Earth's Future

Supporting Information for

Adaptation strategies strongly reduce the future impacts of climate change on crop yields

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Introduction

This supporting information consists of figures and tables which are referenced in the text of the manuscript.

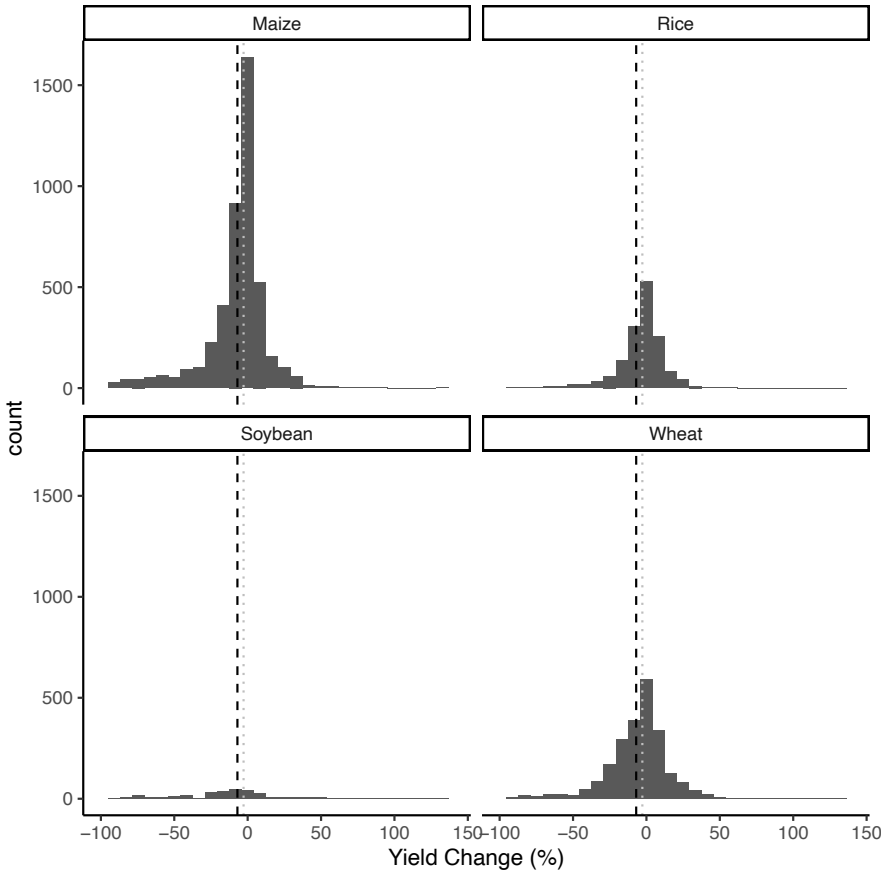

Figure S1. Histograms showing the distribution of yield change projections (%) for maize, rice, soybean and wheat. The median and mean changes in yield relative to the baseline period are depicted as short dash gray lines and long dash black lines, respectively.

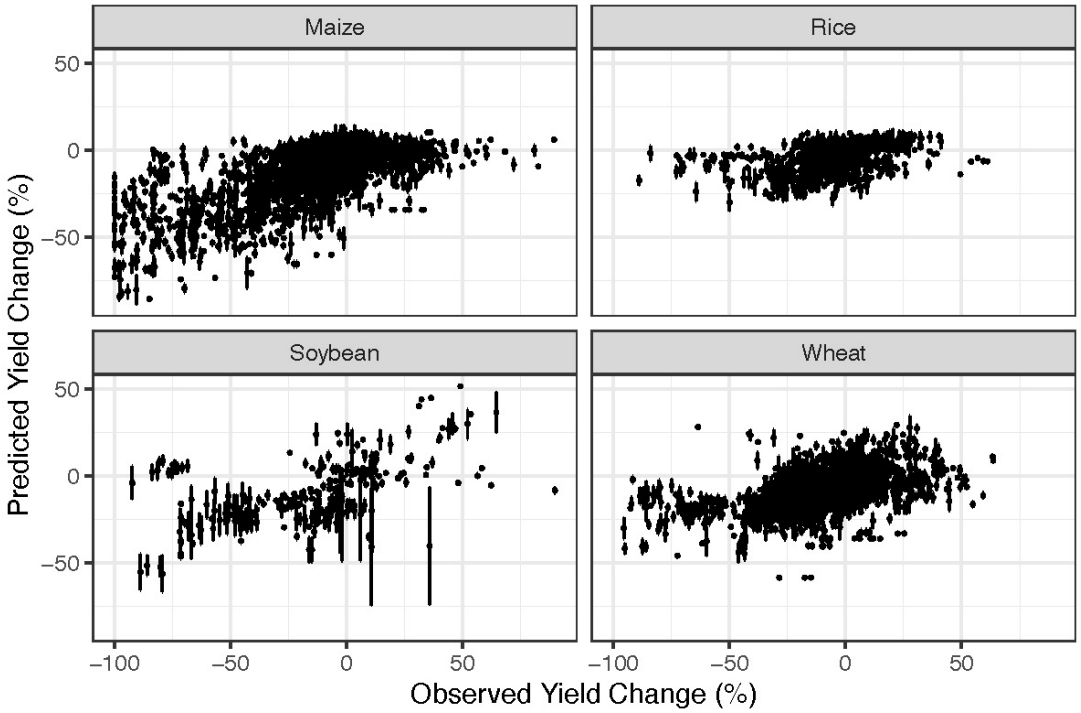

Figure S2. Predicted Yield Change vs Observed Yield Change for Maize, Rice, Soybean, and Wheat. Error bars represent the standard error of replicated sites from the 10 models generated from randomly splitting the dataset for cross-validation. For this cross-validation, the testing dataset did not include any locations used in the training dataset.

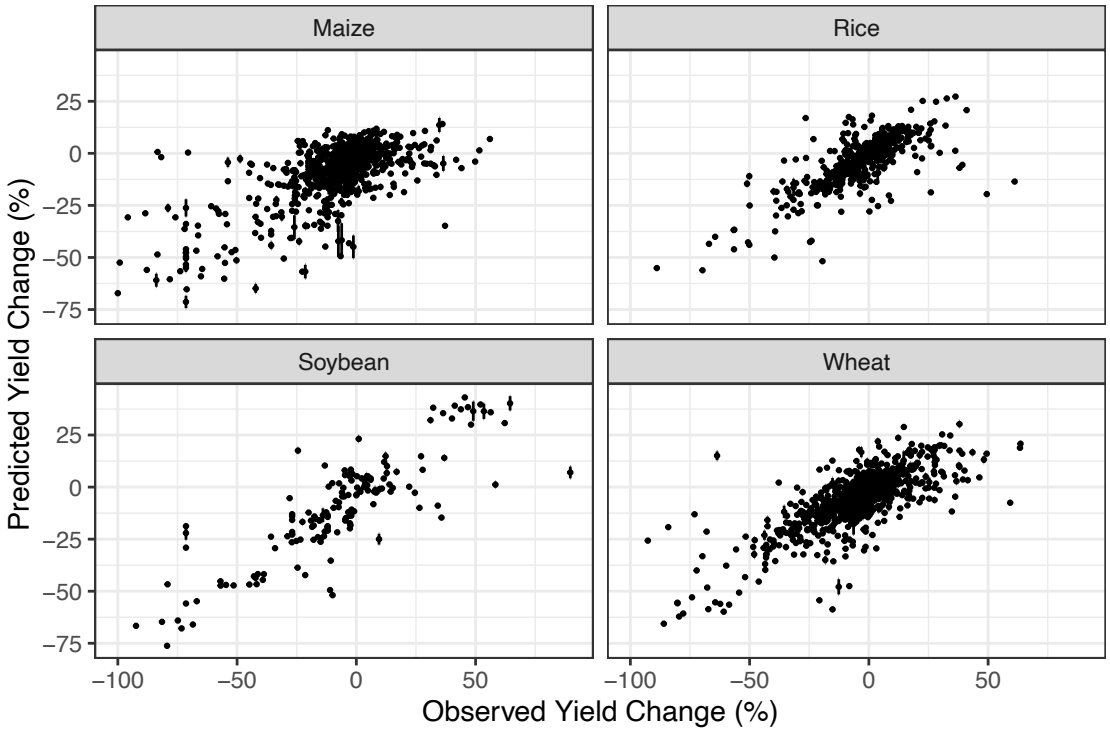

Figure S3. Predicted Yield Change vs Observed Yield Change for Maize, Rice, Soybean, and Wheat. Error bars represent the standard error of replicated sites from the 10 models generated from randomly splitting the dataset for cross-validation. For this cross-validation, the testing dataset included locations used in the training dataset, and error bars are not always large enough to be apparent.

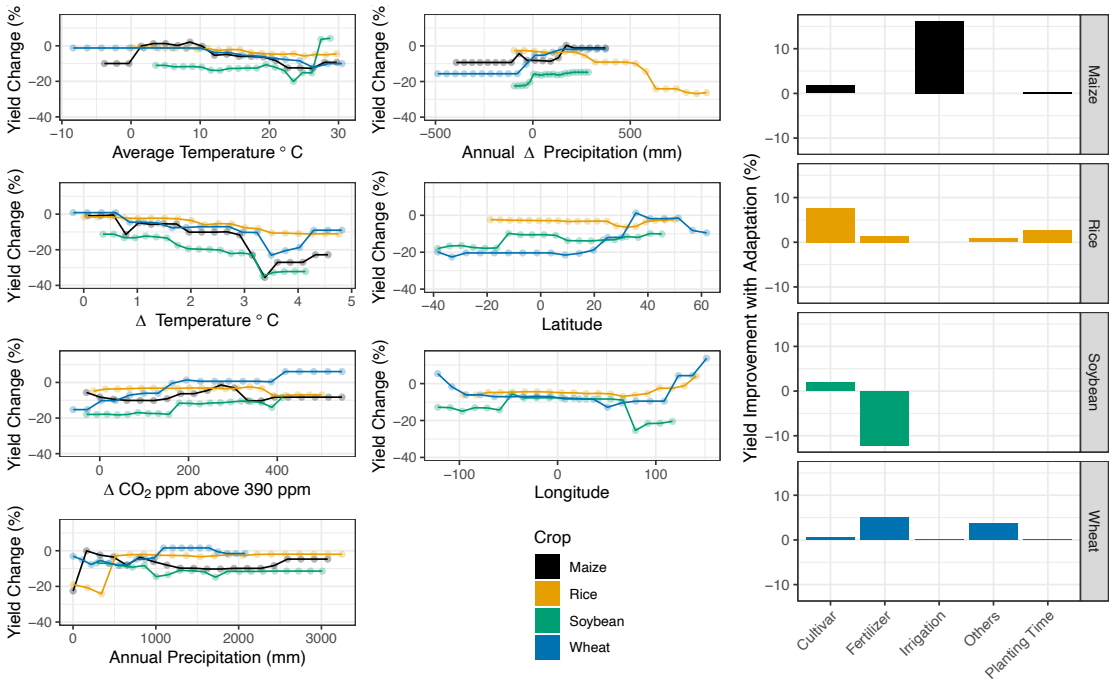

Figure S4. Partial dependence plots showing the marginal effect of each predictor variable (average temperature, change in temperature, change in CO_2 above 390ppm, average annual precipitation (mm), annual change in precipitation (mm), Latitude and Longitude [only used as predictors in Maize, Rice, and Soybean best models] on the yield change (%). The bar plots show the marginal improvement of yield with adaptation (marginal effect of: adaptation applied – no adaptation) for each adaptation type [Cultivar, Fertilizer, Irrigation, Others, Planting Time]) and each crop.

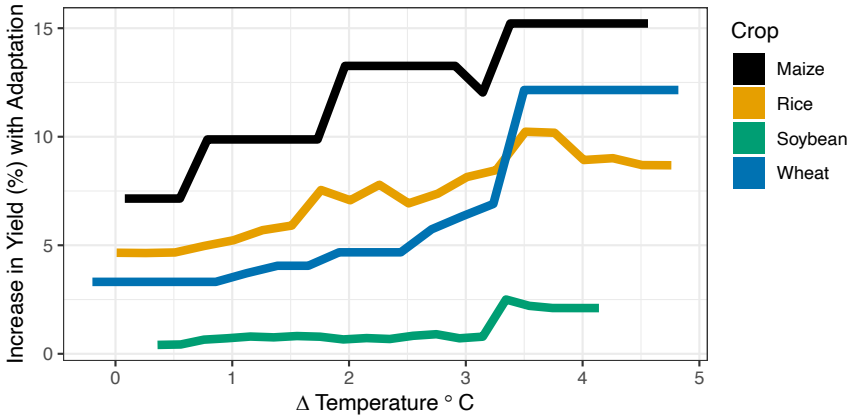

Figure S5. Partial dependence plots showing the marginal effect of the change in temperature on the yield increase with Adaptation (marginal effect of warming on yield with: adaptation applied – no adaptation). Colors indicate the crop: Maize, Rice, Soybean, and Wheat.

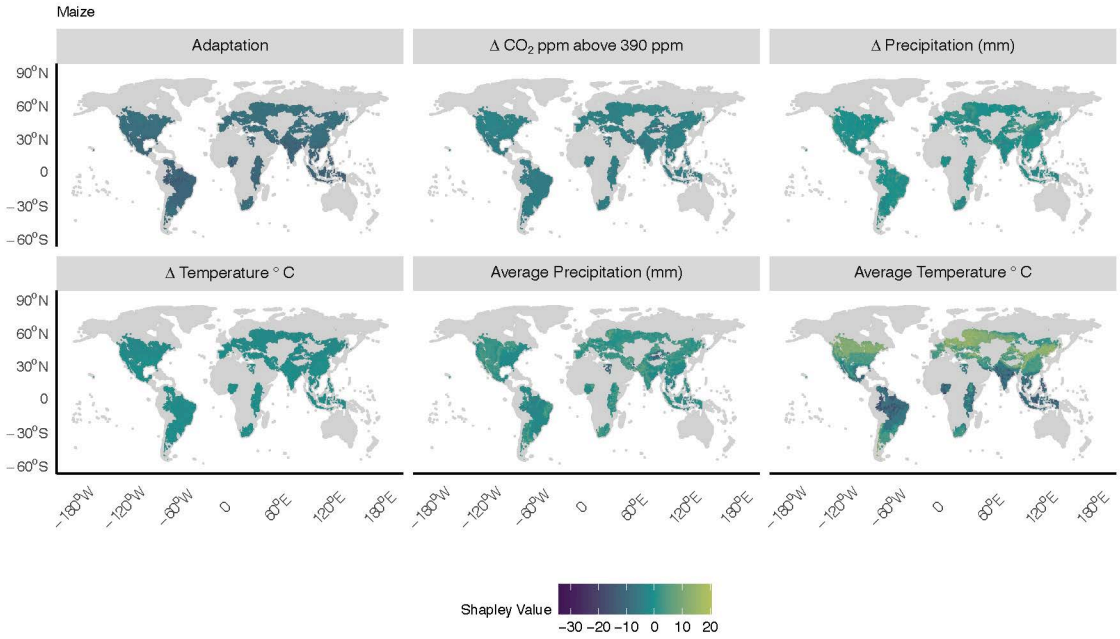

Figure S6a. Shapley additive explanation contribution to the predicted yield change (%) for maize under RCP4.5 without adaptation. The four predictors considered are adaptation (Yes/No), change in CO_2 concentration above 390ppm, change in precipitation, warming level, average precipitation, and average temperature. The color bar indicates the Shapley value.

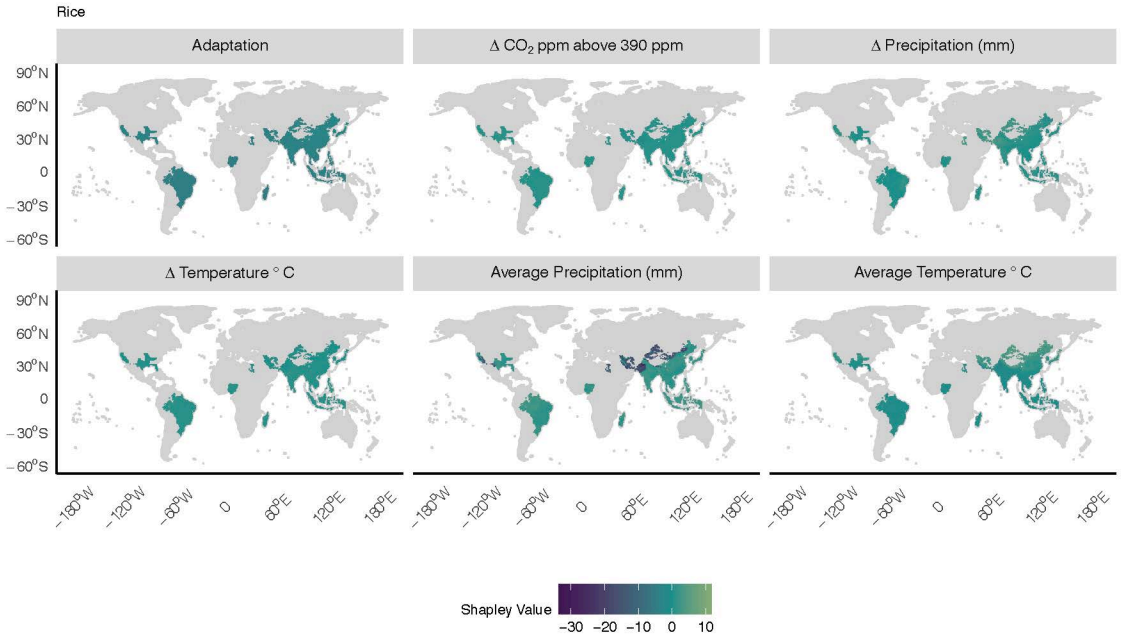

Figure S6b. Shapley additive explanation contribution to the predicted yield change (%) for rice under an RCP4.5 scenario without adaptation. The four predictors considered are adaptation (Yes/No), change in CO_2 concentration above 390ppm, change in precipitation, warming level, average precipitation, and average temperature. The color bar indicates the Shapley value.

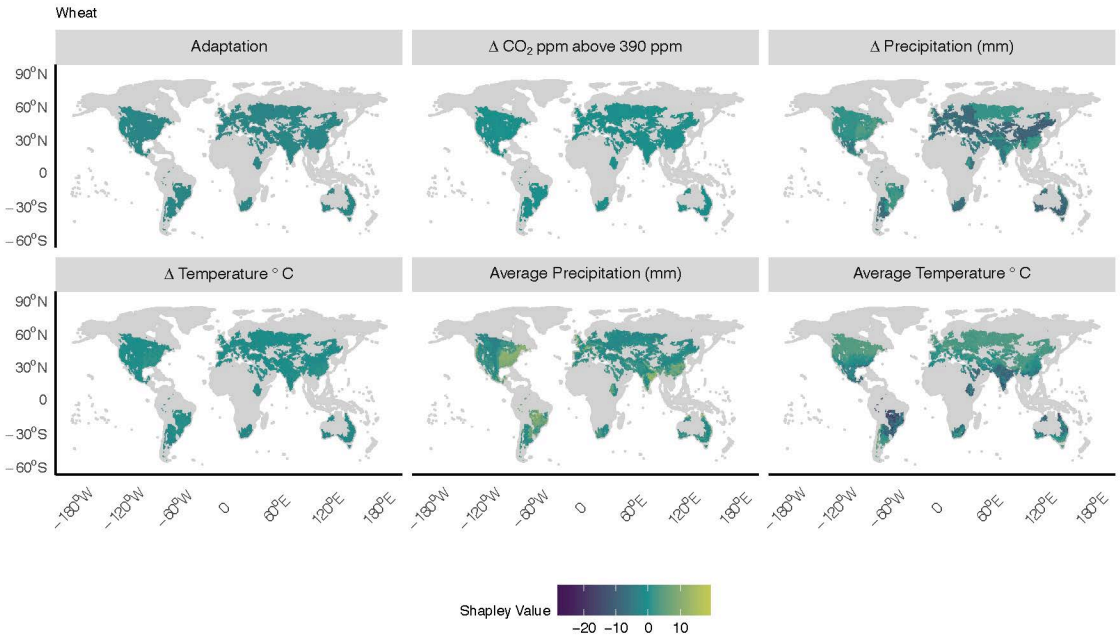

Figure S6c. Shapley additive explanation contribution to the predicted yield change (%) for wheat under an RCP4.5 scenario without adaptation. The four predictors considered are adaptation (Yes/No), change in CO_2 concentration above 390ppm, change in precipitation, warming level, average precipitation, and average temperature. The color bar indicates the Shapley value.

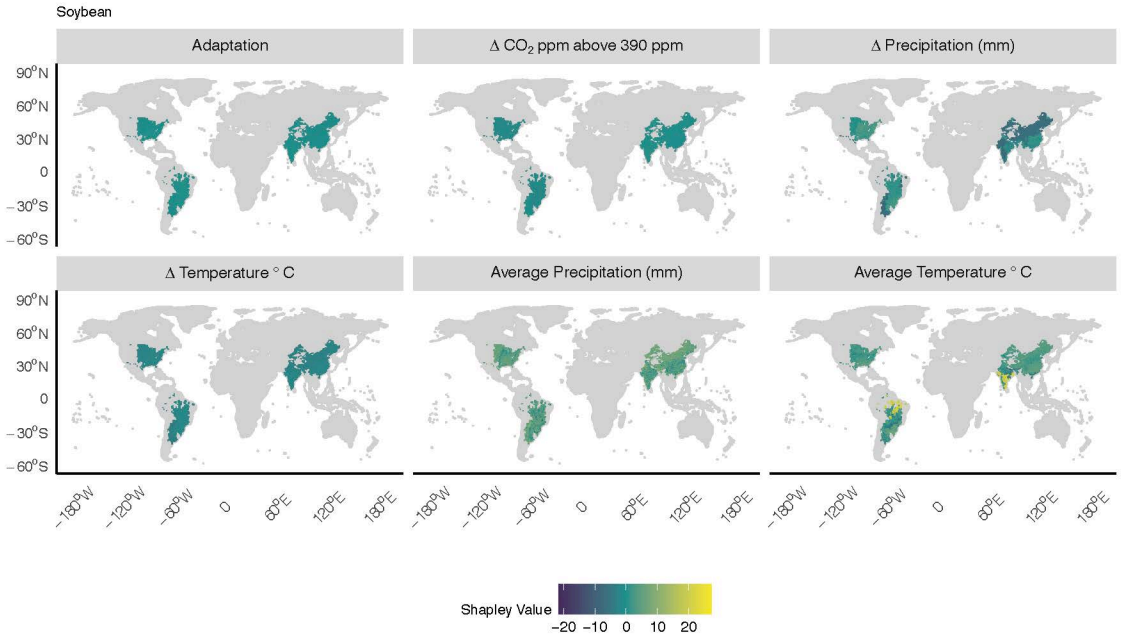

Figure S6d. Shapley additive explanation contribution to the predicted yield change (%) for soybean under an RCP4.5 scenario without adaptation. The four predictors considered are adaptation (Yes/No), change in CO_2 concentration above 390ppm, change in precipitation, warming level, average precipitation, and average temperature. The color bar indicates the Shapley value.

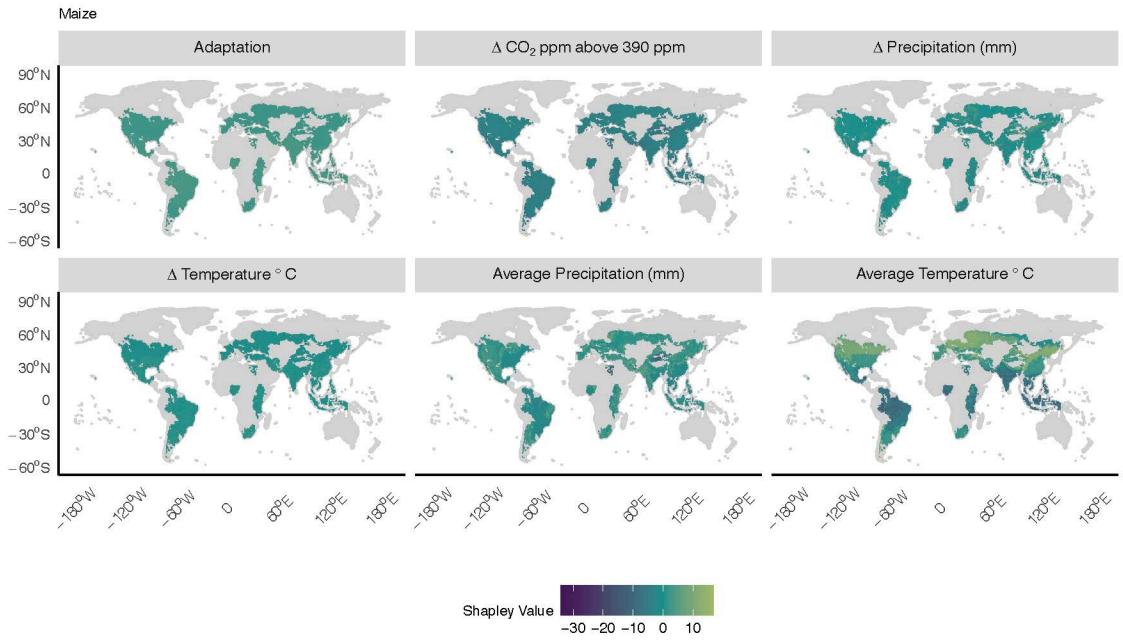

Figure S7a. Shapley additive explanation contribution to the predicted yield change (%) for maize under an RCP4.5 scenario with adaptation. The four predictors considered are adaptation (Yes/No), change in CO_2 concentration above 390ppm, change in precipitation, warming level, average precipitation, and average temperature. The color bar indicates the Shapley value.

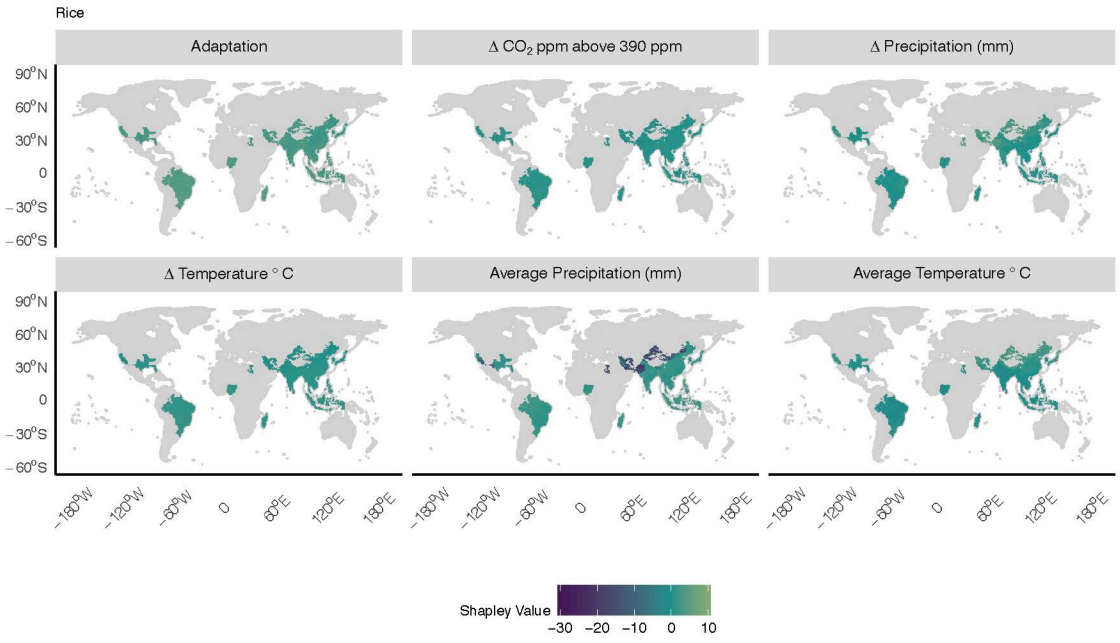

Figure S7b. Shapley additive explanation contribution to the predicted yield change (%) for rice under an RCP4.5 scenario with adaptation. The four predictors considered are adaptation (Yes/No), change in CO_2 concentration above 390ppm, change in precipitation, warming level, average precipitation, and average temperature. The color bar indicates the Shapley value.

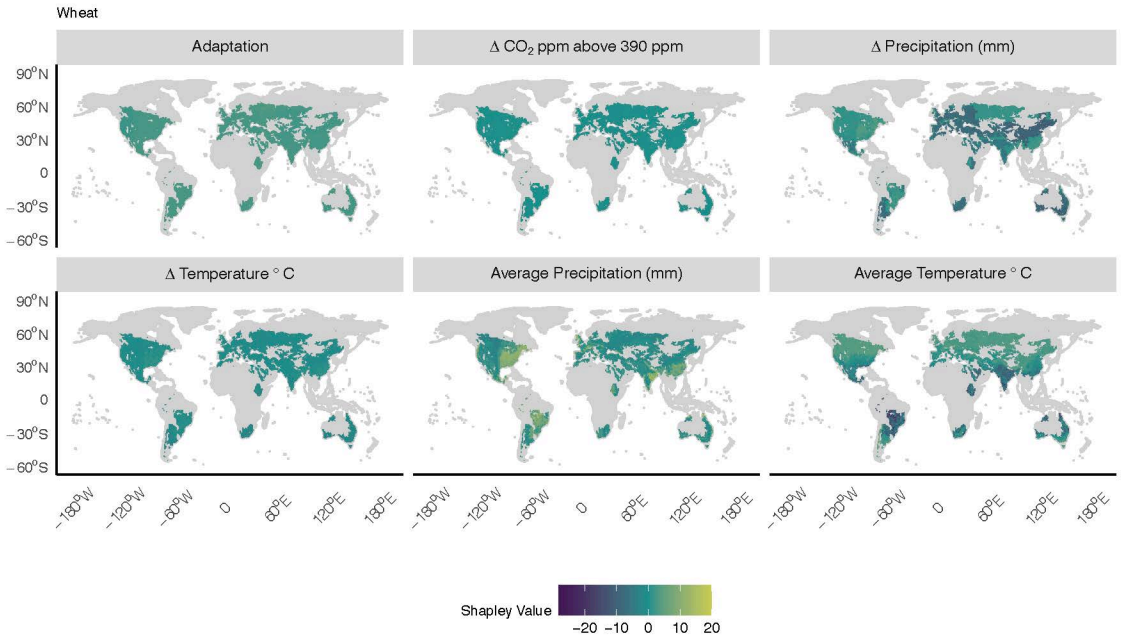

Figure S7c. Shapley additive explanation contribution to the predicted yield change (%) for wheat under an RCP4.5 scenario with adaptation. The four predictors considered are adaptation (Yes/No), change in CO_2 concentration above 390ppm, change in precipitation, warming level, average precipitation, and average temperature. The color bar indicates the Shapley value.

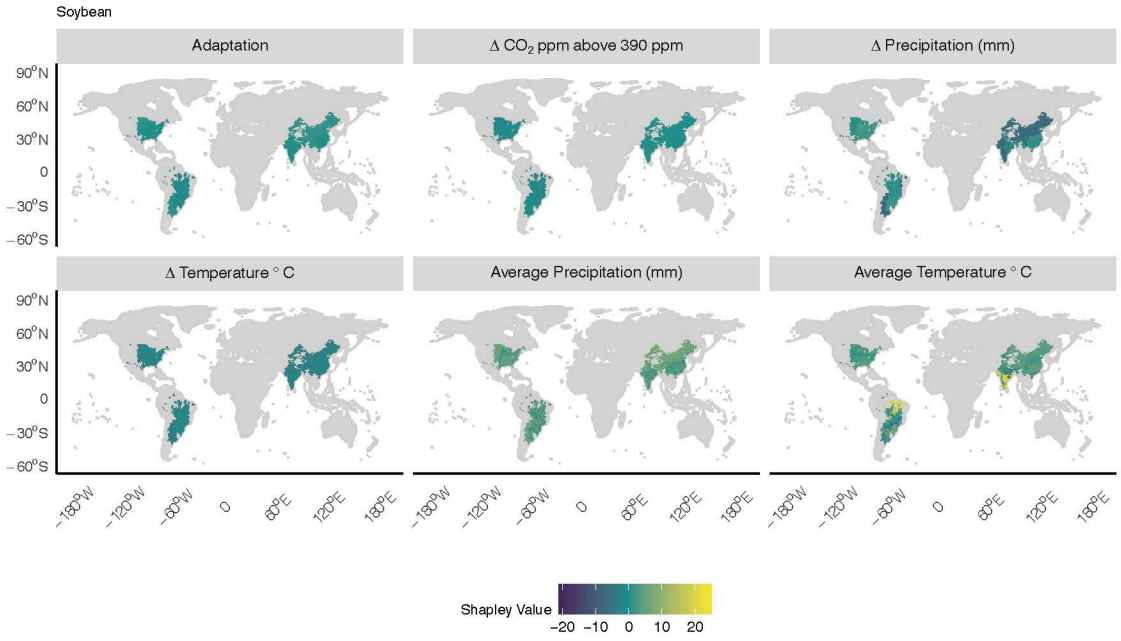

Figure S7d. Shapley additive explanation contribution to the predicted yield change (%) for soybean under an RCP4.5 scenario with adaptation. The four predictors considered are adaptation (Yes/No), change in CO_2 concentration above 390ppm, change in precipitation, warming level, average precipitation, and average temperature. The color bar indicates the Shapley value.

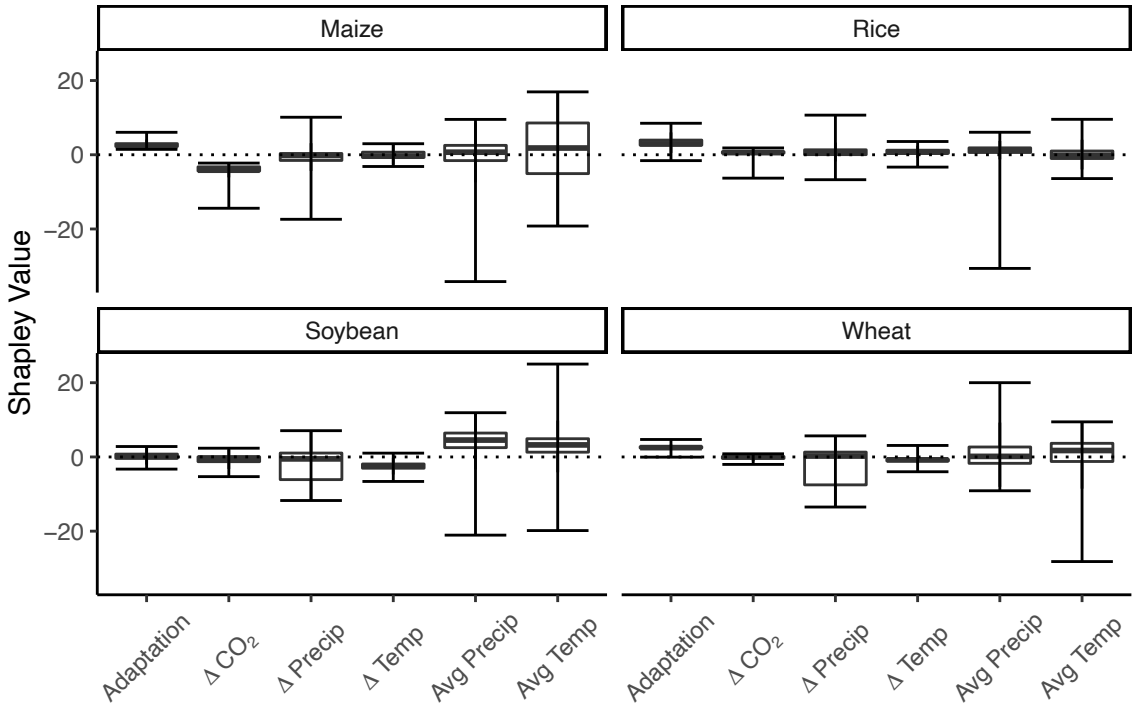

Figure S8. Shapley additive explanation contribution to the predicted yield change (%) for all crops under an RCP4.5 scenario with adaptation. The five predictors considered are application of adaptation strategies (Adaptation), change in CO_2 concentration above 390ppm (Δ CO_2), change in precipitation (Δ Precip), warming level (Δ Temp), average precipitation (Avg Precip), and average temperature (Avg Temp). Box represents the 1st quantile, median, and 3rd quantile. Whiskers show the minimum and maximum values.

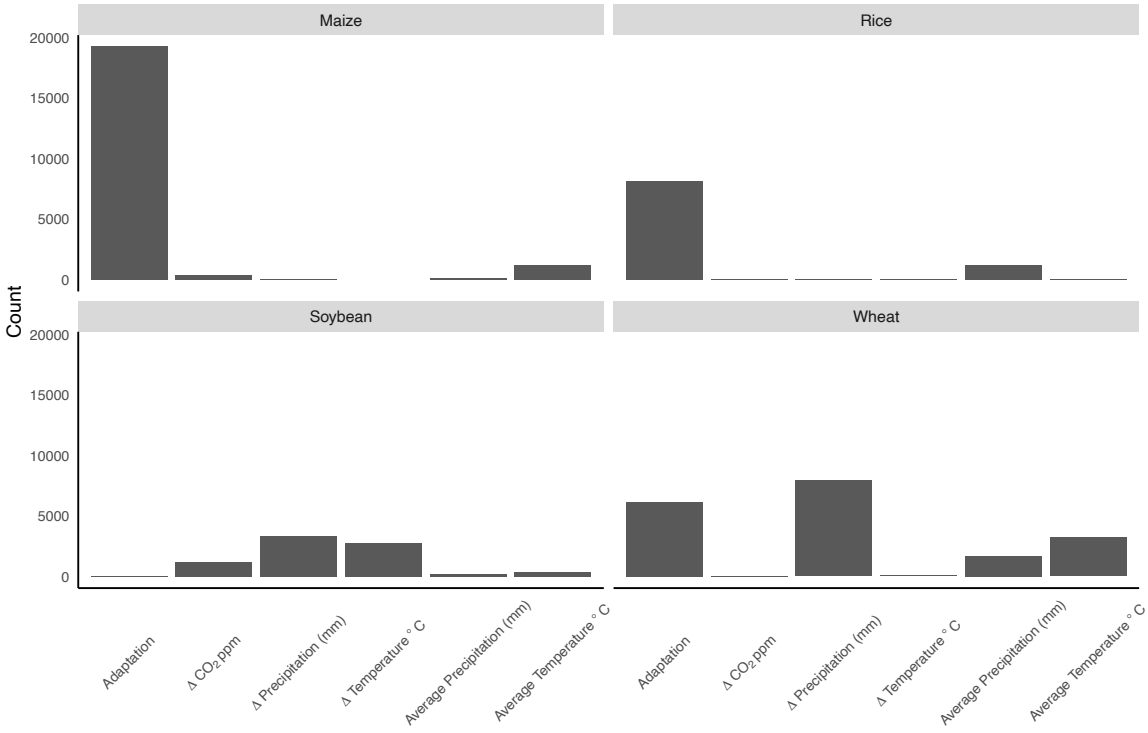

Figure S9. Barplots showing the number of grid cells in Figure 3 that are attributed to either adaptation, change in CO_2 concentration above 390ppm (Δ CO_2 ppm), change in precipitation (Δ Precipitation), warming level (Δ Temperature °C), average precipitation (mm), and average temperature (°C) for yield predictions under an RCP4.5 scenario with no adaptation.

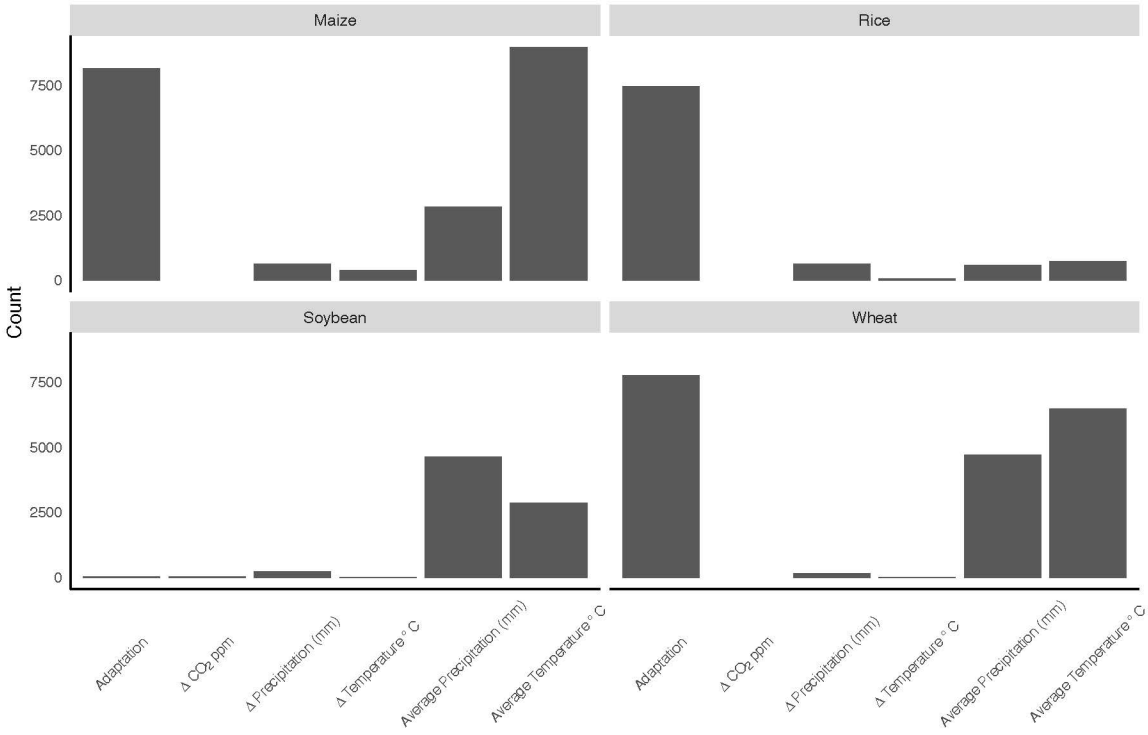

Figure S10. Barplots showing the number of grid cells in Figure 4 that are attributed to either adaptation, change in CO2 concentration above 390ppm (Δ CO2 ppm), change in precipitation (Δ Precipitation), warming level (Δ Temperature °C), average precipitation (mm), and average temperature (°C) for yield predictions under an RCP4.5 scenario with adaptation.

Crop	Number of yield simulations	Number of locations
Maize	4589	194
Rice	1519	99
Wheat	2298	174
Soybean	297	53

Table S1. Summary information for the synthesis dataset

Crop	*Model No.*	*RMSE*			*R^2*			*AIC*		
Maize	1	25.8	±	0.7	-0.27	±	0.07	676	±	38
	2	24.3	±	0.8	-0.11	±	0.04	601	±	43
	3	17.5	±	0.8	0.43	±	0.02	324	±	31
	4	**17.5**	±	0.8	**0.43**	±	0.02	**323**	±	31
	5	18.7	±	0.7	0.35	±	0.02	369	±	29
	6	17.5	±	0.8	0.43	±	0.02	328	±	29
	7	21.9	±	0.9	0.11	±	0.01	504	±	44
	8	22.5	±	0.9	0.06	±	0.02	530	±	44
	9	24.0	±	0.8	-0.07	±	0.03	598	±	41
	10	23.0	±	1.1	0.02	±	0.02	557	±	51
Rice	1	16.5	±	1.1	-0.09	±	0.04	288	±	38
	2	16.2	±	1.0	-0.06	±	0.04	274	±	32
	3	15.1	±	1.1	0.09	±	0.04	252	±	34
	4	15.8	±	1.0	-0.02	±	0.08	270	±	30
	5	**14.8**	±	1.1	**0.12**	±	0.04	**246**	±	33
	6	15.6	±	1.0	-0.01	±	0.11	269	±	33
	7	16.3	±	1.1	-0.07	±	0.03	295	±	36
	8	16.0	±	0.9	-0.06	±	0.07	281	±	30
	9	16.3	±	1.2	-0.07	±	0.04	296	±	38
	10	16.0	±	1.1	-0.02	±	0.03	285	±	36
Wheat	1	22.2	±	1.1	-0.09	±	0.05	508	±	51
	2	21.4	±	1.0	-0.02	±	0.05	471	±	42
	3	20.2	±	1.2	0.11	±	0.03	430	±	49
	4	20.3	±	1.3	0.10	±	0.04	441	±	59

	5	19.3	±	1.0	0.18	±	0.03	398	±	40
	6	**19.0**	±	1.1	**0.21**	±	0.04	**387**	±	42
	7	23.5	±	0.9	-0.24	±	0.08	579	±	43
	8	25.7	±	1.5	-0.46	±	0.08	699	±	82
	9	21.3	±	0.9	0.00	±	0.03	478	±	41
	10	21.7	±	1.0	-0.05	±	0.05	496	±	42
Soybean	1	29.6	±	3.8	0.12	±	0.11	1010	±	274
	2	29.9	±	3.7	0.11	±	0.10	1025	±	280
	3	29.5	±	4.3	0.12	±	0.14	1048	±	290
	4	30.8	±	4.8	0.05	±	0.17	1170	±	356
	5	**28.2**	±	3.8	**0.21**	±	0.10	**946**	±	264
	6	28.5	±	4.6	0.20	±	0.15	1020	±	338
	7	37.6	±	3.1	-0.43	±	0.04	1518	±	261
	8	450	±	409	-1764	±	1763	1713233	±	1711521
	9	34.9	±	3.2	-0.26	±	0.13	1325	±	235
	10	38.4	±	4.6	-0.48	±	0.18	1681	±	415

Table S2. RMSE, R^2, and AIC for the 10 models tested for maize, rice, wheat, and soybean. Model performance metrics are calculated using different locations that those of the training dataset. The model with the lowest RMSE, highest R^2, and lowest AIC for each crop is indicated in bold.

Crop	*Model No.*	*RMSE*			*R^2*			*AIC*		
Maize	1	15.2	±	0.4	0.32	±	0.01	236	±	12
	2	16.9	±	0.5	0.16	±	0.02	292	±	16
	3	12.3	±	0.6	0.54	±	0.04	166	±	15
	4	15.0	±	0.5	0.33	±	0.04	240	±	14
	5	**12.0**	±	0.6	**0.56**	±	0.04	**164**	±	14
	6	14.9	±	0.5	0.34	±	0.04	240	±	14
	7	14.6	±	0.3	0.37	±	0.02	232	±	9.7
	8	21.1	±	0.5	-0.33	±	0.06	467	±	22
	9	15.8	±	0.5	0.26	±	0.01	271	±	16
	10	14.5	±	0.3	0.37	±	0.02	231	±	9.9
Rice	1	15.6	±	0.3	-0.02	±	0.05	248	±	8.9
	2	14.0	±	0.4	0.18	±	0.03	202	±	10
	3	11.3	±	0.4	0.46	±	0.04	141	±	9.9
	4	12.3	±	0.4	0.36	±	0.04	164	±	8.5
	5	**11.1**	±	0.4	**0.48**	±	0.04	**140**	±	9.5
	6	12.0	±	0.4	0.40	±	0.04	160	±	8.9
	7	12.7	±	0.3	0.32	±	0.03	181	±	7.8
	8	14.0	±	0.4	0.19	±	0.03	215	±	11
	9	14.9	±	0.3	0.06	±	0.05	241	±	8.7
	10	13.1	±	0.3	0.28	±	0.04	190	±	7.0
Wheat	1	14.2	±	0.2	0.51	±	0.03	206	±	7.0
	2	16.1	±	0.2	0.37	±	0.02	264	±	8.0
	3	13.9	±	0.4	0.53	±	0.01	206	±	10
	4	15.6	±	0.3	0.41	±	0.01	257	±	10

	5	**12.3**	±	0.3	**0.63**	±	0.01	**169**	±	7.1
	6	14.2	±	0.3	0.51	±	0.02	219	±	9.7
	7	13.8	±	0.2	0.54	±	0.02	208	±	6.3
	8	21.8	±	0.6	-0.14	±	0.03	495	±	26
	9	14.2	±	0.2	0.51	±	0.02	220	±	6.8
	10	13.6	±	0.3	0.55	±	0.02	205	±	7.0
Soybean	1	19.5	±	0.7	0.54	±	0.05	389	±	27
	2	19.8	±	0.7	0.53	±	0.06	399	±	27
	3	21.1	±	1.2	0.48	±	0.06	470	±	54
	4	20.2	±	0.9	0.52	±	0.05	427	±	36
	5	18.8	±	0.9	0.58	±	0.04	379	±	36
	6	**17.3**	±	0.8	**0.65**	±	0.04	**320**	±	27
	7	25.2	±	0.6	0.25	±	0.07	655	±	31
	8	36.2	±	2.3	-0.57	±	0.22	1377	±	190
	9	20.2	±	0.6	0.51	±	0.06	428	±	24
	10	25.1	±	0.6	0.25	±	0.07	654	±	32

Table S3. RMSE, R^2, and AIC for the 10 models tested for four crops: maize, rice, wheat, and soybean. Model performance metrics are calculated using data split such that test locations are the same as those of the training dataset. The model with the lowest RMSE, highest R^2, and lowest AIC for each crop is indicated in bold.

Crop	Coefficient	SE	F-value	p-value
Maize	6.1	0.92	$43.4_{1,4438}$	<0.0001
Rice	11.6	0.84	$189_{1,1403}$	<0.0001
Wheat	7.3	0.84	$83.1_{1,2126}$	<0.0001
Soybean	7.9	2.3	$11.9_{1,262}$	0.0007

Table S4. F and p-values for adaptation as a fixed effect in the linear mixed model (Model 7).