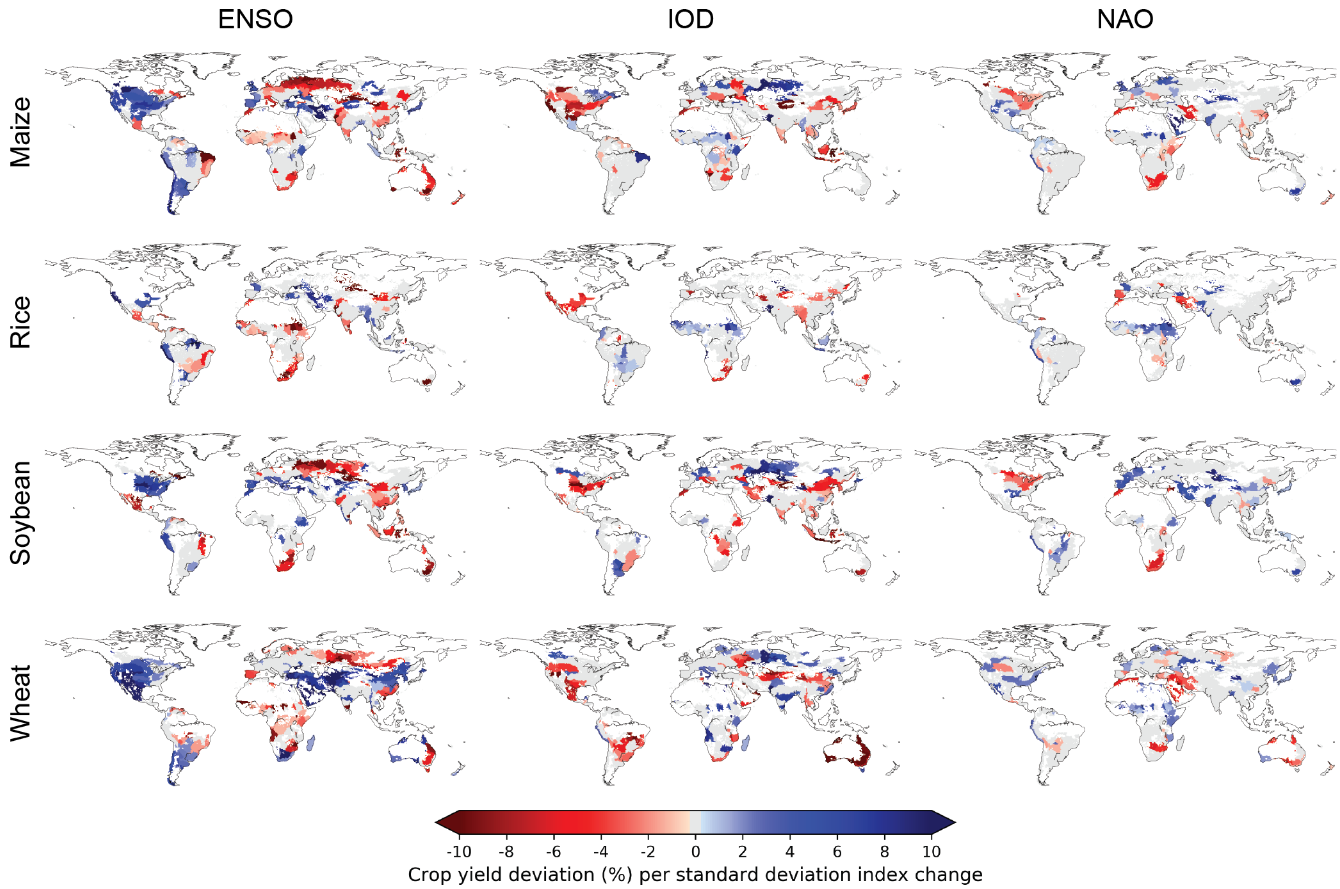

Figure S15. Rainfed crop yield sensitivity to ENSO, IOD and NAO at FPU scale. The sensitivity values are derived using crop yield data from all GGCMs that simulate the crop in question with the AgMERRA climate input using the fullharm (harm-suffN for LPJmL and LPJ-GUESS) set-up. Statistically insignificant ($p > 0.1$) sensitivity values are marked as zero. White color denotes that the crop in question is not produced in that area.

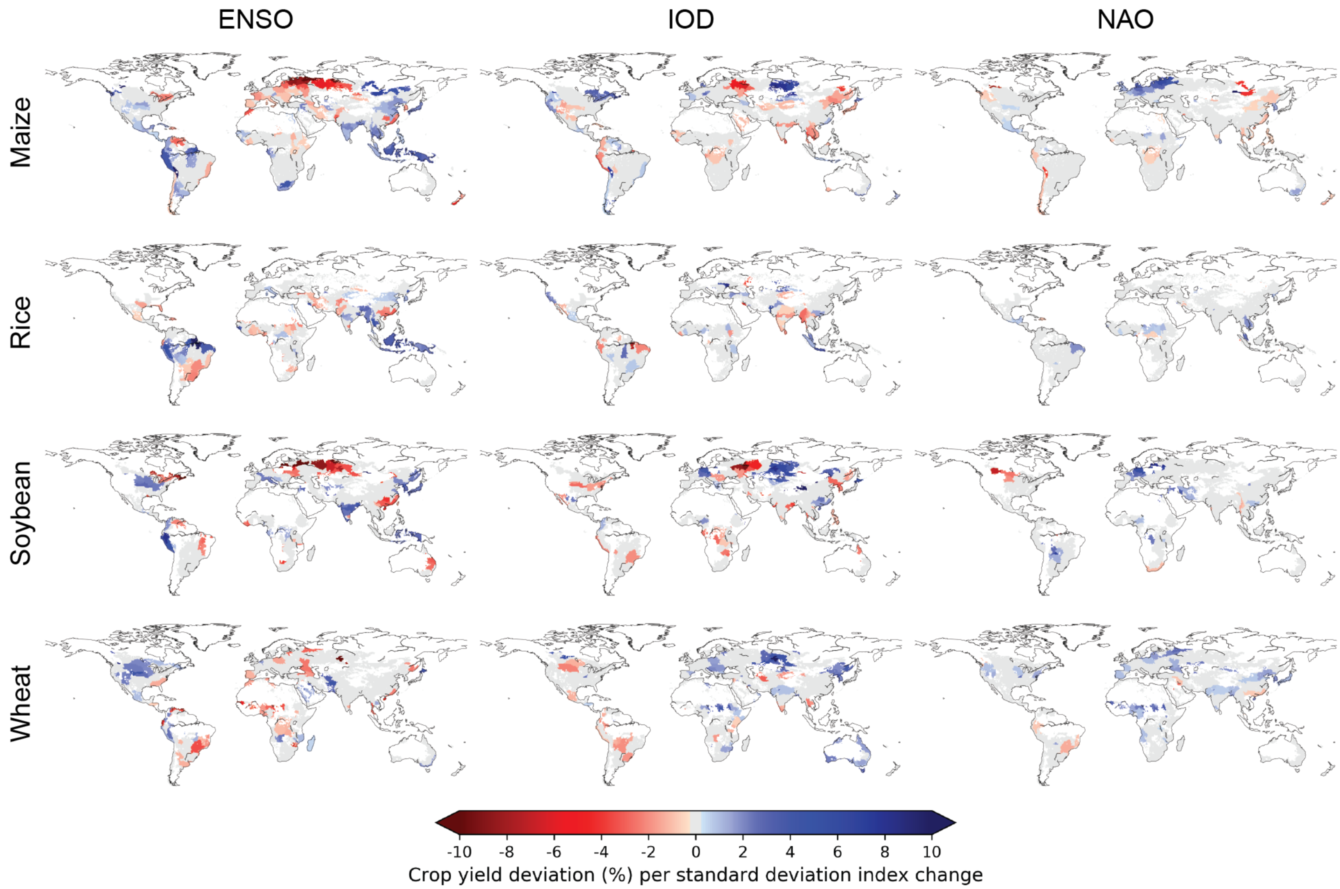

Figure S16. Fully irrigated crop yield sensitivity to ENSO, IOD and NAO at FPU scale. The sensitivity values are derived using crop yield data from all GGCMs that simulate the crop in question with the AgMERRA climate input using the fullharm (harm-suffN for LPJmL and LPJ-GUESS) set-up. Statistically insignificant ($p > 0.1$) sensitivity values are marked as zero. White color denotes that the crop in question is not produced in that area.

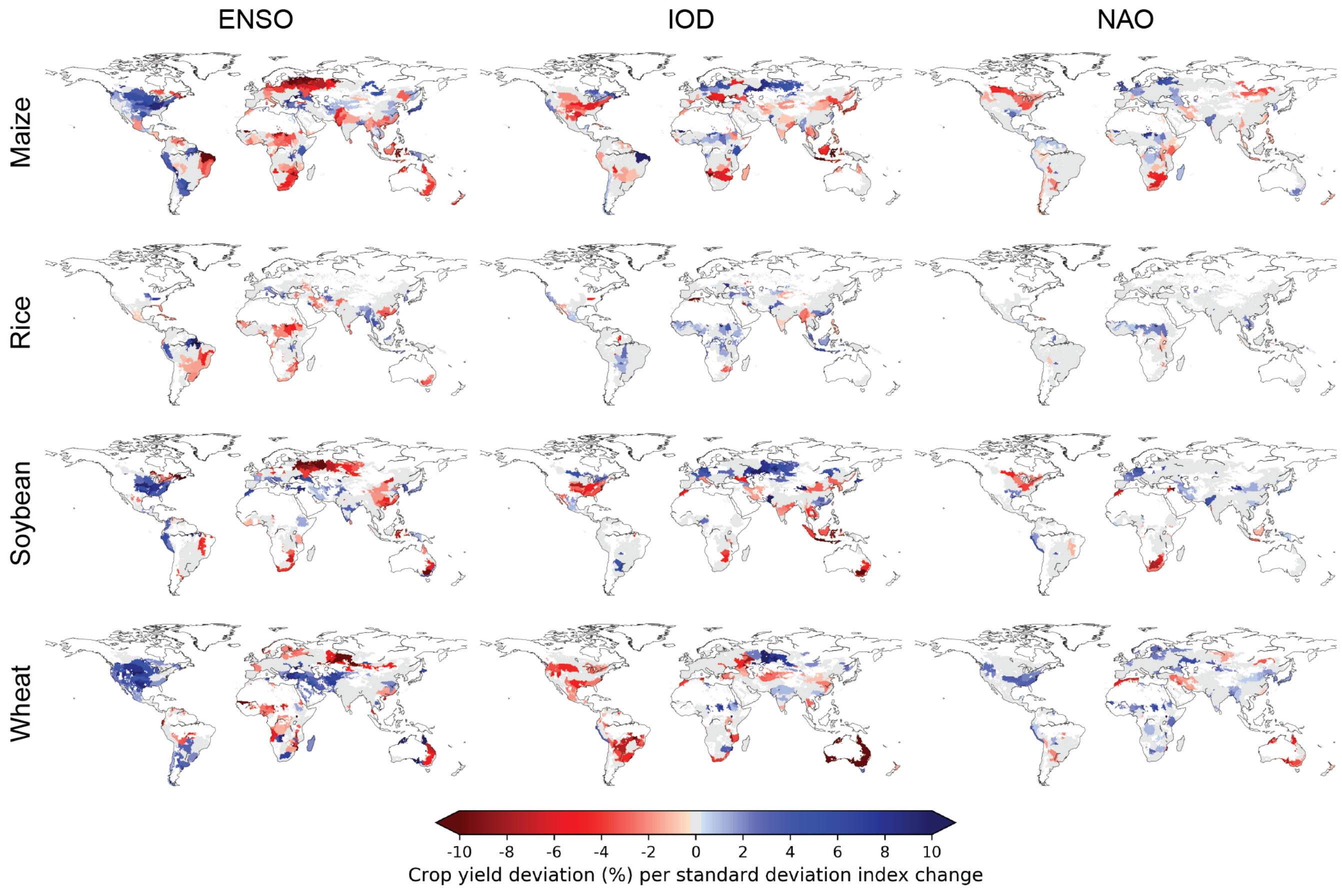

Figure S17. Fully fertilized crop yield sensitivity to ENSO, IOD and NAO at FPU scale. The sensitivity values are derived using crop yield data from all GGCMs that simulate the crop in question with the AgMERRA climate input, and have data for both 'fullharm' and 'harm-suffN settings: pDSSAT, EPIC-Boku, EPIC-IIASA, GEPIC, pAPSIM, PEGASUS, EPIC-TAMU, ORCHIDEE-crop, PEPIC. Statistically insignificant ($p > 0.1$) sensitivity values are marked as zero. White color denotes that the crop in question is not produced in that area.

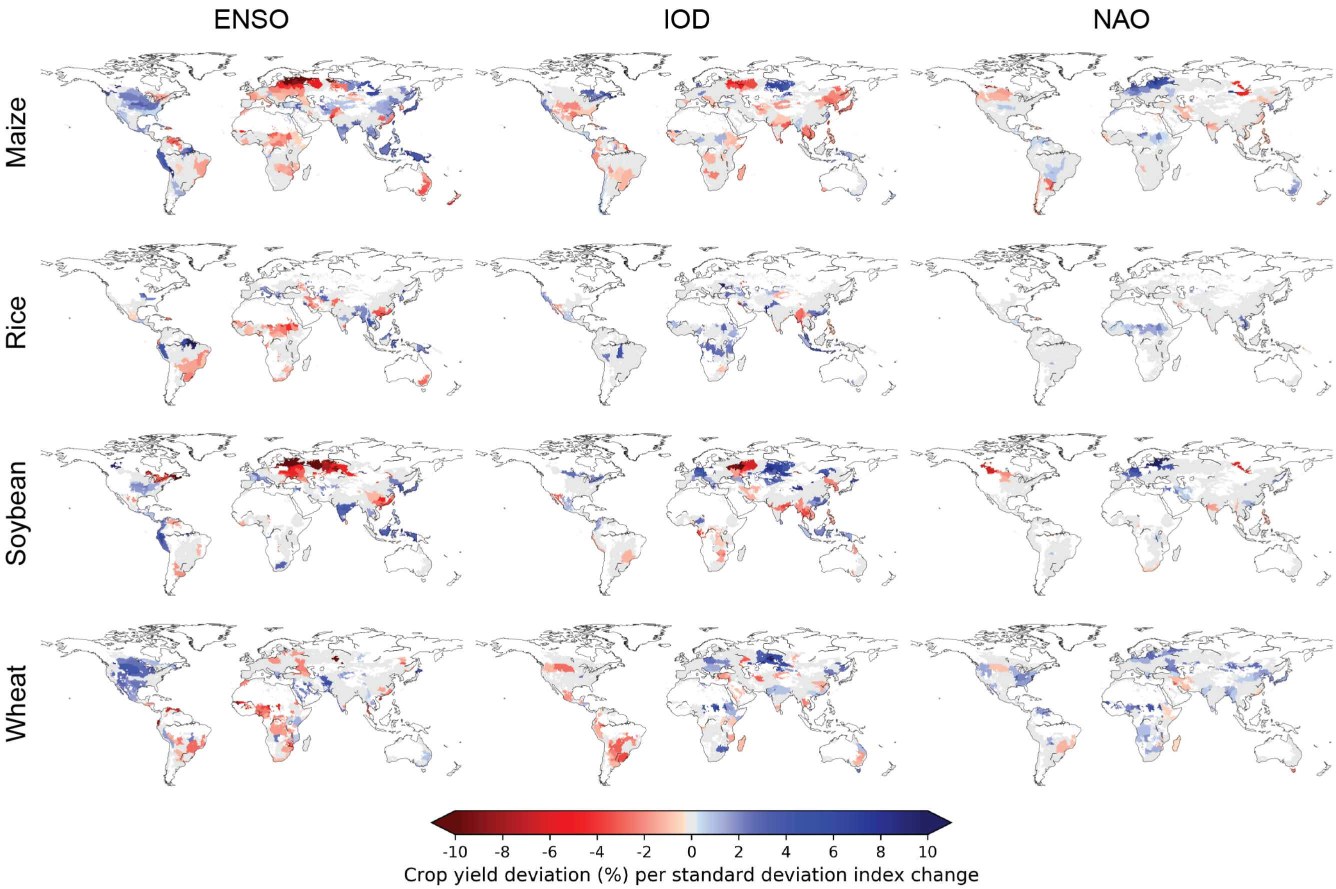

Figure S18. Fully fertilized and irrigated crop yield sensitivity to ENSO, IOD and NAO at FPU scale. The sensitivity values are derived using crop yield data from all GGCMs that simulate the crop in question with the AgMERRA climate input, and have data for both 'fullharm' and 'harm-suffN settings: pDSSAT, EPIC-Boku, EPIC-IIASA, GEPIC, pAPSIM, PEGASUS, EPIC-TAMU, ORCHIDEE-crop, PEPIC. Statistically insignificant ($p > 0.1$) sensitivity values are marked as zero. White color denotes that the crop in question is not produced in that area.

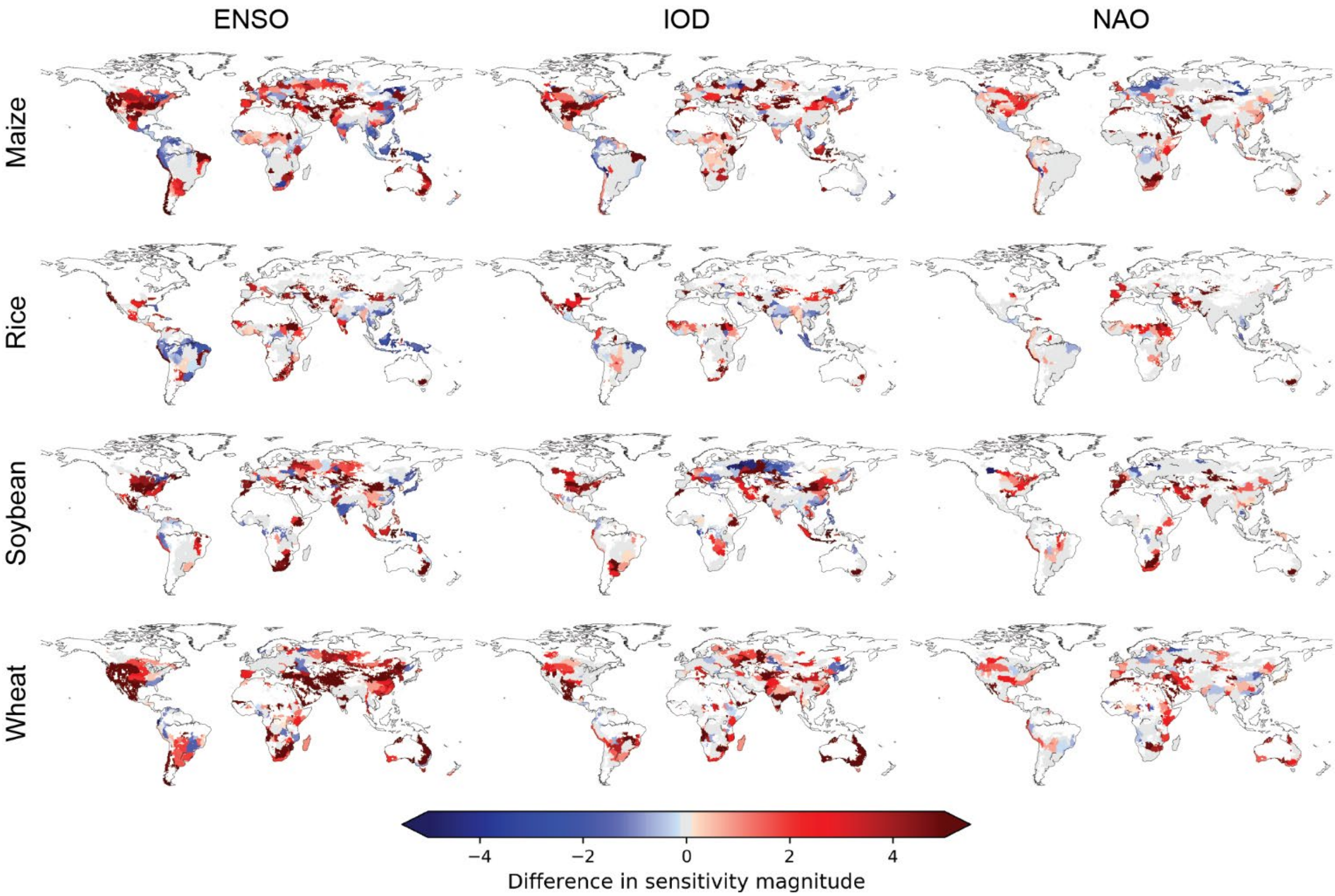

Figure S19. Fully irrigted vs rainfed sensitivity. Difference in magnitude of crop yield sensitivity to ENSO, IOD and NAO between fully irrigated and rainfed scenario at FPU scale. Results are shown only for those FPUs that show statistically significant (p > 0.1) sensitivity in either scenario. If neither scenario shows significant sensitivity, difference is marked as zero (gray color). The sensitivity values are derived using crop yield data from all GGCMs that simulate the crop in question with the AgMERRA climate input using the fullharm (harm-suffN for LPJmL and LPJ-GUESS) set-up. White color denotes that the crop in question is not produced in that area.

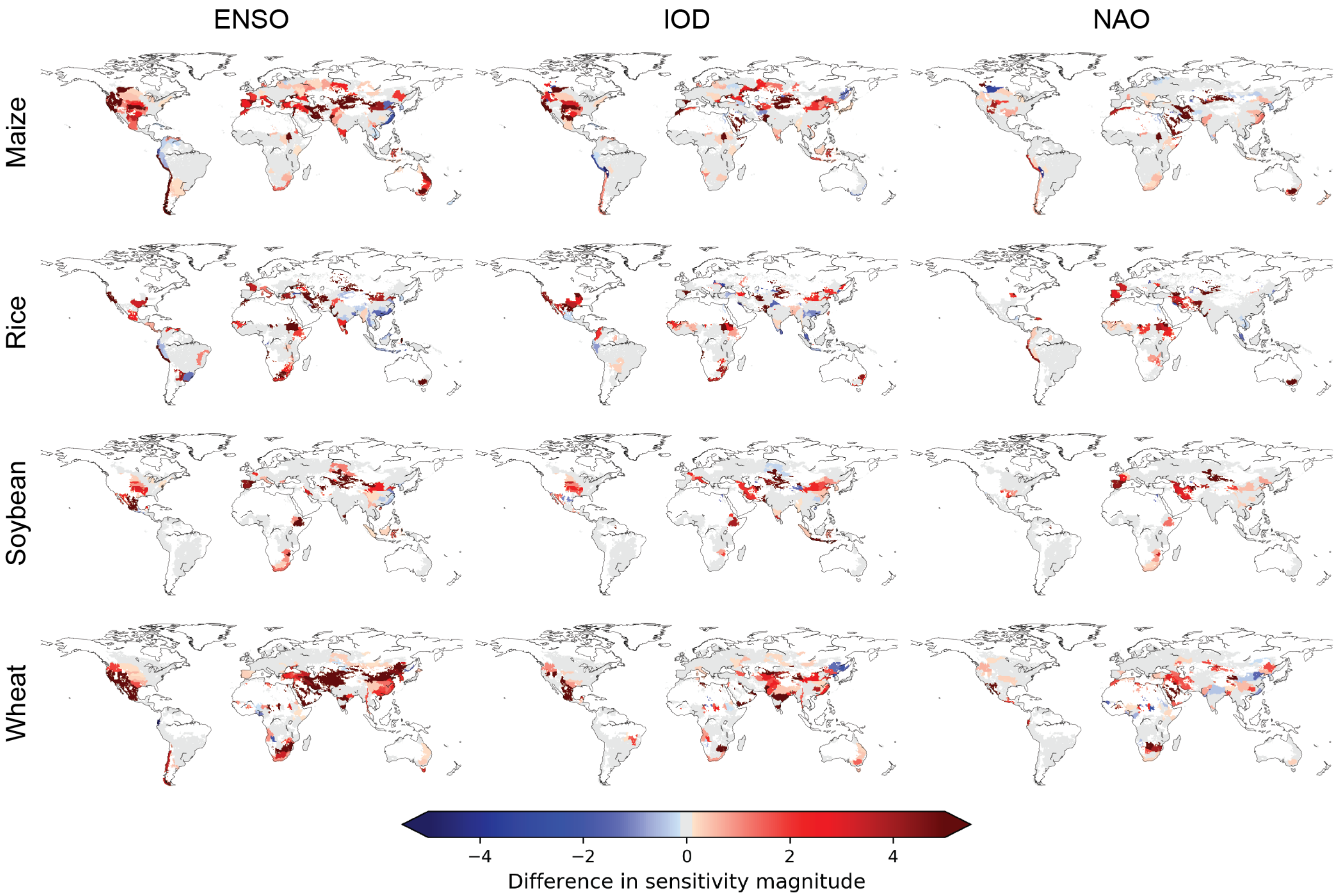

Figure S20. Actual vs rainfed sensitivity. Difference in magnitude of crop yield sensitivity to ENSO, IOD and NAO between actual and fully rainfed scenario at FPU scale. Results are shown only for those FPUs that show statistically significant ($p > 0.1$) sensitivity in either scenario. If neither scenario shows significant sensitivity, difference is marked as zero (gray color). The sensitivity values are derived using crop yield data from all GGCMs that simulate the crop in question with the AgMERRA climate input using the fullharm (harm-suffN for LPJmL and LPJ-GUESS) set-up. White color denotes that the crop in question is not produced in that area.

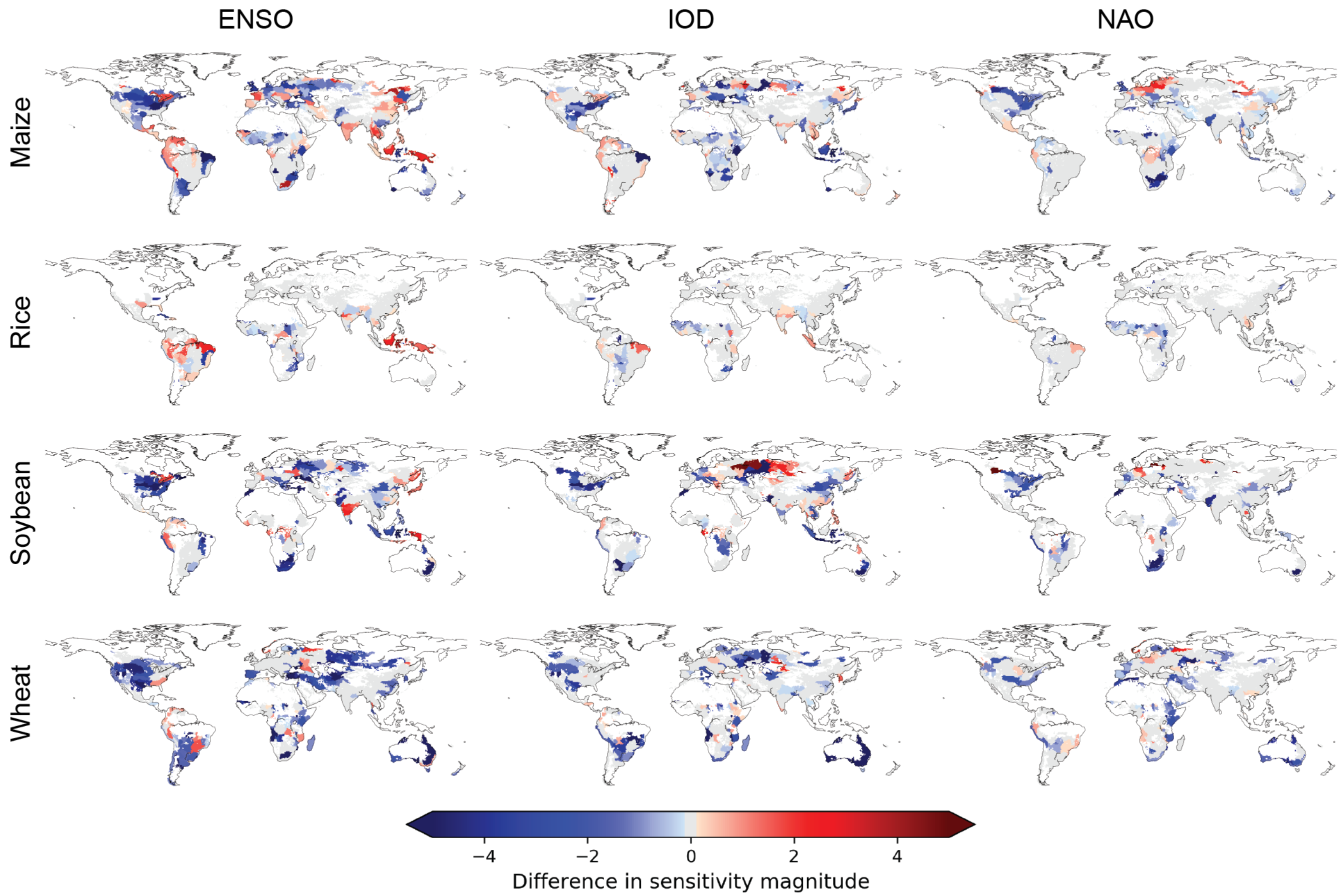

Figure S21. Actual vs fully irrigated sensitivity. Difference in magnitude of crop yield sensitivity to ENSO, IOD and NAO between actual and fully irrigated scenario at FPU scale. Results are shown only for those FPUs that show statistically significant (p > 0.1) sensitivity in either scenario. If neither scenario shows significant sensitivity, difference is marked as zero (gray color). The sensitivity values are derived using crop yield data from all GGCMs that simulate the crop in question with the AgMERRA climate input using the fullharm (harm-suffN for LPJmL and LPJ-GUESS) set-up. White color denotes that the crop in question is not produced in that area.

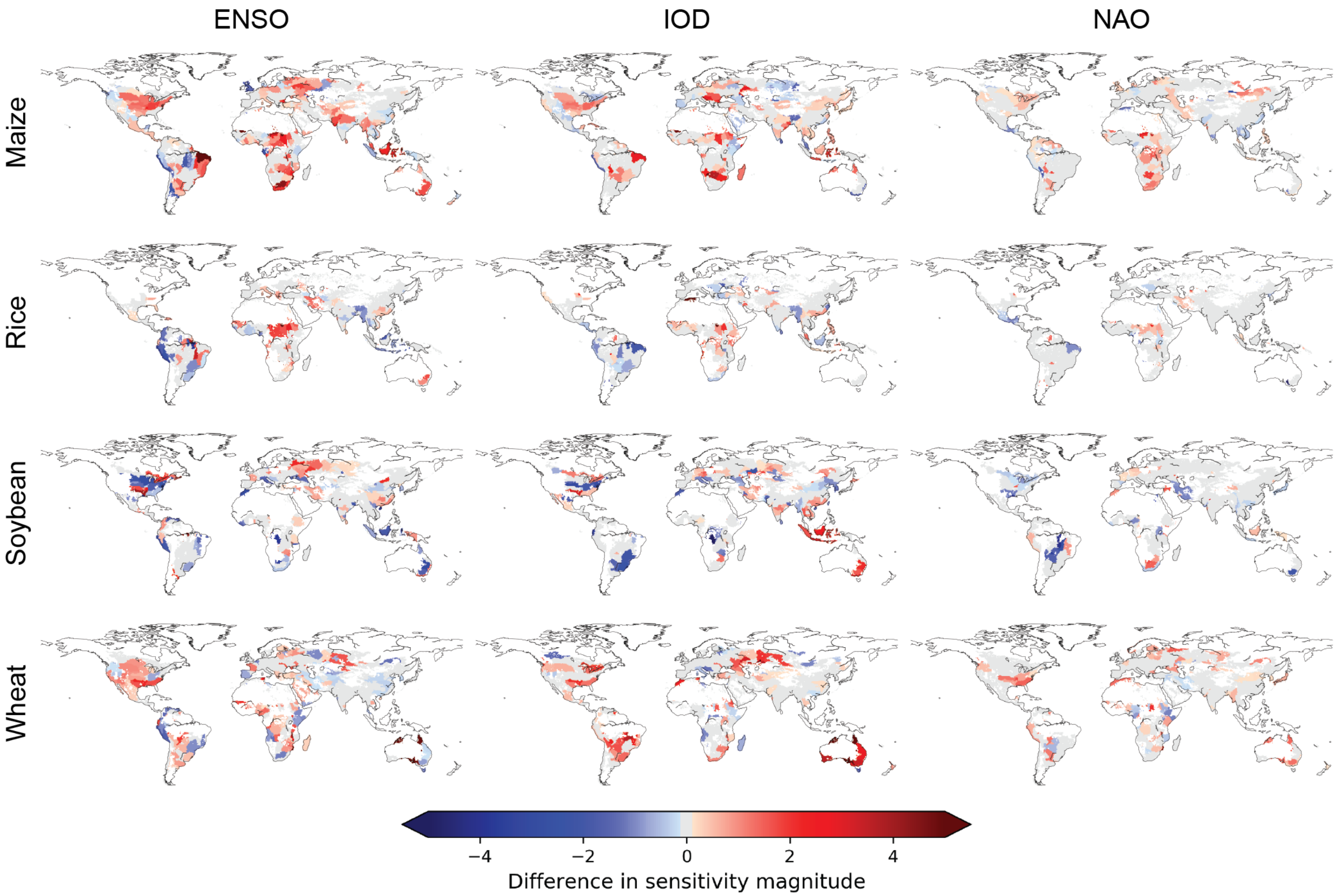

Figure S22. Actual vs fully fertilized sensitivity. Difference in magnitude of crop yield sensitivity to ENSO, IOD and NAO between actual and fully fertilized scenario at FPU scale. Results are shown only for those FPUs that show statistically significant ($p > 0.1$) sensitivity in either scenario. If neither scenario shows significant sensitivity, difference marked as zero (gray color). The sensitivity values are derived using crop yield data from all GGCMs that simulate the crop in question with the AgMERRA climate input, and have data for both 'fullharm' and 'harm-suffN settings: pDSSAT, EPIC-Boku, EPIC-IIASA, GEPIC, pAPSIM, PEGASUS, EPIC-TAMU, ORCHIDEE-crop, PEPIC. White color denotes that the crop in question is not produced in that area.

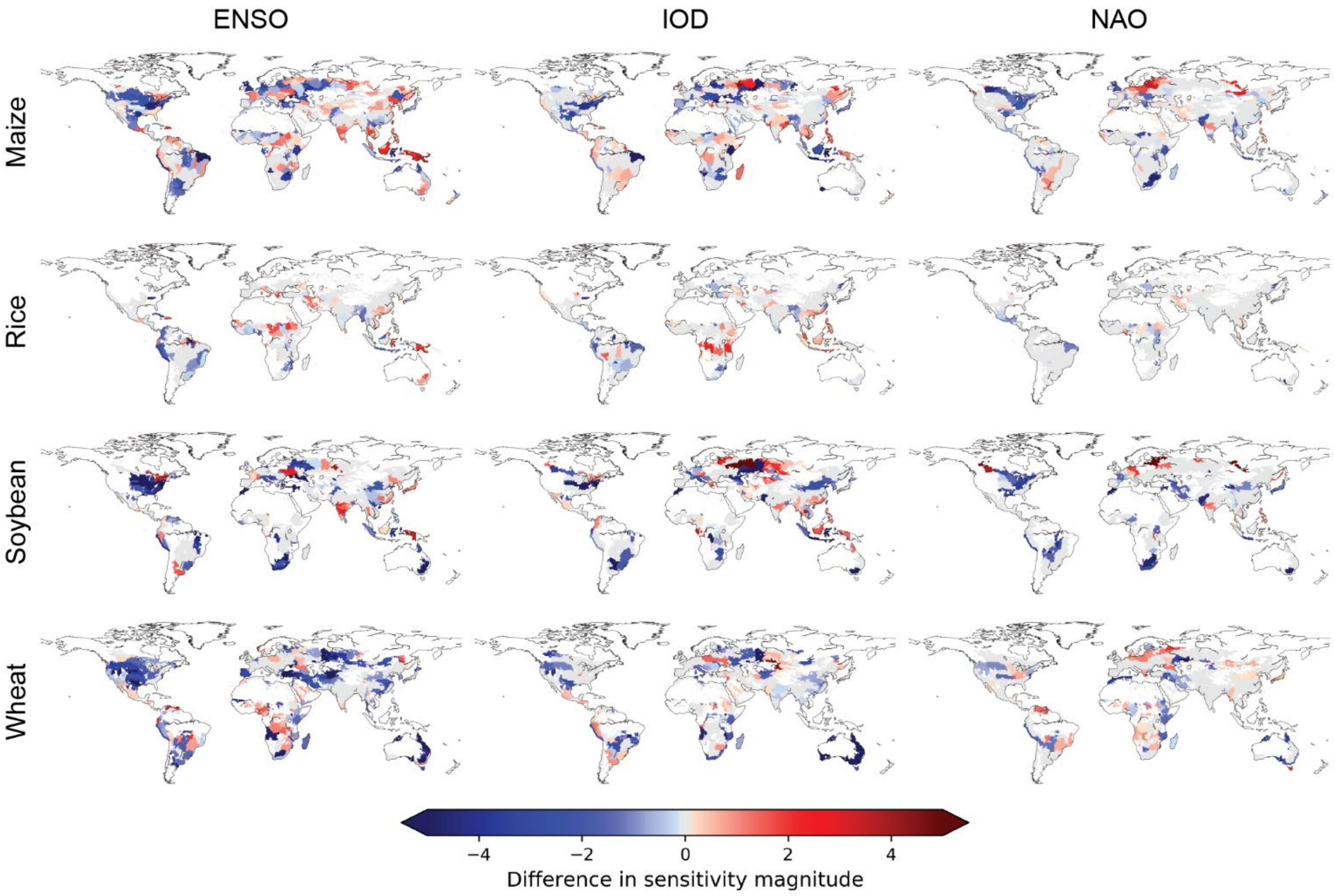

Figure S23. Actual vs fully fertilized and irrigated sensitivity. Difference in magnitude of crop yield sensitivity to ENSO, IOD and NAO between actual and fully fertilized and irrigated scenario at FPU scale. Results are shown only for those FPUs that show statistically significant ($p > 0.1$) sensitivity in either scenario. If neither scenario shows significant sensitivity, difference marked as zero (gray color). The sensitivity values are derived using crop yield data from all GGCMs that simulate the crop in question with the AgMERRA climate input, and have data for both 'fullharm' and 'harm-suffN settings: pDSSAT, EPIC-Boku, EPIC-IIASA, GEPIC, pAPSIM, PEGASUS, EPIC-TAMU, ORCHIDEE-crop, PEPIC. White color denotes that the crop in question is not produced in that area.

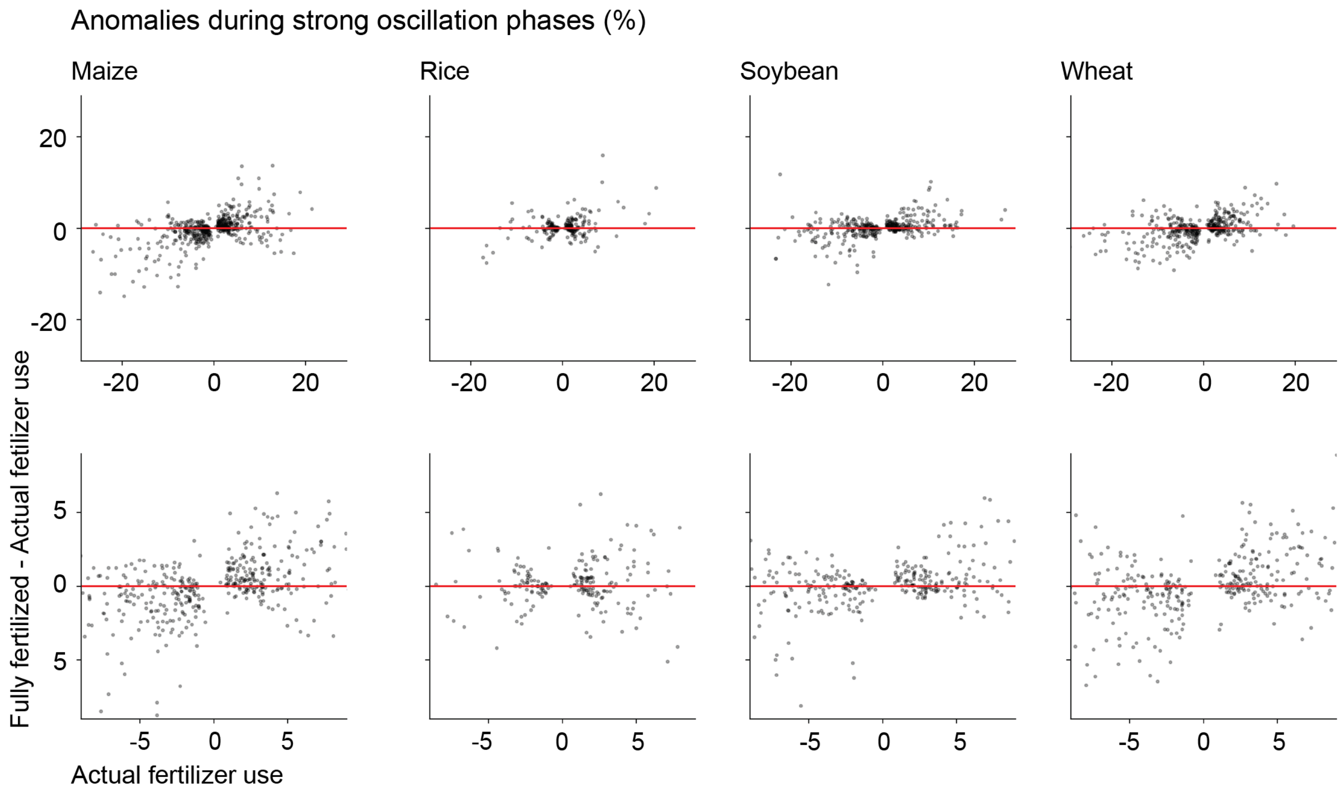

Figure S24. Anomaly difference for actual and fully fertilized cropping systems during strong oscillation phases through all oscillations and FPUs. Anomaly difference between the scenarios is shown in the y-axis, while x-axis shows the anomaly for the actual scenario. Both rows in figure contain the same information, but with different axis span.

References

Heino, M., Puma, M. J., Ward, P. J., Gerten, D., Heck, V., Siebert, S. and Kummu, M.: Two-thirds of global cropland area impacted by climate oscillations, Nature communications, 9, 1257, https://doi.org/10.1038/s41467-017-02071-5, 2018.

Martens, B., Gonzalez Miralles, D., Lievens, H., Van Der Schalie, R., De Jeu, R. A., Fernández-Prieto, D., Beck, H. E., Dorigo, W. and Verhoest, N.: GLEAM v3: Satellite-based land evaporation and root-zone soil moisture, Geoscientific Model Development, 10, 1903-1925, 2017.

Müller, C., Elliott, J., Chryssanthacopoulos, J., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., Folberth, C., Glotter, M., Hoek, S., Iizumi, T., Izaurralde, R. C., Jones, C., Khabarov, N., Lawrence, P., Liu, W., Olin, S., Pugh, T. A. M., Ray, D. K., Reddy, A., Rosenzweig, C., Ruane, A. C., Sakurai, G., Schmid, E., Skalsky, R., Song, C. X., Wang, X., De Wit, A. and Yang, H.: Global gridded crop model evaluation: Benchmarking, skills, deficiencies and implications, Geoscientific Model Dev., 10, 1403-1422, https://doi.org/10.5194/gmd-10-1403-2017, 2017.

NOAA Earth System Research Laboratory: Niño 3.4 SST Index, available at: https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/, last access August 2019.

Ruane, A. C., Goldberg, R. and Chryssanthacopoulos, J.: Climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation, Agric. For. Meteorol., 200, 233-248, 2015.